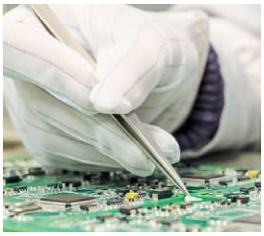


Advances in Transdisciplinary Engineering series

volume 16

Transdisciplinary Engineering for Resilience: Responding to System Disruptions

Proceedings of the 28th ISTE International Conference on Transdisciplinary Engineering, July 5 – July 9, 2021

EDITED BY
Linda Newnes
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Transdisciplinary Engineering for Resilience: Responding to System Disruptions

No one discipline or person can encompass all the knowledge necessary to solve complex, ill-defined problems, or problems for which a solution is not immediately obvious. The concept of Concurrent Engineering (CE) – interdisciplinary, but with an engineering focus – was developed to increase the efficiency and effectiveness of the Product Creation Process (PCP) by conducting different phases of a product's life concurrently. Transdisciplinary Engineering has transcended CE, emphasizing the crucial importance of interdisciplinary openness and collaboration.

This book presents the proceedings of the 28th ISTE International Conference on Transdisciplinary Engineering (TE2021). Held online from 5 – 9 July 2021 and entitled 'Transdisciplinary Engineering for Resilience: Responding to System Disruptions', this is the second conference in the series held virtually due to the COVID-19 pandemic. The annual TE conference constitutes an important forum for international scientific exchange on transdisciplinary engineering research, advances, and applications, and is attended by researchers, industry experts and students, as well as government representatives. The book contains 58 peer-reviewed papers, selected from more than 80 submissions and ranging from the theoretical and conceptual to strongly pragmatic and addressing industrial best practice. The papers are grouped under 6 headings covering theory; education and training; PD methods and digital TE; industry and society; product systems; and individuals and teams.

Providing an overview of the latest research results and knowledge of product creation processes and related methodologies, the book will be of interest to all researchers, design practitioners, and educators working in the field of Transdisciplinary Engineering.

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TRANSDISCIPLINARY ENGINEERING FOR RESILIENCE: RESPONDING TO SYSTEM DISRUPTIONS

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Advances in Transdisciplinary Engineering (ATDE) is a peer-reviewed book series covering the developments in the key application areas in product quality, production efficiency and overall customer satisfaction.

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Volume 16

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Preface

This book of proceedings contains papers that have been peer-reviewed and accepted for the 28th ISTE International Conference on Transdisciplinary Engineering, organized by the University of Bath, United Kingdom, July 5–9, 2021. TE2021 has been the second conference in the series that was organized in a virtual manner due to the COVID-19 world-wide crisis. The papers published in this book of proceedings, as well as video presentations, were accessible from July 5 till July 9 in Teams, while questions and answers were being exchanged.

This is the tenth issue of the series “Advances in Transdisciplinary Engineering”, which publishes the proceedings of the TE (formerly: CE) conference series and accompanying events. The TE conference series is organized annually by the International Society of Transdisciplinary Engineering, in short ISTE (www.intsoctransde.org), formerly called International Society of Productivity Enhancement (ISPE, Inc.) and constitutes an important forum for international scientific exchange on transdisciplinary engineering. These international conferences attract a significant number of researchers, industry experts and students, as well as government representatives, who are interested in recent advances in transdisciplinary engineering research, advancements, and applications.

The concept of Transdisciplinary Engineering transcends Concurrent Engineering (CE). The concept of CE, developed in the 80’s, implies that different phases of a product life cycle are conducted concurrently and initiated as early as possible within the Product Creation Process (PCP), including the implications of this approach within the extended enterprise and networks. The main goal of CE is to increase the efficiency and effectiveness of the PCP and to reduce errors in the later phases, as well as to incorporate considerations for the full lifecycle, through-life operations, and environmental issues. In the past decades, CE has become the substantive basic methodology in many industries (e.g., automotive, aerospace, machinery, shipbuilding, consumer goods, process industry, environmental engineering) and is also adopted in the development of new services and service support. Collaboration between different disciplines is key to successful CE. The main focus, though, is an engineering focus.

While for several decades CE proved its value in many industries and still continues to do so, many current engineering problems require a more encompassing approach. Many engineering problems have a large impact on society. The context of these problems needs to be taken into account. For example, the development of self-driving cars requires taking into account changes in regulations for managing responsibilities, adaptation to road networks, political decisions, infrastructures for energy supply, etc. The impacted society may also be the business environment of networks of companies and supply chains. For example, the adoption and implementation of Industry 4.0 requires taking into account the changes to be expected in the business environment, the people, their jobs, the knowledge needed, technology, organizational rules and behaviours. These kind of engineering problems also require collaboration, but not only between technical disciplines. Disciplines from other scientific fields need to be incorporated in the engineering process, like disciplines from social sciences (governance, psychology, etc.), law, medicine, or other fields, relevant for the problem at hand.

The concept of transdisciplinary engineering transcends inter- and multi-disciplinary ways of working, like in CE. In particular, transdisciplinary processes are aimed at solving complex ill-defined problems or problems for which the solution is not obvious from the beginning. While such problems, including their solutions, have a large impact on society and the context in which the problems exist, it is important that people from society and practice collaborate with people from different relevant scientific communities. Neither one discipline nor one person can bring sufficient knowledge for solving such problems. Collaboration again is essential but has become even more demanding. Disciplines should be open to other disciplines to be able to share and exchange the knowledge necessary for solving the problem.

As indicated above any engineering problem can be put is a context in which the problem is to be solved or in which the solution for the problem is expected to be used. For researchers and engineers, it is important to take this context into account. This could be done, for example, by collaborating with researchers who can study user acceptance of the envisioned solution or with researchers who can apply suitable methods to acquire user preferences in the respective context and translate them into the necessary requirements for the solution to be developed. Validation of a proposed engineering solution will benefit also by incorporating people from other scientific fields.

The conference is entitled: 'Transdisciplinary Engineering for Resilience: Responding to system disruptions' indicating the dynamic and evolving nature of TE processes, requiring new knowledge, methods and tools to support the process. The TE2021 Organizing Committee has identified 36 thematic areas grouped into nine themes within TE and launched a Call for Papers accordingly. More than 80 papers have been submitted from all over the world. The submissions as well as invited talks have been collated into nine themes.

The Proceedings contains 58 peer-reviewed papers presented at the conference by authors from 24 countries. These papers range from the theoretical, conceptual to strongly pragmatic addressing industrial best practice. The involvement of industry in many of the presented papers gives additional importance to this conference.

This book on "Transdisciplinary Engineering for Resilience. Responding to System Disruption" is directed at three constituencies: researchers, design practitioners, and educators. Researchers will benefit from the latest research results and knowledge of product creation processes and related methodologies. Engineering professionals and practitioners will learn from the current state of the art in transdisciplinary engineering practice, new approaches, methods, tools, and their applications. The educators in the TE community gather the latest advances and methodologies for dissemination in engineering curricula, to prepare students for transdisciplinary collaboration in complex engineering processes, while the community also encourages educators to bring new ideas into the field. With the annual contributions of many researchers and practitioners the book series will contribute to the further development of the concept of Transdisciplinary Engineering.

The proceedings are subdivided into several parts, reflecting the themes addressed in the conference programme:

Part 1 is entitled Transdisciplinary Engineering Theory and contains five papers that address the concept of TE. Paper one presents a framework for assisting a TE approach to systemic risk detection. Paper two presents a comparison of a quality and a design approach in a TE context of setting up medical trials. Paper three presents findings of a preliminary exploration of the significance of TE in an industrial context. Paper four is an essay on the multi-dimensionality of TE. Paper five presents results of a workshop to develop an initial version of a disciplinary maturity grid to assess an industry's engineering capability.

Part 2 contains three papers in the field of Transdisciplinary Engineering Education and Training, an important field in our conferences. In paper one, a framework is presented for the analysis of simulation effectiveness in training medical treatment procedures. A discussion of the need for a holistic curriculum design in digital manufacturing in presented in paper two. Design thinking is considered essential for people with different domain knowledge. In paper three, a framework developed by master students is proposed to facilitate design automation in different phases of design. Three SMEs have used variations of the framework.

Part 3, PD Methods and Digital TE, contains 11 papers. In paper one, a conceptual approach is presented to incrementally update a Digital Twin, especially suited for SMEs. In paper two, the basis for the method described in paper one, is presented with a use case. In paper three, a proposal for automated logo recognition and legal analysis for IP protection is presented. Activities to develop a tool to support the design of CPSs are described in paper four. In paper five, an NLP approach is presented for chatbots. The approach is applied to the management of patent trends. In paper six, a framework is proposed aimed at identifying, categorizing, prioritizing, and mitigating uncertainties in the process of digitization of life-cycle product models. In paper seven, IT tools are described for automating the generations of Digital Twins of machine tools. Paper eight contains a study into improving interoperability in the new manufacturing environment. In paper nine, also interoperability is addressed. An approach is presented for the automatic prediction of failure in the manufacturing process. The authors of paper 10 investigate issues in optimising end-to-end maintenance within manufacturing with DTs, IM, and Its. In paper 11, a five-dimensional DT framework has been proposed linking physical data and virtual data with an ERP for modelling the digital twin of electric vehicle batteries.

Part 4 contains 15 papers in the theme Industry and Society. In paper one, a method for implementing flex-time schedules in a service industry. An optimal production planning method for high-mix low-volume production is proposed in paper two. Paper three contains a literature study into the use of 4.0 technologies in Product Lifecycle Management with a focus on Sustainable Development. In paper four, an analysis is presented of different scenarios for resource planning in a multi-project environment. Based on a literature review the first of three artefacts is presented in paper five: a model to characterize Agriculture 4.0. In paper six, a proposal for a metro-car tracking system is proposed. A theoretical exploration into challenges and opportunities for the digitization of product development and manufacturing process is presented in paper seven. In paper eight, a study is presented into the existing gaps between reshoring drivers and critical operations capabilities. Paper nine contains a system dynamic modeling approach and an empirical study on innovation diffusion for subsystems in the automotive industry in the past decades. In paper 10, a cause-effect diagram is presented for analysing risks in the civil industry. Paper 11 contains a proposal for a framework of questions to identify risks in different phases of a civil engineering process. In paper 12, a model is proposed for the digitization of the railway industry, using the Balanced Score Card and Multi-Criteria Decision making. Paper 13 contains research that contributes to the reshoring literature by providing a multi-stage fuzzy-logic model that simultaneously handles different groups of criteria, and to practitioners by contemplating different key competencies within a company during the reshoring decision process. In paper 14, results of twenty-four multiple case studies in the construction sector are presented, which suggest new quality dimensions and ways to adapt to changed service-quality demands. Paper 15 contains a literature study and case studies into the level of alignment between product development and production. Several problems have been identified.

Part 5 is entitled Product Systems and contains 13 papers. Paper one contains a comparison between two tools for predicting human effort and ergonomic risk related to a series of tasks. In paper two, the TRIZ approach is applied to the non-trivial design of a Wire Electric Discharge Machining (WEDM). The work presented in paper three is an exploration of the possibility to analyse the performance of production lines through digital models. In paper four, a proposal is presented of an associative framework between processes and related data, which are following the recommendations of currently applied frameworks for Business Process Management and Big Data Analytics. In paper five, a literature study is described on APSs, as well as the impact of Industry 4.0 on the development of these systems. Paper six contains a simulation model developed for allowing the selection of appropriate parameters of a power supply system and a drive system for an electric go-kart to meet criteria assumed. In paper seven, research is presented into semantic and syntactic knowledge boundaries that play a role in introducing new products with its accompanying production processes. Paper eight contains a literature study into Advanced Manufacturing, the results of which have been applied to an experimental case. In paper nine, an exploration is presented of opportunities for Kazakhstan to recycle CFPR waste originating in this country and neighbouring countries. Paper 10 contains an exploration of the possibility to automate the design of a wing structure. In paper 11, the possibility of supporting the vertical take-off and landing unmanned aerial vehicle electric power systems by means of photovoltaic cells. An approach for optimizing floor plans using data collected from workplaces and a physics-based planning algorithm utilizing GPU-acceleration is presented in paper 12. In paper 13, a research step is presented to develop a methodology for designing and analysing a propeller, which can be used in a calculation backgound for a CAD model.

Part 6 contains 11 contributions on Individual and Teams. In paper one, a demonstration Is presented of a virtual tour in a cheese factory. The multi-faceted nature of a virtual tour is highlighted. Paper two contains a design of a rescue helicopter that can approach mountain tops and dangerous terrains. In paper three, a new AR/VR methodology is presented that allows an operator to touch any object in a virtual cabin design of a medical helicopter. Feedback from medical professionals is included. A patent portfolio analysis for VR tools is presented in paper four. Promising areas for further development in the medical domain have been identified. Paper five contains a patent analysis to discover trends in HCPSs in manufacturing. In paper six, an approach is presented to enhance human perspectives by introducing a semiotic framework for representing different aspects of human and organizational meaning formation. The approach is illustrated in a translational medicine organization. Paper seven contains a demonstration of a technology to detect behavioural states of team members during a meeting. In paper eight, a numerical method is presented that is a good step towards systematic design of attractive product shapes. In paper nine, a first design iteration is demonstrated in which a framework is applied that provide disciplines guidelines for achieving health-related objectives. Paper 10 contains a specification of a generic user interface that makes computational systems models more accessible to non-technical decision makers. Finally, paper 11 is a research paper containing research into the generation of a functional structure of a product connected with a Multi-interfaces Entity Model that supports risk assessment.

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Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Towards a Transdisciplinary Approach to Systemic Risk Detection

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Abstract. Systemic risks are potentially harmful events, that could severely disrupt an entire industry or economy. Examples include the bankruptcy of keystone companies and biosecurity incursions. According to the United Nations, detecting and managing systemic risk represents one of the main challenges of the 21st century. Due to increasing complexity and interconnectedness of today's social-technological-biophysical systems, stakeholders relying on individual disciplines to systemic risk detection, or a combination of disciplines that are not well coordinated, will fail to promptly identify key early warning signals of threats. Our paper argues that transdisciplinary approaches are required to make comprehensive and integrative assessments of complex systems. To support stakeholders undertaking such assessments, we propose a framework that will assist them in: (1) better understanding their system and the risks to which it is exposed; (2) selecting complementary disciplines, theories and methods that are relevant to the system and risks in question; and (3) integrating knowledge from these different disciplines to detect a wide range of early warning signals of systemic risk. The framework can be used as a foundation to build transdisciplinary approaches to risk detection.

Keywords. Transdisciplinary, systemic risk, risk detection, early warning systems

Introduction

Our social, technological and biological systems are becoming ever more integrated through trade, travel and communication. This makes these systems more complex and dynamic, preventing equilibria from forming and establishing, and so makes them increasingly unstable. In such systems, it is hard to identify and mitigate systemic fragilities and risk. According to the United Nations (UN), the management of systemic risk is expected to be the main global challenge of the next decades [1].

Over the last half a century or so, researchers, analysts, regulators and other stakeholders[2] have started to build Early Warning Systems (EWSs) for detecting systemic risks. EWSs have been developed and deployed for the detection of a wide range of risks, including: missile attacks, virus outbreaks, earthquakes, and financial

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[2] Stakeholders refers to the actors that have an interest in a system's functioning or success. This includes the actors directly involved in a system (e.g., farmers in the food production system), but also some external actors (e.g., consumers of food products).

crises [2][3][4]. Many of these EWSs have been constructed with a narrow focus in mind – dedicated to spotting warning signals in specific sub-systems and rely upon a limited range of indicators, tools and science disciplines. However, due to the increase in complexity and interconnectedness of our systems, such narrow-focused approaches to systemic risk detection will likely either miss key warning signals of threats or not anticipate their impact correctly [5][6].

To be able to understand complex social-technological-biophysical systems, and what types of risks lurk within them, we argue that insights from a wide range of science disciplines and stakeholders are necessary, and a transdisciplinary approach is required in order to make these different disciplines and stakeholders work well together. Narrow-focused approaches will be unable to detect enough systemic vulnerabilities in modern day complex systems [1]. Therefore, there is a need to enhance the ability to look at a system from different angles, reducing blind spots and developing a variety of scenarios about how a system may evolve.

While some integrated research approaches to the study of systemic risk have been undertaken [7][8], work in this area is still at an early stage. Especially, a robust framework for linking and integrating knowledge from different disciplines and stakeholders in a coherent fashion is lacking. Thus, developing such a framework is critical to bringing research in this area forward. Failing to synchronize and combinations of non-complementary disciplines, theories, methods, and models will not help researchers and stakeholders make comprehensive assessments of complex systems.

In this paper, we present a framework for developing transdisciplinary approaches to systemic risk detection. The framework is meant to assist researchers and stakeholders in: (1) better understanding their system and the risks to which it is exposed; (2) selecting complementary disciplines, theories and methods that are relevant to the system and risks in question; and (3) integrating knowledge from these different disciplines to detect a wide range of early warning signals of systemic risk. The remainder of the paper is organized as follows. Section 1 outlines the basics of systemic risk. Section 2 gives a brief overview of the theories and methods used to detect systemic risk based on a targeted literature review. Articles for the review were selected based on the scalability of the discussed theories and methods to different types of context and risks. Section 3 discusses some of the difficulties that arise in systemic risk detection and explains how transdisciplinary approaches can help to overcome these difficulties. Section 4 presents a framework for developing such approaches. The final section concludes the paper.

1. Systemic risk

Systemic risks are potentially harmful events that could severely disrupt or even do unrepairable damage to a network if they were to occur [5][9]. Systemic risks are often triggered by failures at key nodes within the network, which can cause rippling effects across the remainder of the network [10]. For example, in financial networks, the bankruptcy of a large and well-connected bank, may cause other banks to go bankrupt as well.

Systemic risks tend to arise predominantly in complex networks [7]. The relationships and interactions between the numerous elements making up such networks (e.g., cities, markets, coral reefs) are often difficult to comprehend. This complexity is accentuated by their dynamism, which may make these relationships also unstable [11][5]. As a result, researchers and stakeholders struggle to understand what types of risks may be hiding within the network and find it difficult to predict how the network may respond to external events or threats.

Systemic risks can be distinguished alongside various dimensions. First, is the time-interval between the first signal of an upcoming event and its impact. The onset of a systemic event can be very rapid or a train wreck in slow motion. Covid 19 is a good example of the former and climate change exemplifies the latter. For an EWSs to be of value, intervention needs to be possible between the time a signal is detected, and the time the event occurs or makes its impact (e.g., a tsunami alert in case of an earthquake).

Second, systemic risks can be classified based on the strength of the signal. Signals can be non-existent, weak, or strong. In general, signals increase in strength as a crisis draws closer. For example, signals that something was wrong in the financial services system became clearer over time in the lead-up to the 2008 sub-prime mortgage crisis. EWSs are mainly valuable in the context of picking up weak signals early, so that stakeholders have more options to mitigate a risk or prepare for its adverse consequences.

Third and last, systemic risks can be differentiated based on their genesis: internally or externally generated. An internal risk is caused by factors endogenous to a system (e.g., mismanagement at a key company), while an external risk is caused by exogenous factors (e.g., an energy crisis because of global political tension). However, it can be difficult to distinguish between internal and external risks, as exogenous factors often interact with endogenous factors (e.g., as when the effect of mismanagement at a key company become more glaring and pronounced because a global recession is ongoing). In today's interconnected world, for an EWS to be of value in making a comprehensive assessments of threats to a system, both internal and external risks need to be considered.

2. Systemic risk detection: theories and methods

We briefly discuss some of the key theories and methods/tools used to detect systemic risk. "Detection" refers to the process of: (1) identifying a risk; (2) assessing its likely impact; and (3) communicating this assessment to analysts. A theory or tool may cover the whole process of risk detection, or just one or two components of it.

2.1. Examples of theories

A wide range of theoretical perspectives is used to study systemic risk [7][11]. Due to space limitations, we will focus on two relatively widely used frameworks: system theory and network theory. As both theories have their limitations as stand-alone frameworks, researchers and stakeholders should consider using multiple theories when studying systemic risks, including other perspectives.

System's theory is used to identify and assess the processes that cause a system's structure to change and evolve. Systems theory focuses on the self-organizing capabilities of complex systems or structures [12][7][13]. How does a complex system evolve and adapt over time? What is the influence of the system's initial structure or conditions on the system's evolutionary path? How do a system's constituent components interactions influence this process? What feedback loops keep the system on a relatively predictable path? What are the interactions and feedback loops that make a system go 'off-track'?

System theory is foundational for systemic risk analysis but has a few limitations. Firstly, the theory gives limited guidance to researcher on the specific aspects of the system that they should focus on. Questions, such as how the boundaries of the system should be determined or how key interdependencies and feed-back loops of a system can be identified a priori, remain insufficiently addressed. This limits its usefulness for model variable selection. For example, if a system's boundaries, or interactions with neighboring systems are not well-understood, externally generated systemic risks may be missed. Secondly, many approaches based on system theory are preoccupied with bottom-up changes to the system and often insufficiently consider top-down driven changes. As a result, certain risks may be missed, such as rapid on-set events arising from failure at central institutions.

Network theory describes a system's structure in terms of relationships between the elements [11]. Activity within the system, such as the sharing of information between human agents or the spread of a viral disease, is considered to be enabled or constrained by that structure [14]. For example, all else being equal, a viral disease will spread more easily within dense networks than in sparsely connected networks with largely self-contained, isolated hubs of agents.

Like systems theory, network theory is central to understanding and analysing systemic risk. However, also like systems theory, it has a couple of limitations. For example, many approaches that rely on network theory insufficiently consider the multi-layered nature of complex systems, which have a range of different types of overlapping networks. Researchers that don't take this property of systems into accounts are likely to make erroneous conclusions. For example, the complexity of the economic ties between agents in the financial system has increased drastically over the last three decades. But, this complexity has been for a large part enabled by an accompanying increase in the complexity of the communications network supporting those economic ties. Without taking this into account, assessments about the stability of the current structure of the financial system are going to be ill-informed.

2.2. Trends in systemic risk detection methods and tools

Multi-agent simulations, sentiment analysis, graph theory, network modelling, Bayesian networks, and systems dynamics are some of the key methods, tools and techniques that have been applied to the study of systemic risk [15][9][16][17]. These techniques have been used at various levels of system analysis, including to simulate the micro-level behaviour of market participants, to identify critical clusters within networks, to simulate interaction effects between different sectors of the economy, and more generally to anticipate positive feedback loops and non-linear transformations in the system.

Furthermore, researchers have started to develop hybrid approaches, whereby a combination of different types of techniques is applied to the study of systemic risk. For example, Paulin et al. combine an agent-based model with network modelling to study the conditions that lead to "flash crash" events in financial markets [18]. The Bank of England uses a collection of models to cross-check projections made based on a general equilibrium model [19]. Bradhurst et al. combine a population-based model with an agent-based model to simulate the spread of livestock diseases [20].

The basic logic behind the trend towards hybrid approaches is that while individual techniques can be useful for studying individual parts of the system, or to obtain a narrow perspective on the functioning of the system as a whole, they need to be combined with other tools and techniques to address the limitations of each individual tool and to obtain a more comprehensive view of the system. Hybrid approaches address the need for more integrated, comprehensive approaches to the study of complex systems.

However, they are at an early stage of development, often only loosely linking a limited number of techniques from closely related disciplines. At present, such approaches are unable to capture all key interdependencies that exist amongst system components.

3. Systemic risk detection challenges

Section 3.1 discusses the difficulties in information- access and processing that risk-managers face in their systemic risk detection attempts and argues that inter- or transdisciplinary approaches are required to help them deal with these difficulties. Section 3.2 discusses some of the conflicts of interests and biases that a wider group of stakeholders face in dealing with complex systems and explains how they tend to lead to under-investment in risk management activities. More active stakeholder involvement in risk-management decision making could help to address this. Transdisciplinary approaches are especially suitable for enabling such stakeholder involvement.

3.1. "Technical" difficulties in systemic risk-management

Systemic risk management activities are usually carried out by regulatory agencies representing the interests of external stakeholders (e.g., a food safety regulator), through collective institutions that represent a wider range of agents (e.g., an industry board), as well as by the larger agents within the system (e.g., a large slaughterhouse that keeps track of food safety issues across the meat industry). Such risk-managers usually face various difficulties in identifying, assessing, and managing systemic risk.

Firstly, information about the system may be missing or out-of-date. For example, assessments of financial systemic risk based on the balance sheet data of large financial institutions maybe a good reflection of the state of the system at a particular point in time. However, the system may have already shifted towards a new state by the time this data becomes available to analysts. *Secondly*, even if key information is promptly available, it may be difficult to process it in a timely manner. For example, thousands of pages would have had to been read to fully assess the risks of some of the securities that helped cause the subprime crisis [11]. *Thirdly,* the state of the system that increases the likelihood of a systemic risk occurring may not be fully transparent to (external) stakeholders. For example, many food systems are made up of numerous actors, operating in a wide range of countries. This makes it complicated to promptly detect fraudulent activities, such as those that led to the European horse meat scandal. *Fourthly*, the consequences of systemic events are generally difficult to estimate ex-ante, even in the case of well-known and widely assessed risks (e.g., climate change).

Ultimately, the above-mentioned difficulties tie back to the problem of anticipating the evolutionary path of complex systems based on incomplete information and limited information processing abilities. With complex systems, often a plurality of opaque, future scenarios is plausible [6]. To be able to anticipate as many of these scenarios as is possible, it is necessary to assess the system from multiple angles, disciplines, and techniques. This helps to hedge the risk that any individual technique will fail to promptly identify a warning signal of risk. However, to detect systemic risk requires not only that a wider range of disciplines study the system, but also smarter approaches for making these different disciplines work in sync. Individual disciplines cannot offer stakeholders the diversity of models and perspectives that is necessary to untangle a complex system, while a combination of disciplines that are not well-coordinated (a multidisciplinary approach) will not help stakeholders to link or integrate these perspectives into a well-rounded picture of the system.

3.2 Disincentives, biases, and under-investment in systemic risk management

In addition to imperfect insight into the system's possible evolutionary paths, risk-managers and other stakeholders also often face various disincentives and biases against undertaking sufficient risk-management activities [21][22] [13], including:

- Many systemic risks are rare events (e.g., a global financial crisis), appear to be in the distant future (e.g., job losses as a result of advances in AI and robotics), or are "slow-burner" events (e.g., climate change). Companies due to shareholders and politicians due to voters usually take a more shorter-term view. Therefore, agents and external stakeholders often defer adequately preparing for systemic risk.
- Consumers and citizens more generally, often take a short-term view as well. This is in part due to reasoning errors where future probable costs are overly discounted.
- Conflicts of interests may also exist. For example, an older citizen may be less willing to commit resources to preventing distant future or slow-burner events than a younger citizen (who will bear the brunt of these events).
- Humans evolved in small, technological undeveloped groups and communities. Our ability to intuitively understand complex systems is thus naturally poor.

Interdisciplinary approaches deal with well-defined scientific problems. The conflicts of interests between stakeholders in complex systems mentioned above suggest that interdisciplinary approaches will be insufficient to deal with many systemic risks. Combining interdisciplinary research with multi-stakeholder discourse, i.e. transdisciplinary approaches are thus required [23]. Transdisciplinary research deals with problems that are less clear (e.g., how to anticipate black swans). They also have more explicitly normative components (e.g., how to balance inter-temporal trade-offs) [23]. Such problems are common in complex systems, where many different actors operate with competing interests [24].

4. Towards a transdisciplinary approach

Our framework for developing transdisciplinary approaches to systemic risk detection is visualized in Figure 1. The framework is based both on the characteristics of complex systems and systemic risks, as well as on our own experiences in developing an approach to detecting biosecurity-related systemic risks in New Zealand.

The framework consists of three iterative loops which feed into each other. In the *integrated development loop*, the scientific disciplines and stakeholders that are needed to assess the system are selected and an approach for working together is developed. In the *knowledge development loop*, the researchers and stakeholders use this approach to co-develop knowledge about how to assess the risks to which the system is exposed. This knowledge is then applied to assess the system in question in the *system's analysis loop.* During this analysis loop, new information and learnings will be obtained about the system, as well as feedback about the suitability of the developed approach for assessing it. This feedback is then used by the researchers and stakeholders to expand and build on their knowledge about the system and how to best assess it. This modified approach can then be applied to make new system assessments, from which again additional information will be obtained about the suitability of the developed approach for assessing it. This should lead to a continuous learning loop in which the approach and tools used to assess the system – as well as the ways in which people work together to create and modify these tools – are regularly questioned, evaluated and improved, as knowledge is never taken for granted about quickly changing systems.

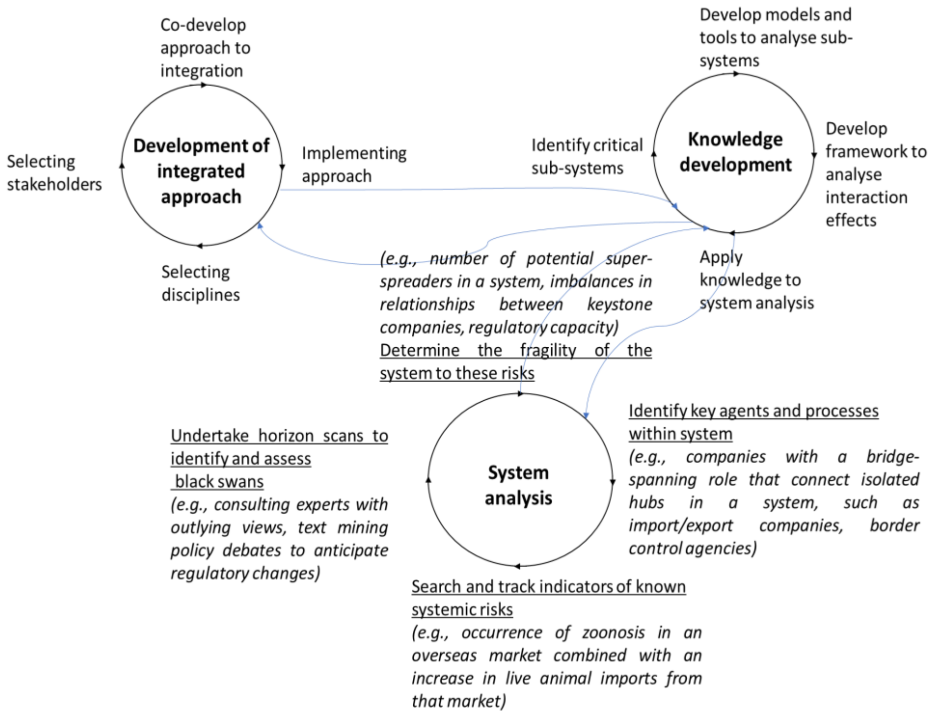

Figure 1. Framework for developing TD approaches to systemic risk detection.

The integrated development loop consists of 4 phases: (1), selecting disciplines; (2), selecting stakeholders; (3), developing an approach to working together; (4), implementation. The initial selection of disciplines and stakeholders will most likely be intuitive, as in many transdisciplinary research projects. However, over time, after the first loop of the integrated development phase is completed, the selection should become more structured and driven by gaps in the approach used to analyse the system. Cognitive diversity is important to the process of systemic risk detection (e.g., see [25]) and it therefore pays to be inclusive during the selection process. In the next phase, researchers and stakeholders have to build consensus and capacity about how to work together and agree upon strategies and methods for integrating knowledge. To be able to deal with system complexity, it is useful to split-up the larger project team into several smaller teams, each responsible for developing a model of a sub-component of the system [26]. Furthermore, it is also necessary to create teams responsible for identifying and studying interaction effects between the various sub-components. To ensure that a plurality of perspectives on the state of the system will be realized, which is important as in complex systems a plurality of different types of futures is often equally likely [6], multiple teams will have to be tasked with assessing the same sub-systems, but through different approaches, lenses and with a different make-up in terms of involved disciplines and stakeholders. Additionally, to help ensure such a plurality of perspectives, interaction between teams analysing the same sub-components of the system needs to be limited until after the system analysis phase (after which mutual learnings can take place about what worked, and what didn't). The teams responsible for integrating results from the different sub-system analysis will have to devise methods for aggregating results, either by combining the results from different types of assessments, or by establishing a hierarchy in the quality of the assessments [27]. A hierarchical approach is preferred in the context of systemic risk, as the underlying assessments are preserved more directly, helping to maintain a plurality of perspectives. Finally, the developed approach is put into practice, first by co-developing the knowledge required to assess the system, and subsequently by applying that knowledge to assess the system.

In the first phase of the knowledge development loop, the system is broken down conceptually into sub-components, which can be more easily modelled and analysed [26]. The focus here should be on those sub-systems that put the survival of the system at risk if they fail to function properly. For example, in the context of economic systems, these are often industries that are both large and that perform a critical service to the other industries within the system [28]. In this phase, also key sub-systems in neighbouring systems should be identified. These are sub-systems that interact with the focal system in question, and which may therefore be a source of systemic risk. In the second phase, models and tools are developed that will help the teams identify and assess early warning signals of potential failure points within the critical sub-systems, both within and outside of the focal system. For example, in the context of biosecurity risks, an internal sub-system may be a country's border biosecurity institutions, while an external sub-system may be the border security institutions of the country's main trading partners. In the third phase, a framework is developed to help the teams look for interaction effects between the different sub-systems, a necessary step when a problem is broken down into constituent components [26]. The theories discussed in section two form useful starting points for developing such a framework. This framework should help the teams to create a "system of models", whereby linkages are established between the sub-system level models and tools. For example, as when the output of a model used to assess "sub-system A" is used as input in a model to assess "sub-system B". This will require the development of tools that help to coordinate the outputs of the sub-system level analyses. Once the framework and tools are developed, the teams can put their knowledge to the test.

In the first phase of the system's analysis loop, the objective is to identify or confirm for each of the sub-systems, as well as for the system as a whole, which actors (e.g., companies, regulators) and processes (e.g., inter-bank lending) are key to the (sub-)system's functioning. While many actors and processes will have already been identified in the knowledge development phase, it is essential to undertake a dedicated study to ensure that no critical agents or processes are missed, as they are a key source of systemic risk, both of well-known risks and black swans. Subsequently, the teams can use their framework and tools to scan and monitor for early warning signals of both categories of systemic risks [5], as well as for assessing the fragility of the system against these risks [7]. These three phases are tightly interwoven, as the extent to which an event is a risk depends in large part upon the system's fragility against the risk. It is here that the benefits of taking a transdisciplinary approach becomes apparent [1], as people from a wide range of disciplines working together in an integrated fashion will be more likely to identify risks [29].

"Non-transdisciplinary" approaches would miss more risks. Firstly, monodisciplinary approaches assess the system from a single discipline and thus view the system from a limited range of perspectives. Secondly, multi-disciplinary approaches insufficiently integrate the insights from different disciplines and thus will miss more interaction effects between processes or system sub-components. Finally, interdisciplinary approaches fail to integrate "ground truths" from stakeholders and so are likely to have developed models of the system that contain unrealistic assumptions [30].

Key to the final three phases of the system's analysis loop is that the mechanisms to limit group think that were developed in the "integrated approach development loop" are well-functioning. This is to ensure that the assessments of analysts with outlying views about the likelihood or impact of a certain risk are not easily dismissed by the majority opinion. For black swans, which by definition are unexpected events, outlying views will be extremely valuable in picking up early warning signals.

5. Discussion and conclusion

Systemic risks arise predominantly in complex, dynamic systems. Compared to simpler systems, complex systems have a wider set of possible futures, which are more difficult to foresee, and for which it is also more difficult to predict the likelihood of their occurrence. To be able to correctly anticipate and assess as many of these futures as possible, and thus pick up as many warning signals of systemic risks as possible, transdisciplinary approaches to risk detection are necessary.

In the present paper, we have presented a framework that can help researchers and stakeholders co-develop transdisciplinary approaches to systemic risk detection. Key to the successful implementation of the framework is the creation of feedback mechanisms and a culture of continuous learning. Researchers and stakeholders should continuously question, evaluate, and improve the approach and tools used to assess the system, as well as their ways of working together to create or modify these tools. This is essential in the context of complex, dynamic systems, where knowledge quickly can become outdated. Taking an ever-evolving approach to the analysis of complex systems should lead to more competent approaches to systemic risk detection.

References

[1] M. Jahn, F. Gaupp and M. Obersteiner, M. Assessing and analysing systemic risks: mapping the topology of risk through time (Chapter 2.1). In: *Global Assessment Report on Disaster Risk Reduction (GAR)*. United Nations Office for Disaster Risk Reduction (UNDRR), Geneva, 2019, pp. 37-47.

[2] D. Gramlich, G. Miller, M.V. Oet, and S.J. Ong, Early warning systems for systemic banking risk. *Banks and Bank Systems*, 2010, Vol. 5, pp. 199-211.

[3] F. Mostashari, M. Kulldorff, J.J. Hartman, J. R. Miller And V. Kulasekera, Dead bird clusters as an early warning system for West Nile virus activity. *Emerging infectious diseases*, 2003, Vol. 9, pp. 641-646.

[4] M. Erdik, Y. Fahjan, O. Ozel, H. Alcik, A. Mert and M. GUL, Istanbul Earthquake Rapid Response and the Early Warning System. *Bulletin of Earthquake Engineering*, 2003, Vol. 1, pp. 157-163.

[5] N.N., *IRGC Guidelines for the governance of systemic risks: In systems and organizations in the context of transitions*. International Risk Governance Center, Lausanne, 2018.

[6] W.E. Walker, V.A.W.J. Marchau and D. Swanson, Addressing deep uncertainty using adaptive policies: Introduction to section 2. *Technological Forecasting and Social Change*, 2010, Vol. 77, pp. 917-923.

[7] J. Colchester and F. Filia, Financial complexity and nonlinear dynamics, 2018, Complexity Labs and Fasanara Capital, https://www.fasanaracapital.com/financial-complexity-and-nonlinear-, Accessed July, 3 2021.

[8] S. O'Halloran and N. Nowaczyk, An artificial intelligence approach to regulating systemic risk, *Frontiers in Artificial Intelligence*, 2019, https://doi.org/10.3389/frai.2019.00007.

[9] G. Kou, X. Chao, Y. Peng, F.E. Alsaadi and E. Herrera-Viedma, Machine Learning Methods For Systemic Risk Analysis In Financial Sectors, *Tech. and Econ. Dev. of Econ.*, 2019, Vol. 25, pp. 716-742.
[10] V. Sasidevan and N. Bertschinger, Systemic Risk: Fire-Walling Financial Systems Using Network-Based Approaches. In: A.S. Chakrabarti et al. (eds.) *Network Theory and Agent-Based Modeling in Economics and Finance*, Springer Nature Switzerland, 2019, pp. 313-330.
[11] A. Haldane, *Rethinking the financial network*. Amsterdam: Speech delivered at the Financial Student Association, 2009.
[12] D.H. Meadows, *Thinking in Systems*, Chelsea Green, Vermont, 2008.
[13] U. Wilensky and W. Rand, *Modeling Natural, Social, and Engineered Complex Systems with NetLogo*, MIT Press, Cambridge, 2015.
[14] M.O. Jackson and D. López-Pintado, Diffusion and contagion in networks with heterogeneous agents and homophily. *Network Science*, 2013, Vol. 1, pp. 49-67.
[15] R. Ojha, A. Ghadge, M.K. Tiwari and U. Bititci, Bayesian network modelling for supply chain risk propagation. *International Journal of Production Research*, 2018, Vol. 56, pp. 5795-5819.
[16] S.M. Guerra, T.C. Silva, B.M. Tabak, R.A. De Souza Penaloza and R.C. De Castro Miranda, Systemic risk measures. *Physica A: Statistical Mechanics and its Applications*, 2016, Vol. 442, pp. 329-342.
[17] R. Pasqualino, I. Monasterolo and A. Jones, An Integrated global food and energy security system dynamics model for addressing systemic risk. *Sustainability*, 2019, Vol. 11, 3995.
[18] J. Paulin, A. Calinescu And M. Wooldridge, Understanding flash crash contagion and systemic risk: A micro–macro agent-based approach. *Journal of Economic Dynamics and Control*, 2019, Vol. 100, pp. 200-229.
[19] S. Burgess, E. Fernandez-Corugedo, C. Groth, R. Harrison, F. Monti, K. Theodoridis and M. Waldron, *The Bank of England's forecasting platform*. Bank of England. 2013.
[20] R.A. Bradhurst, S.E. Roche, I.J. East, P. Kwan And M.G. Garner, A hybrid modeling approach to simulating foot-and-mouth disease outbreaks in Australian livestock. *Frontiers in Environmental Science*, 2015, Vol. 3, 17, https://doi.org/10.3389/fenvs.2015.00017.
[21] J. Boston, Anticipatory governance: how well is New Zealand safeguarding the future? *Policy Quarterly*, 2016, Vol. 12, No. 3, https://doi.org/10.26686/pq.v12i3.4614.
[22] K. Raworth, *Doughnut economics: Seven ways to think like a 21st-Century Economist*, Chelsea Green Publishing, London, 2018.
[23] R. Scholz and G. Steiner, The real type and ideal type of transdisciplinary processes: Part I – theoretical foundations. *Sustainability Science*, 2015, 10, pp. 527–544.
[24] N. Wognum, W.J.C. Verhagen, J. Stjepandić, Trans-disciplinary systems as complex systems, *Advances in Transdisciplinary Engineering*, 2017, Vol. 5, pp. 745-754.
[25] A.G. Haldane and R.M. May, Systemic risk in banking ecosystems. *Nature*, 2011, Vol. 469, pp. 351-355.
[26] D.E. Goldberg, *The Design of Innovation: Lessons from and for Competent Genetic Algorithms*, Dordrecht, Kluwer Academics Publishers, 2002.
[27] A. Biahmou et al., Towards agile enterprise rights management in engineering collaboration, *International Journal of Agile Systems and Management*, 2016, Vol. 9(4), pp. 302-325.
[28] R. Cont, A. Moussa and E.B. Santos, Network Structure and Systemic Risk in Banking Systems. In: J.-P. Fouque and J.A. Langsam (eds.) *Handbook on Systemic Risk*, Cambridge University Press, Cambridge, 2013, pp. 327-368.
[29] N. Wognum, M. Wever, Stjepandić, J. Managing risks in knowledge exchange: Trade-offs and interdependencies, *Advances in Transdisciplinary Engineering*, 2016, Vol. 4, pp. 15-24.
[30] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, W.J.C. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, Vol. 7, 2018, pp. 753-762.

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Infrastructuring Transdisciplinary Problem Solving in Translational Research

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Abstract. Translational Research in the health sciences endeavors to bring biomedical discoveries into clinical applications that improve human health. This work is complex and long-term with a substantial risk of failure. A key step of clinical trials is needed to evaluate the effects of those interventions on human biomedical or behavioral outcomes. Timely recruitment of human subjects and meeting recruitment milestones is recognized as one of the most significant contributors to delays and failures. Quality and Design approaches have been tried to address the problem but the scope has been limited. We proposed to determine how Quality and Design may lead to complementary solutions for these barriers of Translational Research. The first ten studios using this approach are presented here. Three themes emerged: (1) problems were investigated similarly but there was a difference in insights, (2) quality process-based solutions tended to be specific to the issue discussed whereas the design process often yielded solutions broader or even tangential, and (3) quality solutions demonstrated more immediacy while design solutions showed more systemic ideas. In conclusion, the paper demonstrates how Design and Quality in a transdisciplinary studio may lead to solutions with different characteristics for clinical trials and advance translational science.

Keywords. Transdisciplinary methods, design approach, quality approach, clinical trials, translation, translational science, human centered design, systems design

Introduction

Translational Research, specifically clinical trials, endeavors to bring biomedical discoveries into clinical applications that improve human health [1] [6]. Translation is a complex, long-term, multi-stakeholder process. It is a high-cost quest with substantial risk of failure. Clinical trials involving human participants are a key late stage step in the translation process. Barriers in initiating and completing clinical trials have been well documented [20]. Research shows how significant delays (years or decades) occur in stages of clinical research study start-up, protocol initiation and study implementation, before a successful implementation results in health benefits for patients, communities and/or providers of care [4]. Timely recruitment and meeting milestones is recognized as one of the most significant contributors to clinical trial delays and completion failures. Inefficiencies have traditionally been addressed using quality techniques [7].

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National Center for the Advancement of Translational Sciences (NCATS) at the NIH (including their Clinical and Translational Sciences Award (CTSA) mechanism) is dedicated to advancement of translational sciences. One national CTSA Central program is the Trial Innovation Network [21]. NCATS has created CTSA Program hubs and partners with them to develop and implement innovative, collaborative solutions intended to transform clinical and translation research including through the Trial Innovation Network [22]. The Institute for Translational Medicine (ITM) in Chicago, Illinois, is one of the CTSA hubs funded by NCATS. ITM is composed of 6 Chicagoland health institutes and medical colleges. ITM is a cross-institutional, transdisciplinary endeavor that develops workforce, demonstrates solutions for patient and community engagement, and disseminates holistic approaches for advancing translation as a science. ITM also focusses on equity across underserved populations, process innovation for quality and efficiency of multisite trials through integration of informatics [15] [16].

Translation by nature needs to be inter-disciplinary to deliver interventions and care from the basic sciences research [23]. The interdisciplinary training of future translational workforce is much needed. not a want but a need. The work conducted in this field is often from multiple dynamic and evolving systems including health, clinical care delivery, quality of care, and medical and related sciences. Translation teams could certainly collaborate with others of different disciplines, but there are barriers. An alternative is to teach problem solving skills inspired by multi-disciplinary approaches to reduce the burden of studies and research projects and enable collaboration [24]. Inefficiencies have traditionally been addressed using quality techniques [7].

Trial recruitment and retention innovation is being developed using structured approaches to problem solving [17]. Popular approaches in health care systems are that of quality science. Recentlysome adoption of design science, including human centered design [10], [11] has taken place with the popularity of design thinking based innovation. As part of the ITM's Trial Recruitment Innovation Office (TRIO), transdisciplinary studios were conceptualized. To innovate and address the legacy barriers in the clinical trials, the researchers implemented approaches based in design and quality methods. This paper describes the studios and the design and quality science methods used in the studios and the results found. Research team conducted approximately monthly in-person studios of 90 minutes from December 12, 2017 to September 11, 2019. The studios continue to be held to date. This paper focusses on the the first 10 studios with Design and Quality approaches done simultaneously and reports on the outcomes observed.

1. Research Objectives

The goal of this research is to infrastructure resiliency in translational research teams. Main objective is to determine if design methods and quality methods can accelerate clinical research by solving recruitment and retention issues of participants. Furthermore, this research aspired to determine how the various tools of design and quality approaches help the study teams in different situations and contexts.

2. Literature Review

Translation is the "process of turning observations in the laboratory, clinic and community into interventions that improve the health of individuals and the public."[1]

Translational research is defined by NCATS as *the endeavor to traverse a step of the translational process for a specific target or disease*. Translational science *seeks to understand the scientific and operational principles underlying each step of the translational process* [1].

This process of converting medical science advances into applied bedside interventions for patients has two main road blocks in the transfer of research knowledge into practice. The first is barriers that prevent laboratory advances from being converted into new medical products and the second is inability to enable adoption of proven improvements in treatment in medical practice for instance new drug combination [5] [6]. Barriers to patient recruitment especially diverse participants from ethnic or racial minorities consist of family composition, literacy, and severity of medical diagnosis [7].

The Principal Investigators (PIs) and the study team for clinical trials also face barriers of three kinds [8] [9]. Firstly, PIs have to work with many clinicians who are either not aware of active trials or do not refer their patients for participation in trials. Secondly, substantial costs are necessary to enroll and retain diverse populations. For minorities, extra time is needed to gain individual and community acceptance [7]. Finally, administrative burdens and regulatory requirements present unprecedented challenges, even for experienced trialists [8] [9].

Substantial effort has gone into addressing the barriers over the years. NCATS has funded many such efforts. Researchers have successfully applied and demonstrated that better coordination, timeliness, efficiency and value of clinical and translational research can be achieved by applying the Lean and Six Sigma principles [4]. In recent years [10] [15] it has been successfully argued that Human Centered Design (HCD) has been found to offer specific methods that can readily operationalize implementation strategies to improve the translation of health innovations into practice. Using HCD to identify and execute strategies provides a set of tools for researchers to develop and test health interventions. Implementation scientists refer to this as application of design thinking to health care research [16] [19].

2.1. Quality Approach (QA)

Quality Approach focuses on understanding a situation by breaking the problem into parts. Deductive reasoning is used to then intervene to eliminate process failure(s) [4].

Many healthcare service providers and some research organizations have been adopting quality science-based approaches (QA) in order to improve their organizational performances both in practice and research [4] [15]. Although QA has been proven to be very effective for solving problems and enhancing performances, there are still problems that require approaches in addition to QA. QA methodology has been developed and widely applied in many industries like auto manufacturing, electronic goods and transportation. Previously, quality improvement methodologies have been adopted in approaching system problems associated with health care delivery and (to some extent) research processes. For instance, root cause analysis and failure mode effectiveness analysis have been imported in the health care sector from the manufacturing sector in order to achieve reliable and consistent outcomes [4] [7].

This research has adapted the traditional **DMAIC** – **Define**, **Map** the process, **Analyze** the causes, **Implement** and **Control** approach of Total Quality Management for solving issues and barriers faced by a study team and PI. DMAIC is much more closer to Human Centered Design process so it was easier to compare and contrast as seen in Figure 2.

2.2. Design Approach (DA)

Design Approach focuses on envisioning a solution to best meet the needs of the end-users and other stakeholders. It takes a holistic, abductive approach to problem solving rather than a focus on perfection and avoiding failure at all costs. Early prototyping and accepting failure to build better processes are key learning tools and seminal features of design science thinking [18].

Design Approaches (DA) also have been introduced at different levels in order to address human perspectives from different stakeholders in healthcare systems [18]. Although the term and approaches of "design thinking" have been widely adopted [15] [16] and generated some success stories in many areas in order to enhance innovation capability in organizations, yet no universal understanding has been formed or accepted for translational research. This research constructs its own DA based on the methods proven to be effective in practice [18] [19].

Design methodologies were first described approximately the same time as quality improvement methodologies; however, while their implementation has started to accelerate in other sectors, they have only very recently been introduced in the health care arena. This research has adapted the traditional HCD process into – **Sense Intent**, **Know Context, Know People**, **Frame Insights**, **Explore Concepts** and **Frame Solutions** to a five step process to solve the translational research problems. Figure 2 below shows the two methods side by side as well as elaborates on some of the tools used in each step.

However, no studies have examined whether design is comparable to quality methodology in producing impactful changes in the process of translational research.

3. Method

Collaborative studios with multiple stakeholders were created and sessions conducted to test this approach. The researchers focused on using the concept of collaborative studios to trouble shoot the issues of translational research studies including start up issues as well as recruitment and retention issues. Researchers adapted quality approach and design approach as the framework for problem solving translation research issues. In a studio, principal investigators of translational projects presented their problematic recruitment/clinical trial scenario to TRIO Studio. The studio participants then worked as a group towards solving the issues and suggesting systematic solutions using both Design and Quality processes. The methods have been adapted to fit 90 min sessions format. The studios happened on a monthly basis.

3.1. TRIO Studio process

Preparation for a TRIO studio included setting up of facilities, ensuring the template is shared with the problem presenter and iterating with the presenter on importance of concluding their presentation with a clear statement of problem the group needs to focus on. Also, the facilitator studied the problem beforehand and created prompts and other facilitation materials for the Studio.

Studio participants (SMEs) attended from across six Chicagoland institutions with significant subject matter expertise in Translational Research. SMEs included research regulatory science, informatics and data analytics, community relations and/or research operations. Experts interested in the topic and willing to provide insight and expertise to the problem attended the studios as per their schedule convenience. All studios were facilitated by an experienced researcher. Facilitator are responsible for the adherence to methods. The TRIO team ensured that the discussion was active and all SMEs were contributing.

Each studio started with the TRIO Manager welcoming the multi-institutional attendees. A given studio could be as small as 5-6 people or as large as 40 people. The facilitator then introduced the two approaches of QA and DA. The presenter of the day described their project, explained the current state and the problem(s) in executing the particular recruitment and retention strategy.

The TRIO Design Studio participants were then randomly assigned in each session to use design methodologies or quality methodologies for problem-solving. Once assigned, teams worked in parallel to develop solutions during approximately an hour of work in their assigned methodology to address barriers in steps associated with accelerating clinical research initiation and recruitment in the project presented by investigator(s).

The Facilitator enabled the studio attendees to navigate through the session with the methods chosen to address the presenter's problem(s). TRIO staff from the ITM institutions helped with set up and documentation of the studio. The TRIO staff also assisted with moderation as needed – drawing on whiteboards, taking notes, tendering surveys etc. With permission of the attendees, the sessions were audio and video-recorded for program fidelity and qualitative analysis for generating reports.

The actual studio proceeds as listed below in Figure 1:

Welcome and Introduction of TRIO Studio TRIO Manager		
Method(s) introduction TRIO Facilitator	Ground Rules of the Studio are described by Moderator	
	Presenter presents the case and the problem needing solutions	
	Design Science Approach (DSA)	**Quality Science Approach**
	Sense Intent - Mind Map	Define Problem and Describe details - Current state, future state, and scale of problems
	Know Context - Stakeholder Map	Map the Process - Identify leaks using leaky pipe model
	Generate Insights - How Might We Post its	Analyze the causes of effects observed
	Ideate Solutions - SCAMPER Tool	Ideate Solutions - SCAMPER Tool
	Prioritization of solutions for study team to try systematically	Prioritization of solutions for study team to try systematically
Case Presentation Principal Investigator of the Project or the study team		
Studio	Group splits into 2 and works on the problem with facilitation as necessary	
	Group Presentation and Share-Out	
	Discussion with presenter on the solutions emerged	
Announcements and Wrap up		
Post-Studio Follow up 30 days, 90 days and 1 year		

Figure 1. TRIO Studio Process.

Participants received handouts explaining the methods of Design and Quality. The handout is shown in Figure 2 below.

Figure 2. Illustrated DA and QA handouts for studio participants.

Post-Studio work included survey collection for feedback about solutions and session itself. After each studio,a report was created with in 2 weeks, describing the studio and the solutions generated during the session. Reports were shared with the presenter as well as the attendees. The reports also were hosted on a public wiki page for easy access by anyone interested. Also, the TRIO Manager followed up with the study team at 30 days, 90 days and 1 year timepoints. That feedback from those timepoints also was rolled into the reports with an addendum. For this paper, 10 initial studio reports were analyzed. Problem characteritics, participant attendance as well as qualitative data from the session solutions were analyzed using constant comparative coding.

4. Results

Analysis of 10 TRIO Studios with participation varying from 5-24 SMEs (median = 9 is presented here. At each studio, participants were assigned to Design or Quality team and they accordingly used design or quality methods to address issues faced by a clinical research team. Figure 3 shows the number of participants per studio and Figure 4 shows the nature of problems addressed.

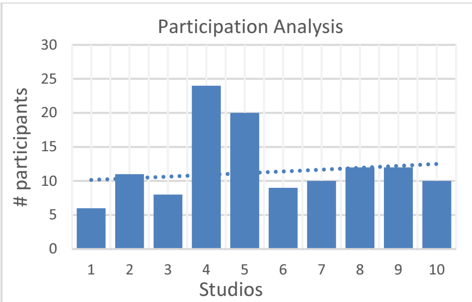

Figure 3. Participation in Studios.

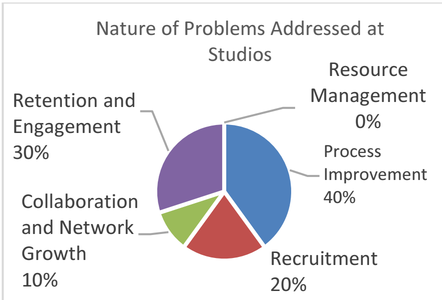

Figure 4. Nature of problems addressed.

The qualitative data of the 10 studio reports was analyzed. The analysis showed that not only did the nature of problems affect the kind of solutions generated by the group but also the method used. In 4 of out 10 studios QA actually produced a greater number of solutions than DA. However, when the solution set was analyzed, the solutions from each approach were not all of the same granularity. In QA the ideas/solutions appeared to be more targeted to problem due to the nature of the process of quality improvement. In DA the ideas/solutions, even though many times less than QA, were broader and even tangential to the exact problem defined by the presenter. In DA, due to explicit step of reframing, the attendees paid more attention to context and pivoted into things that sometimes the study team presenter did not even define at the outset.

For issues related to clinical research initiation and recruitment, quality and design solutions offered complementary approaches. Three presenters (out of 10) selected and retained the use of design solutions over a 12 month follow-up period [16]. Analysis of reports showed nuances in how participants address problem when given design versus quality methods and tools. Three main themes emerged:

4.1. Theme 1: Nature of process guides focus of causality analyses

Problems were investigated in both DA and QA by using relevant tools provided by the facilitator. There was significant difference in insights developed by the two approaches. Due to nature of the processes, DA insights tended to be about stakeholders and QA insights tended to be about process failure points. The tools used directly influenced the group's focus and thinking.

For instance in one particular studio the problem was that of inter-institute collaboration and the idea floated by QA was that of Institutional Review Board (IRB) procedure optimization and DA proposed camping out in the cafeteria and engaging people when they come to café for their breaks.

4.2. Theme 2: Approaches shaped the degrees of freedom of the ideating team

Interestingly, QA-based solutions tended to be specific to issue discovered and discussed by the group. Alternatively, in DA, design process often took the discussion to stakeholders who may or may not be directly involved in the given problem. Often this yielded solutions that were broader or at times tangential to the issues discussed.

For instance in a studio on food and diet study for longer life and well being of people, QA team delved into data needs and so their solution was an ***informatics*** approach to recruitment in a minority population. On the other hand, DA team, the data need was discussed similar to QA team but the solution was quite different. The DA team explored the stakeholder map and converted the clinician who knows their patients well as the ***recruitment ambassador***. From the study team point of view this was a win-win because they got two very different solutions that they could pilot. The difference between QA based solution and DA based solution was stark.

4.3. Theme 3: Depth and breadth of solutions definitely varied by approach used

Quality solutions demonstrated more immediately implementable solutions while design solutions showed more systemic ideas. For instance in a studio on "End of Life Care" the QA group focused on review of training given to nurses as a solution and how to optimize it. Meanwhile the DA team reframed the problem from local to national level. They decided that it is an urgent topic and needs NCATS attention and resources. So a national consortium of collaborators with NCATS funding was proposed as a better solution. Figure 5 below shows the variations.

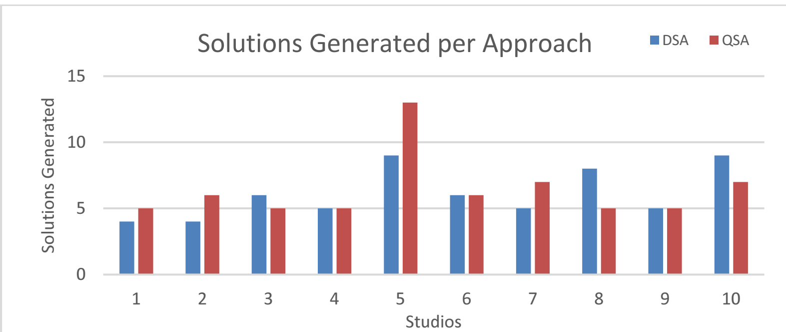

Figure 5. Solutions created per studio (using both DA and QA)

5. Discussion

Through this effort, the techniques of problem solving are being democratized and made familiar to the clinical research study teams. The study teams will directly impact translational science growth as well as build resiliency to challenges of their field. Structured approach helps teams to learn the skill and use it in their day to day work. Also as approaches become repeatable and reliable, the teams become more adaptable to changes in context. For instance, most work went virtual during COVID 19 and translational research had to rapidly adapt itself.

5.1. Advancing the Translational Research

Clinical research initiation, recruitment and retention were addressed holistically by quality and design solutions. These approaches offered complementary ideas and solutions revealing the need for multi-pronged approach. The presenters who did chose design solutions over quality solutions and used them over a 12 month follow-up period. This shows the impact of creative and collaborative solutioning on translational research.

Furthermore, this approach of solving translational science issues with both DA and QA is an example of how to compare and contrast methods from different disciplines [11] [12]. Usually quality and design teams are pitted against each other. This research shows that the teams and their approaches are more complementary than mutually exclusive. When targetted investigation of causality of effect observed in an established process when QA might work better.

5.2. Implications for Transdisciplinary Engineering

Integral approach discovered for problem solving in translational research can inspire approach to problem solving in other domains such as industry 4.0 and cyber physical systems engineering. When human centered analysis, identification of problems, and better fit between people and technology solutions are needed then Design Approach might better fit the needs of research teams [18] [19]. TE researchers can utilize these tools and adapt the approach and experiement in their respective domains.

5.3. Strengths and Weaknesses

Strengths of this research is the scale at which the TRIO studios are being conducted. The research is now running in its 3rd year so diversity of case studies, diversity of SMEs at the table in consistent manner and the execution of studios has been a revelation of how well it has worked out. On the other hand, the sheer size of the operations itself can be a deterrent for someone else to try to replicate this approach for their domain. There can be lot of logistical issues and space availability issues for such a large scale approach.

5.4. Future Work

Dissemination and implementation of studio facilitation tools and knowledge bases is next step. Further work is needed to understand which types of problems are best amenable to a particular methodology. Researchers are exploring collaborations with other TE researchers and apply this method in domains other than translational science.

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References

[1] C.P. Austin. Translating translation. *Nature Reviews: Drug Discovery*. July 2018; 17: pp. 455-456.
[2] A. Dong, D. Lovallo, and R. Mounarath. The effect of abductive reasoning on concept selection decisions. *Design studies*, 2015, Vol. 37, pp. 37-58.
[3] D.L. Dean, J.M. Hender, T.L. Rodgers, and E. Santanen. Identifying good ideas: constructs and scales for idea evaluation, *Journal of Association for Information Systems*, 2006, Vol. 7, Issue 10, pp. 646-699.
[4] S.A. Schweikhart and A.E. Dembe. The applicability of Lean and Six Sigma techniques to clinical and translational research. *Journal of Investigative Medicine*, 2009, Vol. 57, Issue 7, pp. 748-755.
[5] D. Butler, TR: crossing the valley of death. *Nature News*, 2008, 453(7197), pp. 840-842.
[6] S.H. Woolf, The Meaning of TR and Why It Matters. *JAMA*, 2008, 299 (2), pp. 211–213.
[7] S.J. Haley, L.E. Southwick, N.S. Parikh, J. Rivera, D. Farrar-Edwards, B. Boden-Albala, Barriers and Strategies for Recruitment of Racial and Ethnic Minorities: Perspectives from Neurological Clinical Research Coordinators. *J Racial Ethn Health Disparities*. 2017, Vol. 4(6), pp.1225-1236.
[8] J.L. Probstfield, R.L. Frye, Strategies for Recruitment and Retention of Participants in Clinical Trials. *JAMA*. 2011, 306(16):1798–1799. doi:10.1001/jama.2011.1544.
[9] R.B. Gul and P.A. Ali, Clinical trials: the challenge of recruitment and retention of participants. *Journal of Clinical Nursing*, 2010, Vol. 19, pp. 227-233.
[10] E. Chen, G. Neta, M.C Roberts, Complementary approaches to problem solving in healthcare and public health: implementation science and HCD, *Transl. Behavioral Medicine*, 2021, Vol. 11, pp. 1115–1121.
[11] A. Doshi and C. Clay, Rethink space: (Re)designing a workspace using human-centered design to support flexibility, collaboration, and engagement among clinical and translational research support services." *Journal of Clinical and Translational Science,* 2017, Vol. 1, pp. 160 - 166.
[12] Schmidt, S., Shay, L. A., Saygin, C., Schulz, K., Clark, R. A., & Shireman, P. K. Improving pilot project application and review processes: A novel application of lean six sigma in translational science. *Journal of clinical and translational science*, 2018, Vol. 2(3), pp. 135-138.
[13] P.S. Gillam, H.B. Nembhard and D.A. Munoz, The role of quality improvement methods in translational research. *Proc. of the 2014 Industrial and Systems Engineering Research Conf.*, 2014, pp. 4023-31.
[14] J.M. Glasgow, J.R. Scott-Caziewell and P.J. Kaboli, Guiding inpatient quality improvement: a systematic review of Lean and Six Sigma. *The Joint Commission Journal on Quality and Patient Safety*, 2010, Vol. 36(12), 533-540.
[15] A.R. Dopp, K.E. Parisi, S.A. Munson, A. and R. Lyon, A glossary of user-centered design strategies for implementation experts. *Transl Behav Med.* , 2019, Vol. 25;9(6), pp. 1057-1064.
[16] R. Yajima, Catalyzing scientific innovation with design thinking. *Design Mgmt*, 2015, Vol. 26(1), 18-23.
[17] W.F. Pruitt, Some Assembly Required: Structured problem solving demands structured communication, *Quality Progress*, 2020, Vol. 53(5), pp. 16-21.
[18] M. Altman et. Al, Design Thinking in Health Care. *Preventing Chronic Disease*, 2018, 180128.
[19] B. Ku and E. Lupton, *Health Design Thinking*. MIT Press, Cambridge, 2020.
[20] E.A. Neugebauer, A. Rath, ... and C. Gluud, Specific barriers to the conduct of randomised clinical trials on medical devices. *Trials*, 2017, Vol. 18(1), pp. 1-10.
[21] National Center for Advancing Translational Sciences. https://ncats.nih.gov/ accessed 6/2/2021
[22] Webpage of Trial Innovation Network. https://ncats.nih.gov/ctsa/projects/network accessed on 6/2/2021.
[23] A.M. Madni, Transdisciplinary Systems Engineering: Exploiting Disciplinary Convergence to Address Grand Challenges, *IEEE Systems, Man, and Cybernetics Magazine*, 2019, Vol. 5, No. 2, pp. 6-11.
[24] N.J. McNeese, The Pursuit of Transdisciplinary Research: Eight Recommendations for Integrating Disciplines. *IEEE Systems, Man, and Cybernetics Magazine*, 2019, Vol. 5(4), pp. 10-15.

Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Foraging for Transdisciplinary Challenges: Emergent Industrial Themes

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Abstract. This paper presents our findings from thirteen industrial interviews, to investigate the significance of transdisciplinarity (TD) in an industrial context. Thus to gain insight into the resilience of industrial manufacturing in rapidly changing environments and establish what enabling or disabling practices may currently exist. The interviews were conducted as an initial part of a wider case study approach being undertaken by the TREND research team and were semi-structured in format. We present the background and research questions being addressed and outline our exploratory research approach. The analysis of interview transcriptions is provided answering our research questions and identifying any emerging themes. Of the industry interviews, only five interviewees had heard of the term TD, the definition of TD varied between companies and did not align with the primordial system of Jantsch's work. A number of focal enabling and disabling industrial themes emerge from the interviews and related discourse such as the positive and negative human contribution(s) and growing global teams involved in manufacture. For industry to be resilient and meet rapid technological and societal change, these themes should be core for manufacturing solutions. Secondary studies should investigate literature and collaborate with engineering industries to test any potential TD interventions.

Keywords. Transdisciplinary, Industry Context, Semi-Structured Interviews, Industrial Resilience

Introduction

Engineering industries are facing increasing pressure from the need to solve complex societal and global problems, facing rapid change in technological means and societal needs [1][2]. Currency for remaining competitive in recent years has changed from innovative product provision to the addition of services [3]. The requirements to be met by engineers in a modern society is indeed changing again as consumers look to sustainable solutions, to mitigate demanding issues such as climate change or vaccine development [4]. Remaining resilient in the face of dramatic change and disruption in industrial manufacture, is urgently becoming a priority for industries to remain viable [1][5], hence adaptability and strategies in the face of change is the focus of this paper.

One such approach to support industrial resilience that has gained more attention is the development of "transdisciplinarity" (TD) and applying associated methods as a solution [6][7]. This is clearly evident in the increased number of peer reviewed TD literature and in the focus of funding calls of research councils [2]. While TD aims to expand disciplines to address complexity it also contributes to the need to be ahead of

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change, in engaging early with policy and society [8]. The intent being that industry will be aware and develop early capacity, hence being adaptable and more resilient in the face of continuing disruption [1]. Given the notion of TD being a useful solution, research has not yet focussed on the extent of TD projects and its current impact in industry [6] but on specific industrial needs such as collaboration [9]. This paper seeks to close the TD gap and focus on the current needs and understanding of industrial partners, in respect of their position and engagement with the TD agenda.

Without prior established engagment of practitioners in industry to evaluate their TD position and with the knowledge debate in academic circles about the core components of TD projects [10], the language and definitions being utilised cannot be assumed. Hence an exploratory approach using a case study method begins building a robust picture of the current state of TD in industry [11], this was also used in new areas such a collaborative engineering [9]. This paper reports findings from 13 industrial engineering interviews to contribute to understanding concerns in industry in respect of using TD approaches, with a particular focus upon currently enabling or disabling practices. This is a first step to close the gap in industry need for meeting TD projects, facilitating the uptake of industry practice adaptions to meet increasing societal change.

In the sections that follow first we describe the research approach and design of semi-structured interviews. This is split into the overarching case study approach taken by the TREND team [13] with specific research questions, then a semi-structured interview approach is outlined. A description of the data transcription and analysis is then provided and followed by results that describe the industry sampling and summarise themes emerging from the data. Our discussion highlights what the authors perceive are the significant findings and suggest future TD industry collaboration to address complex competing demands and for the resilience of global engineering in the future [1][6].

1. Background Literature

Much work in manufacturing and in engineering design research has sought to develop support interventions to overcome the need for engineers to be adaptable and hence resilient to the operational changes bought about by revolutions such as Industry 4.0 [1]. Work conducted by Carey et al. [14] investigated the reasons for limited uptake of such support interventions. The work suggests that there are eight key issues that pose problems limiting the usefulness of support in practice. These factors likewise will pose limits for wider engineering projects in implementing solutions to remain adaptable and resilient in current manufacturing climes, especially with current focus being societal need [2][4]. Changing requirements and pressures being placed upon engineers are similar to those of design engineering in-service provision changes, where remaining resilient and rapidly adapting skills [15] with limited costs, resources and increasing competition pose overbearing challenge [3][1].

Recent emphasis in projects and engineering is being placed on higher disciplinary approaches such as TD to develop sustainable engineering solutions providing societal value [13]. It is application of TD practices that the explorations of this work investigate, or the readiness and utilisation of such already in industry, if it is indeed present [6]. It is notable in literature that a multiplicity of definitions and language exist for TD projects [2][10]. This poses significant challenges in investigating such issues within industry, both for purporting concepts to those less familiar outside of academia and in interpreting the language being used informally to portray similar concepts. To overcome this it has been necessary to utilise a primordial definition of TD such as the first systematic approaches defined by Jantch [16], to enable clear expression and a framework for presenting TD concepts. In more recent work significant language being used in TD academic literature has been distilled into the top most frequent concepts that should comprise TD projects [10]. This model supports to provide a collective TD representation for comparing the industrial findings and concepts that emerge from this study.

2. Exploratory Research Approach: Case and Interview Design

To date much of literature about TD has placed emphasis on academic research, with one of the definitive TD threads referrring to industry and stakeholders [13]. Engineering research in the UK is embedded in industrial settings [4] and efforts outlined in this paper seek to provide initial insights into the impact of TD in industry and to establish collaboration in TD projects. In the context of research-industry collaboration, interviews are a research method used to build explorative case studies [11][12], with the express goal of identifying industrial contexts, needs and existing practices of engineering organisations dealing with complex problems [4]. The semi-structured interview approach is used to build industrial case studies incrementally, exploring first the uptake of TD and industrial readiness for adaptation and competitiveness in societally focussed projects. This was an express first attempt to communicate complex academic TD conceptualisations to industry, uniting academic and non-academic language, goals and mind-sets [6]. The main research questions investigated in the forage interviews are shown in Figure 1 below.

	Research Questions
1.	How is TD practised and interpreted in industry?
2.	What are TD enabling and TD disabling practices, contexts and tools in organisations?
3.	What are industry needs and potential case studies to apply a TD approach?

Figure 1. Research Questions

Participants invited were in managerial positions, having both authority to engage with our research and having project know how to answer our questions. Engineering companies were contacted by email and asked to participate in our interviews. A pilot interview was conducted with an internal colleague with significant industrial experience, to test question objectives and wording. This led to a two interviewer approach being recorded by dictaphone and informed consent forms signed prior. Copy interview transcripts were sent with a thank you email two weeks after each interview.

2.1. Data Collection Semi-Structured Interviews

Scripted semi-structured interviews and questions [17][18] designed to gather industry expert opinions on the TD topic are shown in Table 1. A semi-structured approach enabled a broad case of each industry to be captured in directly comparable answers. The open ended nature of questions encouraged discourse, seeking depth to find the perspectives of each interviewee, and a rich exploration of the companies involved [18].

The questions were designed to collate background data about the nature of each industry's engineering focus, together with experience levels of each of the interviewees for contrasting in our analysis. In this way both the personal TD mindset could be established as well as understanding the functional industrial readiness.

In the pilot interview it was necessary to present a clear foundational academic TD [17][18] to frame the questions being asked overcoming multiplicity in language and concepts [10]. To avoid personal influence creating bias [17][18], we used scripted TD questions, a short video describing all "disciplinarities" based on Jantsch's definitions not our own [16], an interview protocol and documented information briefings [19].

Table 1. Interview Script

		Interview Question Wording
Background	1.	Organisation name
	2.	Main sector
	3.	Nature of services or products: B2B, B2C, B2G, mixed
	4.	Number of employees
	5.	Role within an Organisation
	6.	Years of experience: in general/in the current Organisation
	7.	Age range: 18-30, 31-40, 41-50, 51-65, 65+
	8.	Gender
	9.	Organisational structure: Traditional Hierarchy, Flatter, Flat, Flatarchies, Holacratic
Main Script	10.	We are conducting research on a TD approach in engineering. Have you ever heard of this term?
	11.	YES: What is it? (Would you consider having social scientists, political scientists in a team beyond marketing, finance, etc. This is transdisciplinary)
	12.	This is what we mean (pyramid of Jantsch's definition of TD explain). What ways do you work in your organisation? Why?
	13.	YES: Could you provide examples?
	14.	YES: What tools helped you to work in a TD manner?
	15.	NO: Are you aware of applications of TD approaches in other organisations?
	16.	NO: Can you think of where it can be useful? Possible problems and contexts?
	17.	NO: What tools can help to achieve TD?
	18.	Could you anticipate barriers for the implementation of this approach?
	19.	How to mitigate these challenges?
	20.	How do you think it's possible to measure/evaluate a TD approach success?
	21.	Do you have a project that has a TD opportunity? We would like to work together on it to improve its efficiency? What's the possibility?
Closing	22.	Feedback on the interview: were the questions appropriate? Were the questions understandable? Was the terminology and wording clear?
	23.	Is interview a good method to gather the information on TD practices or would surveys or focus groups be more convenient or appropriate?
	24.	What can we offer to industry to get them on-board?
	25.	What are your expectations regarding the current collaboration: timeline, outputs, intellectual property (IP)?

2.2. Transcription and Identifying Common Themes

Interview audio recordings totalled 650 hours and were transcribed by the TREND group familiar with its content. Each transcript has been annonymised using interview ID's for subsequent coding of responses into summarised common content. The design of the interviews encouraged discussion and debate about the academic disciplinary schools of thought presented. Due to size, the results presented here are limited to quantitative summaries and richer qualitative data is not presented. The transcript data was analysed by two researchers, independently coding content and collating responses. The enablers, disablers and associated discourse has been coded to group common themes for comparison.

3. Results: Sample Descriptives and Emerging Themes

In total TREND researchers conducted 13 interviews. These were recorded by dictaphone, then transcribed and coded. All interviewees represented an engineering company and held project manager or managerial roles.

3.1. Sample Descriptives

A summary of the companies and their backgrounds is provided in Table 2 below.

Table 2. Companies Background

Company Sector	Products/Services	Number of Employees
Healthcare and Disability	B2B, B2C, B2G	30
Automotive	Design & Manufacture	4000
Water	Services	450
Food Packaging	B2B	24000
IT	B2B, B2C	20
Aerospace	Consultancy	1
Energy	B2B	3
Engineering Consultancy	B2B	2
Design	B2C	7
Automotive	Products & Services	44000
Life Sciences	Mixed	5000
Additive Manufacturing	B2B	57
Defense and Maritime	B2B	1500

The companies participating in the interviews were all engineering businesses, but covered a wide range of sectors, from healthcare, food packaging and maritime, meaning a broad industrial perspective is represented. Similarly the business' agenda extended from design and consultancy through to manufacture and provision of services, encompassing views of the entire engineering product, manufacture to service lifecycle. The size and scale of the companies interviewed ranged from small enterprises with 1 employee, through to large scale manufacturing businesses with approximately 44,000 employees world wide. The sample is broad but useful as an exploratory snapshot of industrial perspectives.

3.2. Question Highlights

Responses to the questions asked in the interviews have been directly coded per question and collectively reported for the purposes of this paper to represent common themes that emerge from the content. The overarching aim of the interviews and value in the study of the additional discourse has been in identifying common content raised. The highlights of which are summarised in this section.

Only 5 out of 13 companies representated had heard the term TD. Of those 5 there was one company represented that had heard of the term in relation to their current work, and a second in a prior company. One interviewee had heard of the term from their own university studies and 2 used different disciplinary concepts such as cross-discipline interchangeably with TD. The other 8 interviewees had not heard of the term prior to discussion with the research team. This was opportunity to present new approaches to industry and to collect their unbiased views on the significance of disciplinarities in the workplace.

The structured TD presentation within the body of the interview, enabled the industrial interviewees to reflect upon projects they have been involved in. Including those, that whilst not named TD within industry, might be deemed to be TD in nature. Each and every interviewee was able to name one or more project that they worked on in their current industry that was in fact TD, suggesting that TD projects are already very much part of current industry portfolios and TD approaches relevant. Table 3 below collates the types of TD projects highlighted and illustrates common TD project topics already in engineering industry.

Table 3. TD Project Examples

Project Type	Number of Suggestions
Health	3
Sustainability	7
Environment	7
Business Planning	3
Product Development	3
Systems Engineering	1
IT	3
Global Supply Chain	1
Design	2
Product Lifecycle	2
Small Medium Enterprise	1

Specific project examples named, are diverse in nature but common topics are respresented, examples of such TD projects included “a powered wheelchair(s)”, “recycling projects”, “reducing emissions in cities” and the “design and implementation of a statue internationally”. Generalised examples included “sustainability projects”, “business plan preparation” or “systems engineering solutions”. Although the number of industries interviewed remains small it is evident that there is overwhelming focus upon “sustainability” and “environmental” TD projects (approximately 42% of projects discussed). Evidence in examples given suggest that TD projects exist through the entire product and manufacture lifecycle.

3.3. TD enablers and disablers

In respect of the TD projects highlighted, interviewees were asked to reflect upon the strengths and weaknesses in their current industrial working practice, in carrying out these projects. These were described as “enablers” or “disablers” in current industrial practice. In analysing these a large list of industrial challenges together with potential solutions was elicited from interview responses. Due to their large number and diverse nature these disablers and enablers have been content coded into common groups for comparison in Figure 2. For the purposes of summarisation representative collective content names have been identified to create themes illustrating the distribution of topics. Common topics emerge such as “communication” or “human” working elements, and each response has been distilled into such categories. It is possible that one response could be categorised into multiple themes, for example “lack of knowledge at the top of command” might fall into “knowledge” and “management” categories. These distilled guiding themes within transcripts are coupled with active verbal descriptors such as "understanding" or "transition" and it is expected that further analysis will change the depth of understanding. These verbal descriptors suggest an element of change is still required to achieve any enabling outcomes, or work to make project(s) achieve TD status in practice. Thus it is possible to infer areas both industry and researchers may need to collaborate and focus efforts to develop approaches to support industrial change in practice.

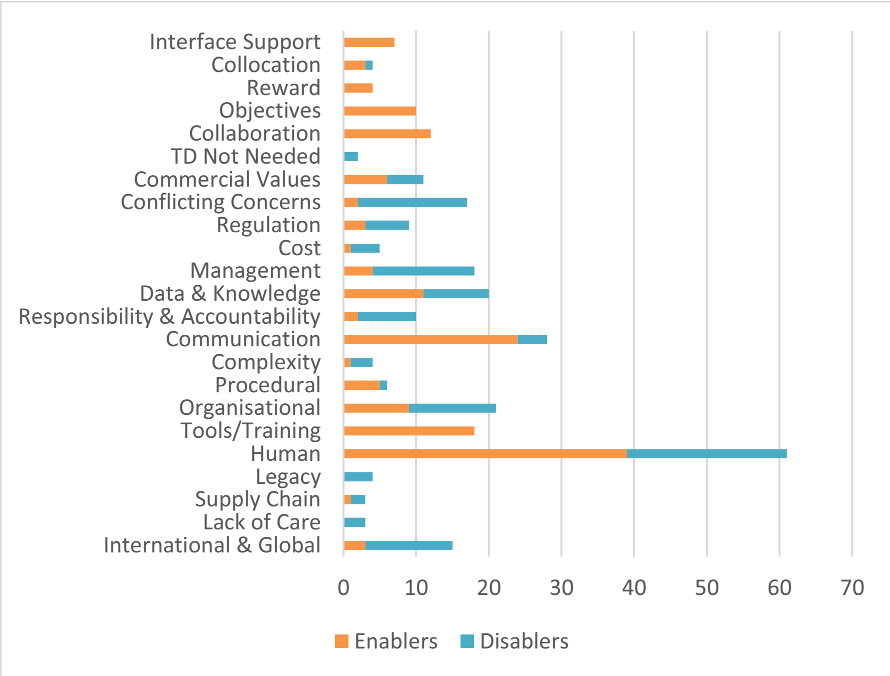

Figure 2. Distribution of Themes

The enablers and disablers presented in figure 2 above illustrate the pervasive presence of TD projects already across the depth and breadth of industrial work, demonstrated in the broad topics. More enablers were suggested than disablers, suggeting a positive approach within indutry to solving such TD problems (50 disablers vs 59 enablers). However, in practice this could mean there are multiple solutions for each and every challenge, whilst this is useful, it could in itself pose the problem of optimal solution finding. Figure 2 above stacks the number of responses that pertain to core themes for all of the responses provided. This provides a useful visual snap shot of current core topics emerging in industry, in repect of enabling vs disabling practices and a summary of the overall themes.

A number of suggestions from responses are evident; 1. The most enabling project features pertain to human working, communication facilitation, collaboration, objective setting, data & knowledge of projects and the tools & technologies available. 2. The most limiting or disabling project features are also human working, organisational set up, international & global projects, management, data & knowledge, responsibility & accountability and the presence of conflicting concerns in projects. 3. The most apparent issues for industry in the low ratio of enabling features vs disabling features could be deemed to be, that TD is not needed, that there are conflicting concerns in projects, difficulties with meeting regulations, cost issues, management issues, responsibility & accountability, organisational conerns and international & global working issues.

It follows the above points are pressing concerns for industry, but interpretation suggests for each disabling project feature, alternative enablers may in fact contribute to providing support. However, the response illustration allows reflection upon project features appearing most enabling or disabling. Owing to the complex nature of descriptions it is possible that one response could be encoded into multiple categories, for example it may pertain to both "knowledge intergration" and "model", indicating difficulty establishing independent themes. It is not possible here to present interdependencies that may exist but requires further in depth evaluation.

4. Discussion

The absence of literature outlining industrial TD engineering studies [6], the complexities of TD definitions from literature [2][10] and the limited uptake of support in industry [14] raise the need for industrial studies such as the interviews in this paper. Hence the findings outlined in this paper provide value in answering the research questions in figure 1 and to begin exploring issues affecting both the resilience of engineering industry [1] and readiness to apply solutions such as TD approaches.

It is a surprise given prior work suggests the TD nature of health [10], that only 3 health projects were found in industry TD project examples. This is in comparison to the 14 for both sustainability and environmental projects. This does not reflect overall funding bodies within UKRI [4] where there appears more equal distribution of topics, however, it may reflect where current engineering industry focus is, or could be popular in societal or government policy [8]. The same studies conducted now during the covid pandemic unsurprisingly would shift significantly towards health, suggesting societal need focuses heavily in industry [15]. This demonstrates the need for resilience within industry to adapt to the rapid changes and effects of government policy and societal need.

It also means that while engineers are typically expected to generate solutions, often project disablers "fall outside of industrial organisations remit" or into catergories outside of a typical engineers skill profile [8][15], such as "management", "organisational" or "international & global". The effects of government and wider policy change in TD challenges such as "sustainability" also raise industrial cost challenges (figure 2), that create further "conflicting concerns". Enablers suggested could be "embed quality engineers" or "members into customer businesses", or other experts into wider team working. This would however in practice require modified engineering skill sets and be difficult to implement across entire projects, especially where data and information is deemed to be either commerically sensitive, or as in most cases has personal informative elements, such as in health.

Themes in interview data highlight huge differences from prior TD language and concepts used in academia [10]. This means that there are still language barriers in interpreting current industrial terminology and contexts. This significant issue must be addressed if one of the disabling and enabling issues is to be overcome "communication", especially if TD is to become relevant to industrial partners. It is also evident many industry challenges raised are not coupled closely to academic suggestion of TD outcomes when we directly compare frequent concepts [10][6][14]. Societal value is a paramount TD output [2][7][16] but the disablers in industry do not map to this directly. This gap between research and practice is also noted in the work by Scholz et al. [6].

Some of the TD approach benefits, such as "effective communication" [16] also feature in the industrial engineering disablers (figure 2), where "global & interntional" teams implement global sustainable solutions. The disabler "conflicting concerns" in industry is prevalent highlighting that industrial benefits of TD may not overlap with societal benefits, indicating there needs to be a resolution or adaptability somewhere in the wider project parties [6][14]. There is no simple solution to this issue, but it reflects industry concerns in management and communication.

Interdisciplinary (ID)/TD overlaps suggested in the work by Carey et al. [10], such as "climate change" appear in the industry projects and arguably many of the disabling and enabling topics could relate to both ID or TD. Further issues in the uptake of solutions [14] show considerable overlap in industry disablers, such as "data and knowledge". This raises two issues for the future, that industry continues to use different language and academic efforts should seek to understand the overlap. Secondly, it raises the question whether issues already being worked on as ID in industrial practice or indeed in wider intervention fields such as knowledge managament [3][14] also need to be acknowledged as their methods may support TD practice. It was indeed suggested within interviews that "TD is not needed" and being clear about where it may be more beneficial to industry needs clarity. A TE index measure to resolve where there is need for TD is currently being worked upon by the TREND team [13]. It illustrates the limiting human understanding factors in TD, that have sought to be solved in the work by [3][14] and further establishment of core clusters of TD concepts in the artifical clustering work being used by TREND [13]. With future research in mind, methods need to extend the findings of such academic literature content into industry to better understand language and relevant conceptual themes in engineering contexts.

5. Conclusions

In this paper we set out an initial industry exploration using semi-structured interviews with the express aim of understanding TD concepts, language and approaches being utilised in engineering projects. This included answering three research questions, to establish is there TD work already in industry without explicit mention of TD, what are the enabling and disabling factors for TD in industry and to initiate deeper case study of TD in practise.

In describing our 13 industrial interviews we found industrial projects that could be defined as TD, but limited industry understanding mean the concept of TD is not widely used. This highlights continued communication and language barriers to overcome in differing industrial disciplinarities and wider engagement. Even though terms being utilised in engineering industries do describe projects bearing similarity to those academics might consider TD, such as sustainability or environment. TD projects exemplified span the product/manufacturing lifecycle, meaning TD need is pervasive and evidence suggest disablers include mitigating for conflicting project concerns, management, international or global working and human obstacles. Enabling features include similar themes such as human solutions, tools and training, communication, collaboration and data and knowledge. Gaps appear in provision where disabling issues reside with little counteracting enabling practise, such as mitigating for conflicting concerns, international and global working and management.

It is these gaps research work for TD industries should be focussed upon supporting, especially if industry is to remain resilient whilst establishing TD projects. With this in mind researchers should drive deeper understanding of specific industry need, to establish common language across societal, industrial and policy actors and act as a bridge to implement TD tools, training and technologies. This will better common understanding of the value that is required of engineering solutions, that all stakeholders can buy into and be achievable for industries given the current working climates.

Acknowledgement

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6. References

[1] C. Goncalves Machado, M. Peter Winroth, E. Hans Dener Ribeiro da Silva, Sustainable Manufacturing in Industry 4.0: An Emerging Research Agenda, *International Journal of Production Research*, 2020, Vol 58:5, pp. 1462-1484.
[2] S. Lattanzio, E. Carey, A. Hultin, R. Imani Asrai, M. McManus, N. Mogles, G. Parry and L.B. Newnes, Transdisciplinarity Within the Academic Engineering Literature, *International Journal of Agile Systems and Management*, 2020, Vol. 13(2), pp. 213-232.
[3] E. Carey, S. Culley, & F. Weber, Establishing Key Elements for Handling In-Service Information and Knowledge, *International Conference on Engineering Design*, 2013, pp. 11-20.
[4] UKRI. *Manufacturing the future*. 2021 [cited 2021 24 February]; Available from: https://epsrc.ukri.org/research/ourportfolio/themes/manufacturingthefuture/.
[5] M. Morisse & C. Prigge, Design of a Business Resilience Model for Industry 4.0 Manufacturers, *Twenty-Third Americas Conference on Information Systems*, 2017, https://core.ac.uk/download/pdf/301371962.pdf, Accessed July, 1 2021.
[6] R.W. Scholz and G. Steiner, Transdisciplinarity at the crossroads. *Sustainability Science*, 2015, Vol. 10(4), pp. 521-526.
[7] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandic and W.J.C. Verhagen, Transdisciplinary systems engineering: implications, challenges and research agenda, *International Journal of Agile Systems and Management*, Vol. 12, 2019, pp. 58-89.
[8] Rhodes, C., *Briefing Paper Number 01942. Manufacturing: statistics and policy*. 2020, The House of Commons Library research service: UK.
[9] M. Borsato, M. Peruzzini, Collaborative Engineering. *In: Stjepandić, J., Wognum, N., et al (Ed.). Concurrent Engineering in the 21st Century*. Springer International Publishing, 2015, pp.165-196.
[10] E. Carey, J. Gopsill & L. Newnes, Text Analysis of Disciplinary Research Papers, *Advances in Transdisciplinary Engineering*, Vol. 12, 2020, pp. 32-41.
[11] Gillham, B. (2000). *Case study research methods*. Bloomsbury Publishing.
[12] Yin, R. K. (2011). *Applications of case study research.* Sage.
[13] The University of Bath. *TRansdisciplinary Engineering Design (TREND)*. 2021 [cited 2021 24 February]; Available from: https://www.bath.ac.uk/projects/transdisciplinary-engineering-design-trend/.
[14] E. Carey, S. Culley, H. McAlpine, F. Weber & Y. Xie, Key Issues in the Take-Up of Knowledge Management Interventions in Engineering Design, *International Design Conference*, 2012.
[15] J. Sajdakova. E. Carey, V. Dhokia & L. Newnes, Mapping the Competencies of Design Engineers Against the Jantsch's Hierarchical System, *Advances in Transdisciplinary Engineering*, Vol. 12, 2020, pp. 13-22.
[16] CERI, *Interdisciplinarity: Problems of teaching and research in Universities*. 1972.
[17] M. C. Harrell & M. A. Bradley, *Data collection methods. Semi-structured interviews and focus groups.* Rand National Defense Research Inst santa monica ca, 2009.
[18] S. E. Rabionet, *How I Learned to Design and Conduct Semi-Structured Interviews: An Ongoing and Continuous Journey*. Qualitative Report, 16(2), 2011, pp. 563-566.
[19] Hierarchy illustration. Accessed:14122019. [online]. Available: https://online.pointpark.edu/business/types-of-organizational-structures/

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Transdisciplinary Engineering for Market Development

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Abstract. Transdisciplinary engineering is composed of analysis and synthesis. Most of current engineering is focused on analysis and based on Euclidean Space, mathematical solutions are developed for product development. But if we pay attention to synthesis or design, we cannot satisfy the requirements of orthonormality and Euclidean distance with units. This paper discuss how we can challenge transdisciplinary engineering for market development, which requires Non-Euclidean Space approach.

Keywords. Transdisciplinary Engineering, Synthesis. Design, Market Development, Non-Euclidean Space

Introduction

Engineering is composed of two main fields. One is product development and the other is market development. But currently most engineering efforts are paid to product development. In other words, product development can be described as analysis and market development as synthesis.

In analysis, we look for how we can organize our tools and knowledge and focus on how we can achieve the goal effectively. Thus, the goal is fixed from the first and we pay our efforts to find the best HOW to produce better products in a shorter time and with less cost. It is problem solving. Synthesis is design and we look for WHAT product we should develop. It is goal finding and problem setting. Thus, it calls for trials and errors. And in analysis, we go deeper and deeper. But in design or market product, we need to look wider and wider to find out a new market with the currently available resources.

Thus, market development is nothing other than exploration. President Theodore Roosevelt, who is also famous as explorer, left the following famous words,

Do what you can, with what you have, where you are.

We need to make efforts to find out WHAT we should do, and we should consider WHY we are trying to explore.

S-growth curve is well known, and most engineering now is focusing on analysis or product development. Goal is fixed from the first and HOW we can produce better products effectively is focused. Thus, with time, product development accelerates and finally it reaches the ceiling, and we start to look for another product to develop. But in market development, the form is trapezoidal. And we need to find a market that grows immediately with lifetime as long as possible (Figure 1).

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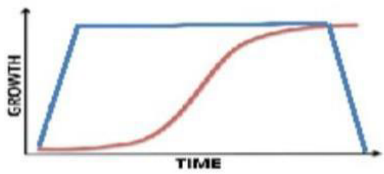

Figure 1. S-curve and trapezoid.

Transdisciplinary Engineering for product development follows s growth curve and engineering there is tree-structured. As the goal is fixed from the first and the goal is single. It is nothing other than a tree. So, how we can assign appropriate tools is important. If appropriate tools are not available, we need to develop them. Thus, the process goes on, the development grows in the form of letter S. In product development, Trans- in Transdisciplinary means to look at tools from a higher viewpoint.

But Trans- in Transdisciplinary Engineering for market development means middle or media. Thus, it is deeply related to communication. In fact, Kevin Ashton proposed IoT (Internet of Things) [1]. This internet means nothing other than communication. Ashton worked in supply chain management. So, it is market engineering. He pointed out also that it is important to work with machines on the same team as Things Team. So, we need to communicate with machines.

This paper points out that to explore market, we need to evaluate performance of each candidate model and compare and prioritize them to make a strategic decision. And a new approach called Mahalanobis Distance-Pattern (MDP) Approach is proposed.

1. Our World is Changing

Our world is changing frequently and extensively.

(1) Yesterday, there were changes. But they changed smoothly, so that we could differentiate them and could predict the future. Engineers could foresee the operating oruse conditions of their products. So, they could focus their attention on their functions. So, engineers focused their attention on how they can control them and secure reproducibility.

But today, changes are sharp, so we cannot differentiate them. We cannot predictthe future anymore (Figure 2).

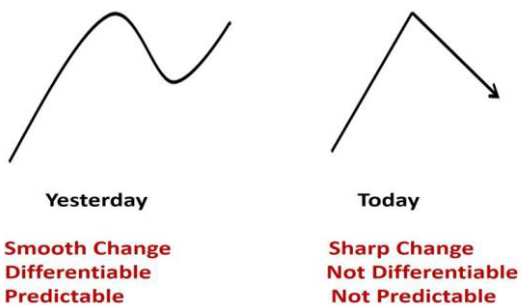

Figure 2. Changes of yesterday and today.

(2) Yesterday, our world was closed with boundary. So, we could apply mathematical approaches in a straightforward manner. But our world keeps on expanding and now it becomes open world without boundary. When the world was not so wide open, we could apply system identification approach, so we could manage to apply mathematical approaches.
System identification shares the same idea how we identify the name of a river (Figure 3). If we look at the flow, it is changing every minute. So, we cannot identify its name. But if we look around, we find mountains and forests and we can identify its name.

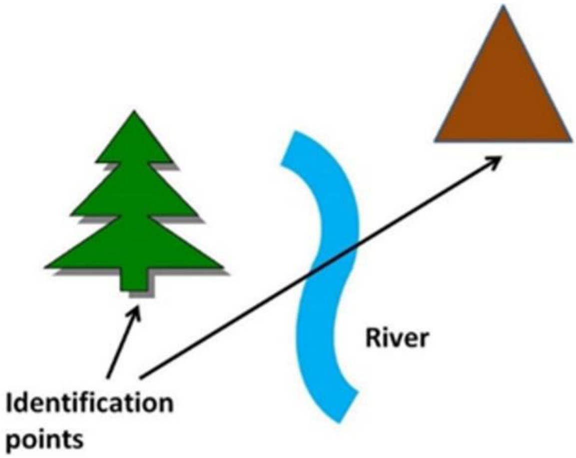

Figure 3. How we identify the name of a river.

This approach worked very well. But now our world is changing frequently and extensively and in a unpredictable manner. So, in short, now we are thrown into the flow. How should we manage to get to our goal? This is the challenge we are going to discuss here.

(3) Materials are getting softer and softer.
Materials used to be hard. So, even from a distance, we could understand how we should maniputate them. But today, materials are getting softer and softer, so that we cannot understand how we should manipulate them. Vision alone does not work anymore. We need to directly interact with them to decide how we should deal with them. When we try to pick them up and it does not work then we need to scoop them, etc. Direct interaction becomes crucial.

2. Euclidean Space Approach

Most engineering research are based on Euclidean Space approach. It requires orthonormality on all datasets and it is based on interval scale with units. And datasets are related. So, when the dimensions are small, we can obtain wonderful results, but then from there we cannot step forward easily. This is called either Devil River, Valley of Death, or Darwinian Sea. It means there is a big gap between the basic research and industrialization.

In fact, when the number of dimensions increases, the curse of dimensionality emerges, and we cannot solve the problem mathematically. Then, how can we solve the problem against the curse of dimensionality? The curse of dimensionality emerges because we stick to the Euclidean Space. Then, how can explore Non-Euclidean Space?

3. Non-Euclidean Space Approach

3.1. Pattern

Shuichi Fukuda and his group carried out a research to detect emotion from face. They tried many image processing techniques, but they took too much time and without satisfactory resulsts. Then, Fukuda suddenly realized that we can detect emotion from cartoon characters at once. At that time, most cartoons aere just in black and white, but we could immediately understand their emotion. So, we developed a carttoon model approach and we succeeded in detecting emotion in a very short time and without any difficulty [2], (Figure 4). At this time, we used Euclidean Space and cluster analysis.

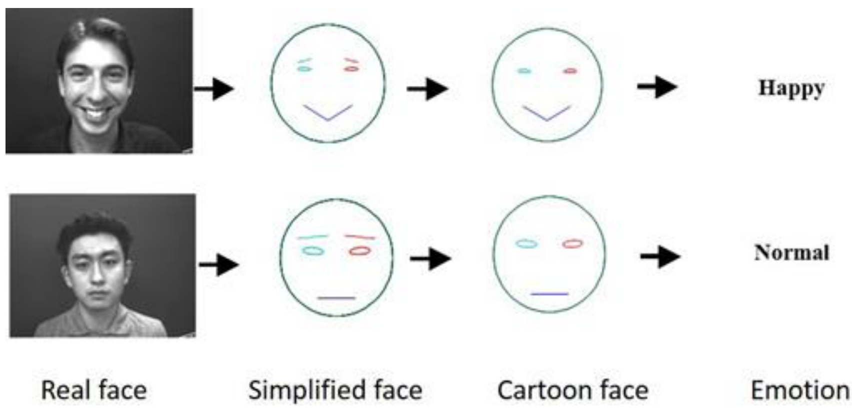

Figure 4. Detection of emotion from face using cartoon model.

3.2. Mahalanobis Distance

Mahalanobis proposed Mahalanobis Distance, which is ordinal scale [3]. Its purpose is to remove outliers and to improve design of experiments. So, his original paper is to improve Euclidean Space approach. But if we note that his distance is not Euclidean distance, i.e., interval scale distance with unit and that it is ordinal scale, we can utilize it as Non-Euclidean Space approach.

Mahalanobis Distance (MD) is defined as how far away the point P is from the mean of the dataset as shown in Figure 5. And MD does not call for its dataset to be orthonormal. Any collection of data is allowed. As customers have a wide variety of preferences or expectations, this distance can provide a truly adaptive performance indicator. In fact, the idea of KPI, Key Performance Indicator, plays a very important role in business. So,MD is a perfect fit for market engineering.

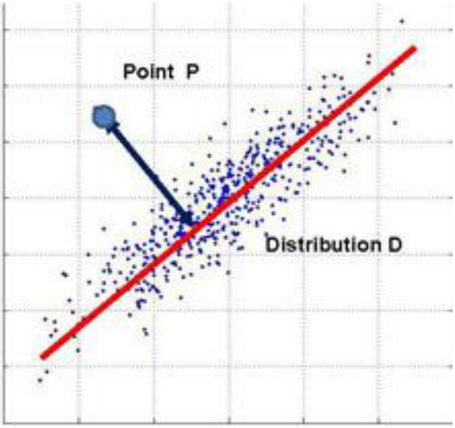

Figure 5. Mahalanobis Distance.

3.3. Mahalanobis-Taguchi System

Around the same time when Fukuda and his group developed pattern-based cartoon model, Genichi Taguchi, founder of quality engineering, developed Mahatanobis-Taguchi System [4]. His idea was unique.

In quality control, it has been a tradition to control quality element by element. But in practical applications, most industries find it very difficult to carry out element by element quality control. What they can do is to manage quality holistically.

Taguchi realized if he introduces MD and combine it with pattern, he can respond to their needs. Let me explain using an example of number. We write number 2 differently from time to time and from person to person. But if we average these samples, we can obtain a standard pattern of number 2. Taguchi calls this standard pattern Unit Space (Figure 6). And he introduce Threshold. If MD is smaller than this threshold, then we can identify the letter as number 2. If it is larger than the threshold, we cannot (Figure 7).

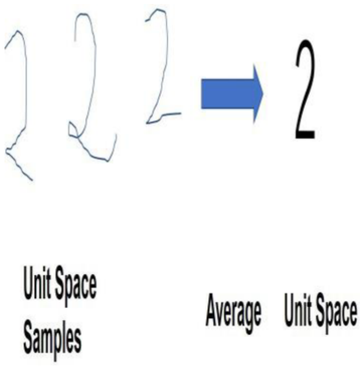

Figure 6. Defining Unit Space.

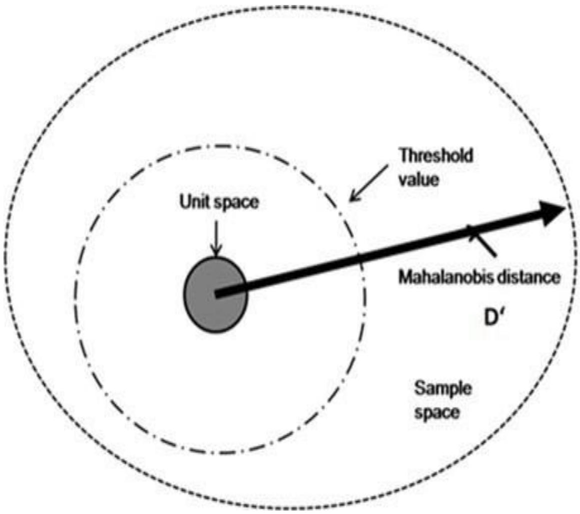

Figure 7. Mahalanobis-Taguchi System.

4. Performance Evaluation

Yesterday, customers were called Consumers, because their needs were material-focused. They wanted products. But as Abraham Maslow pointed out [5], Human needs shift to mental satisfaction and we finally look for Self-Actualization (Figure 8). Edward Deci and Richard Ryan proposed Self-Determination Theory [6] and made it clear that if the activity is internally motivatedand self-determined, we have the maximum satisfaction and sense of achievement, which no external rewards can provide.

Figure 8. Maslow's hierarchy of human needs.

When we wanted products, the goal is fixed from the first, so we can sell our products based on a tree structure. What we needed was to assign persons best fitted to the position (Figure 9). But the changes become frequent, extensive and unpredictable, so, we need to organize a team which adapt to the environments and situations flexibly and adaptively.

Amy Edmondson at Harvard Business School pointed out our team organization and management have been too much static. If we consider the current situation of frequent, extensive and unpredictable changes, we need to introduce dynamic team organization and management. She calls it Teaming [7].

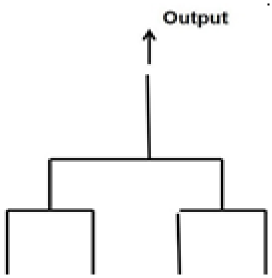

Figure 9. Tree.

Thus, teaming organization and management have to be a network, because our goal varies from case to case and from time to time (Figure 10).

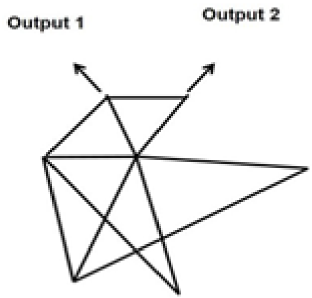

Figure 10. Network.

5. Conclusions

Mahalanobis Distance Pattern (MDP) Approach is basically the same as MTS. But MTS is static pattern matching. MDP, on the other hand, focus on dynamic variation. Instead of static pattern, we take up dynamic pattern variations and we calculate MD in the same way as in MTS. Then, we can have the dynamic pattern variation. And we evaluate performance. MTS provides static performance indicator, while MDP provides dynamic one.

As this paper is focused on Transdisciplinary aspect [8][9], the details of MDP are not described here.

For its details, visit [10].

References

[1] A. Kevin, That "Internet of Things" Thing, *RFID Journal*, June 2009, Vol. 22, pp. 97-114.

[2] V. Kostov, S. Fukuda and M. Johansson, Method for Simple Extraction of Paralinguistic Features in Human Face, Images & Visual Computing, *The Journal of the Institute of Image Electronics Engineers of Japan*, 2001, Vol, 30, No. 2, pp.111-125.
[3] P. C. Mahalanobis, On the Generalized Distance in Statics, *Proceedings of the National Institute of Science of India*, 1936, Vol.2, No.1, pp.49-55.
[4] G. Taguchi, S. Chowdhury and Y. Wu, *The Mahalanobis-Taguchi System*, McGraw-Hill Professional, New York, 2000.
[5] A. H. Maslow, A Theory of Human Motivation, *Psychological Review*, 1943, Vol. 50, No. 4, pp. 370-396.
[6] E. L. Deci and R. M. Ryan, *Intrinsic Motivation and Self-Determination in Human Behavior*, Plenum Press, New York, 1985.
[7] A. C. Edmondson, *Teaming: How Organizations Learn, Innovate, and Compete in the Knowledge Economy*, Jossey-Bass, San Francisco, 2012.
[8] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, W. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 753-762.
[9] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić and W.J.C Verhagen, Transdisciplinary systems engineering: implications, challenges and research agenda, *International Journal of Agile Systems and Management*, 2019, Vol. 12, No. 1, pp. 58-89.
[10] S. Fukuda, Invited Talk, Lecture Note, Making Strategic Decisions by Instinct, *International Conference of Center for Mathematical Modelling and Applications, ICMMA 2020*, Meiji Institute for Advanced Study of Mathematical Sciences, Meiji University, 2021.

Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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The Transdisciplinary Engineering Index: Towards a Disciplinary Maturity Grid

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Abstract. The adoption of transdisciplinary capabilities within UK manufacturing could strengthen resilience in response to system disruptions. We propose a Disciplinary Maturity Grid (DMG) as a means through which industry can assess the disciplinarity of their engineering capability. The design of methods to assess maturity of disciplinary working is hindered by a lack of empirical evidence to support identification of the important dimensions. A workshop involving twelve academic experts was used to create a maturity grid. Workshop tasks focussed on defining the appropriate number of maturity levels, the dimensions of those levels, and the maturity assessment questions. The DMG contains five maturity levels and seven dimensions, providing a preliminary design from which to build in future studies.

Keywords. Transdisciplinary Engineering, Disciplinary Maturity Grid

Introduction

Manufacturing plays a significant role in the UK economy, contributing £191 billion of economic output (10% of the UK total), and employing 2.7 million people (8% of jobs) [1]. UK government aims to ensure the resilience of the sector in the face of challenges including plateauing productivity levels and a widening trade deficit in manufactured goods, together with uncertainty around the UK leaving the European Union. In support of this aim in 2011 UK Research and Innovation (UKRI) initiated the Manufacturing the Future Challenge theme. Under this theme funding awards in excess of £300 million have been pledged to support research in three priority areas: drawing on opportunities from emerging research, promoting collaboration between academia and innovative manufacturing businesses, and fostering a research community with the appropriate skills and leadership in manufacturing research [2].

UKRI recognised the potential benefits from adoption of transdisciplinarity within manufacturing and in 2018, under the Manufacturing the Future Challenge, awarded £1.8m for research focussed on enabling transdisciplinary working within the sector [3]. Under the terms of the award the ultimate ambition is to design and validate a Transdisciplinary Engineering (TE) Index [4]. The Index will comprise of three elements: a means for industry to assess their current disciplinary state; a means for industry to assess the level of disciplinarity that is required; and tools to help them move

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from one level to another. The focus of this paper is the first of these three elements – a means for industry to assess their current disciplinary state. This is approached through the creation of a Disciplinary Maturity Grid (Figure 1).

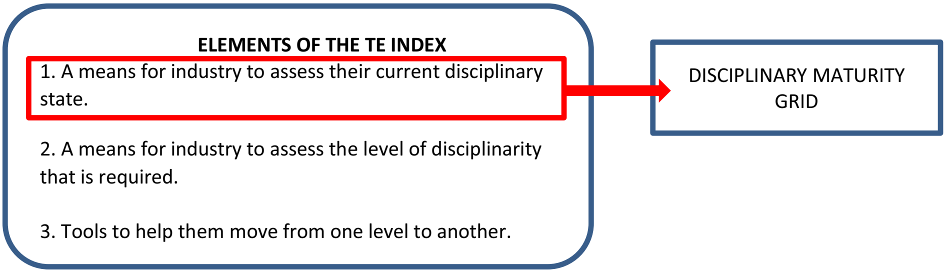

Figure 1. Mapping the elements of the TE Index to the Disciplinary Maturity Grid.

Within this paper we present the results of a workshop undertaken as a means to create a Disciplinary Maturity Grid (DMG). Specific design aspects include the number of maturity levels, the number and focus of the dimensions, definition of the maturity assessment questions. The paper is structured as follows: First the background literature is presented (Section 1). The methodology and processes followed within the workshop are described (Section 2). The DMG created within the workshop is presented (Section 3) and discussed in light of the literature (Section 4). Finally, conclusions are formulated, and future work identified (Section 5).

1. Background

Since its emergence in the 1970s, transdisciplinarity has been positioned as a level of working which exceeds interdisciplinarity [5]. Although there is no universally accepted definition, transdisciplinarity is often characterised as an approach which brings together academic and stakeholder perspectives and integrates physical and social sciences to understand the context in which a challenge exists [6-10].

Transdisciplinary approaches are considered to be particularly useful in dealing with complex challenges. In the 1990s, a growing concern for the environment, a challenge that requires many different disciplines to address, brought with it a requirement for new ways of working, and transdisciplinarity came to the fore [11, 12]. From this point forwards the number of published papers referencing the term are seen to accelerate [13]. Subsequently, new technologies and Industry 4.0 have led to increasingly complex engineering systems. This has resulted in interest in transdisciplinary working from the engineering academic and research funding communities [13]. There is also evidence that transdisciplinarity has been embraced by practitioners [14, 15]. However, how theory can be operationalised within industry setting requires research.

One of the challenges in operationalisation of transdisciplinarity is the lack of a universal definition [8, 16-18]. What is generally accepted is that there is a hierarchy of disciplinarities, which starts with a single discipline, progresses through multi- and inter- and ends with transdisciplinarity [7, 8]. By aiming to understand at which disciplinary state(s) a company is currently capable of working, it is in fact creating a measure of disciplinary 'maturity'. Maturity is the capability to consistently achieve organisational objectives. To deliver on this, a company should be able to work appropriately at all levels of the hierarchy. This raises the question: What approaches have been used to assess maturity?

1.1. Maturity Assessments

Maturity assessments are extensively used within industry both as an informed approach for continual improvement and as a means for self or third party assessment [19]. As shown by the review conducted by Maier, Moultrie [20], assessments have an extremely broad focus and consider all manner of organisational aspects including, but not limited to, quality management, project management, capability, safety, research and development effectiveness, information security, innovation, and communication.

Although the term ‘model’ is often used as a catch-all, the literature identifies two distinct types of maturity assessments: Capability Maturity Models (CMM)-like models, and Maturity grids / Likert-like questionnaires [20, 21]. CMM-like models identify ‘best practice’ in a specific process and measure against how many of these practices the organisation demonstrates. They often follow a formal format allowing them to be used in certification of performance [20, 21]. In contrast maturity grids are simpler. Presented as a matrix they provide a text description for defined activities or dimensions at each maturity level. Likert-like questionnaires are similar to maturity grids but rather than provide descriptions at each level of maturity, assessments are based on performance against a statement of good practice. Unlike the CMM model, maturity grids do not usually aspire to provide certification and can be used as a stand-alone assessment or as part of a wider initiative [20, 21].

In the context of a TE Index a grid is preferable to a CMM-like model for two main reasons. First, the CMM-like model is built on the belief that there is a best practice. When it comes to disciplinarity we assert that there is no best practice, rather different disciplinarities will be more or less appropriate depending on context. Second, a matrix is simpler and has a less prescriptive format than a CMM-like model. In this way it is more suitable for self-assessment and offers more flexibility for combining with the other elements required to form the Index. Having decided a grid is most suitable we ask, what are the main design elements of a grid?

1.2. Design elements of a maturity grid

Grids are presented as a matrix, each having a number of maturity levels, and a number of dimensions (the areas which are considered), with assessment questions to evaluate the maturity level of each dimension. Figure 2 presents an example maturity grid, the Energy Management Matrix, produced by the Carbon Trust. The figure is annotated to identify the three common grid elements: maturity levels, dimensions, and maturity assessment questions.

Figure 2 shows The Energy Management Matrix has five maturity levels and six dimensions. However, there is no set format and the number of levels and the dimensions included can vary [22]. A common criticisms of maturity grids is that they rarely describe how the grid was developed. The occasional papers where a method is provided demonstrate a mix of approaches which aim to bring together literature with expert opinion [22]. Maturity assessments have been criticised for a lack of rigour during their design. There have been some efforts in proposing maturity assessments design methodologies [19, 22-28]. Although with individual nuances, studies by Metler (2011) and García-Mireles, Moraga [29] have found the different methodologies contain common steps. Garcia-Mireles et al. define four steps: establish goals for maturity model development, design model architecture, set out capability levels and dimensions, and pilot testing. Metler identifies five steps: identify need or new opportunity; define scope; design model; evaluate design; and reflect evolution. Although similar, where the two studies differ is that Garcia-Mireles et al. found a lack of reference within the proposed methodologies to specific activities for maintenance.

DIMENSIONS

MATURITY LEVELS

	Energy Policy	Organising	Training	Performance Measurement	Communication	Investment
4	Energy Policy, Action Plan and regular reviews have active commitment of top management	Fully integrated into senior management structure with clear accountability for energy consumption	Appropriate and comprehensive staff training tailored to identified needs, with evaluation.	Comprehensive performance measurement against targets within effective management reporting.	Extensive communication of energy issues within and outside of the company.	Resources rout... to ...y
3	Formal policy but no active commitment from top management	Clear line management accountability for consumption and responsibility for improvement	Energy training targeted at major users following training needs analysis	Weekly performan... measuremen... proce...		...ficiently ...for other cost reduction projects
2	Un-adopted policy	Some delegation of responsibility	A...		... use of ...ganisational communication mechanisms to promote energy efficiency	Low or medium cost measures considered if short payback period
1	An u...		... staff ...y attend ...ecialist coursed	Invoice checking only	Ad-hoc informal contacts used to promote energy efficiency	Only low or no cost measures taken
0	No polic...	...ation of ...nsibility for managing energy policy	No energy related staff training provided	No measurement of energy costs or consumption	No communication or promotion of energy issues	No investment in providing energy efficiency

Maturity Assessment Questions

Figure 2. Energy Management Matrix [30].

2. Method

The TREND Research Group seeks to create and validate a TE Index and use this as a means to enable transdisciplinarity within the manufacturing sector. The focus of this paper is the first element of the Index, the creation of a Disciplinary Maturity Grid through which industry can assess their current disciplinary state. The methodology through which the grid is created is now presented.

2.1. Methodology

TREND recognise the design of a maturity grid to be an iterative process in which a preliminary grid is created, evaluated and then evolved. As such, the five steps defined by Melter were selected as the approach to be followed in the design of the Disciplinary Maturity Grid (Figure 3).

Figure 3 details the design steps, showing the iterative nature of the development. In Step 1, identify need / new opportunity, was addressed within the funding request bid documentation, that identified a need within UK manufacture to develop TD capability. Step 2, define the scope (e.g. the focus and audience), was constrained by the terms of the funding award. Step 3, Design model, is undertaken by way of the workshop described in this paper. Evaluation of the design (Step 4), and reflect evolution (Step 5), will be undertaken as future work.

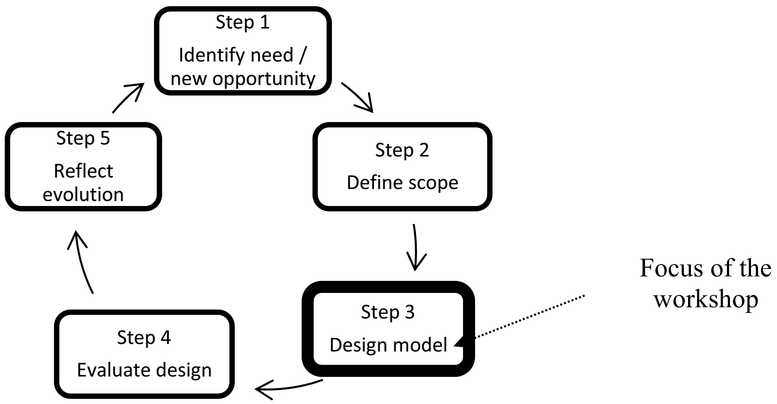

Figure 3. Disciplinary Maturity Grid Methodology.

Although Figure 3 presents the overall research methodology, it does not provide the detail of why a workshop approach was used, or how the workshop was organised. This detail follows.

2.2. The Workshop

Workshops are a widely used research approach that seeks to bring about an outcome, such as generating insights, or contributing to the design of a product, process, or innovation [31]. A common feature of workshops is the bringing together of a small number of people with experience in a certain domain [31]. The workshop participants here comprised of twelve members of the TREND research group, all experienced in transdisciplinary concepts and research. The choice to limit the workshop to only academic participants was based on the research of Carey [15] which highlights that TD has not widely penetrated industry. Table 1 provides details of the participants.

Table 1. Workshop participants.

Position	University of Bath	University of Bristol	University of Surrey
Academics	3	3	1
Researchers	3	1	0
PhD students	1	0	0

The desired outcome of the workshop was to create a Disciplinary Maturity Grid (DMG). Literature identifies that maturity grids have three common elements (maturity levels, dimensions, and maturity assessment questions). In designing the DMG, three design aspects were addressed: The number of maturity levels, the dimensions to be included, and how the maturity assessment questions would be defined. These aspects are now addressed in order.

2.2.1. How many maturity levels should the grid have?

Typically assessments are seen to have between three and six maturity levels [21], with the most common number being five [20]. With no literature to support the optimum number, a decision was made that the Disciplinary Maturity Grid would contain five maturity levels.

2.2.2. What dimensions should be included?

Although the number of maturity levels is generally consistent, the number and areas defined as the grid dimensions have a considerable range with examples found in the literature ranging from four to over one hundred [20]. If a maturity grid is being developed in an area which is mature, it is likely that there will be literature on the critical areas and in some cases existing models which can be built upon [23]. In an emerging domain, as is the case for transdisciplinarity within an engineering context, this body of evidence is not available

In designing the Disciplinary Maturity Grid ensuring that the relevant dimensions are included will be fundamental to its success. To uncover these dimensions a research experiment was undertaken. This experiment is presented in detail in the work of Hultin, *et al.* (2021), but in summary it involved an automated search of Scopus to identify all the papers with the term transdisciplinary or trans-disciplinary in the title, abstract or keywords. The abstracts were then analysed to extract any nouns directly following the term 'transdisciplinary' or 'trans-disciplinary'. The 100 most common terms, (70.3% of term frequency), were subjected to a card sorting experiment whereby 20 TD subject-matter experts individually sorted the terms into clusters comprising of similar terms. A categorical clustering algorithm was then used to identify the optimal grouping.

Within the workshop a Delphi like approach was used to name the clusters and these became the dimension names. The process used in naming the clusters follows:

- Workshop participants put into breakout rooms (3 groups x 4 people) and asked to discuss the clusters.
- Participants brought back to main room to discuss as a group.
- Participants put back into breakout rooms and asked to discuss again.
- Participants individually asked to come up with clusters names and enter them onto Padlet, (Microsoft collaboration tool).
- The workshop facilitator entered responses for each cluster (duplicates removed) into Mentimeter (a platform which enables live polls).
- Participants asked to vote for up to three names per cluster.
- Participants brought back to main room to discuss as a group.
- Top three names (or four in case of a tie in 3rd place) with more than 2 votes, retained on Mentimeter.
- Second round of voting. Participants asked to vote (max. two names per cluster).
- Cluster name with the highest number of votes identified.

2.2.3. How should the maturity assessment questions be defined?

Research by de Bruin, Rosemann [23] identifies that when designing the maturity assessment questions, the literature provides a starting point. However, for richness the literature should be considered alongside other inputs. Figure 4 presents the inputs brought together in defining the maturity assessment questions.

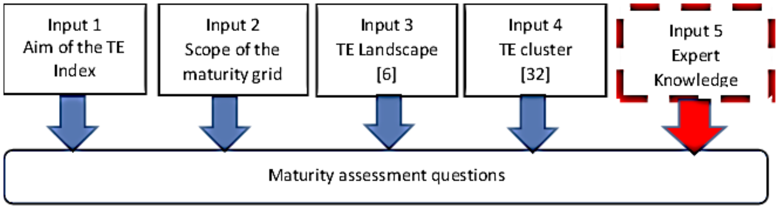

Figure 4. Inputs informing the maturity assessment questions.

Figure 4 shows the five inputs which inform the definitions of the maturity text descriptions. Aim and scope (Inputs 1 & 2) are defined and constrained by the terms of the funding award. The TE Landscape and TE clusters (Inputs 3 & 4) bring the understanding gained through prior research studies. Finally, Input 5 recognises the contribution made by way of expert knowledge and expertise of the participants. The process for defining the maturity assessment questions follows:

- Activity introduced by independent workshop facilitator including presenting a worked example of assessment questions for one dimension.
- Participants put into breakout groups (3 groups x 4 people) and asked to discuss and critique the worked example.
- Participants brought back to the group to discuss.
- Participants put back into breakout groups. Each group asked to define assessment questions for one dimension.
- Participants brought back to the group to discuss.
- Participants put back into breakout groups. Each group asked to define assessment questions for a second dimension.

3. The Disciplinary Maturity Grid

The preliminary Disciplinary Maturity Grid created through the workshop is presented in Appendix 1.

4. Discussion

The aim of this research was to populate a first draft Disciplinary Maturity Grid this involved design decisions around the number of maturity levels, the dimensions, and how the assessment questions are defined.

The literature highlights that little attention is given to how the number of levels within a grid is decided. In the absence of a more rigorous approach it was agreed that the Disciplinary Maturity Grid would have five levels, thus reflecting what Maier, Moultrie [20] found to be the most common number. Despite making this design decision, for two of the dimension's maturity assessment questions, six levels were defined. This raises the question can the different levels for these dimensions be adequately encapsulated within five levels or are more levels necessary? Although, in each of the examples provided by Maier, et al. the number of dimensions was consistent across each of the dimensions, within a disciplinary maturity grid should/could the different dimensions have a different number of levels?

Similar to the number of levels, within the literature there was little discussion of how the dimensions were selected. On the rare occasions where this was provided it was justified as being evidenced through the literature, or chosen based on the input of experts [22]. Within this work we used the literature and extracted the types of things which have been given the label of transdisciplinary. Although a rigorous approach to identify clusters of transdisciplinary ‘things’, do these translate to be the important dimensions?

Through a collaborative approach and utilising various input sources the participants were able to define the maturity assessment questions. However, during this process a specific question arose - should the assessment questions be phrased as objective or subjective measurements? Within the literature this question is given little consideration. Indeed, within the work of Mettler [32], which seeks to define the parameters which should be considered when designing a maturity assessment, although the question of “application of method” (i.e. whether the grid is completed as a self-assessment, with the assistance of a third party, or certified professionals), and the “respondents” (management, staff, business partners etc.) are both included, the specifics of whether the questions used in the assessment of maturity are objective or subjective is not.

5. Conclusions and Future Work

The aim of this work is to provide industry with a means through which to assess their current level of disciplinary working. Through the literature we identify that a hierarchy of disciplinarities exist and propose that in assessing disciplinarity it is in effect a measure of maturity. Using a workshop approach, we bring together understanding of the constraints, evidence from prior research studies, and expert knowledge to create a preliminary Disciplinary Maturity Gird. The grid comprises five maturity levels and seven dimensions (situation/stakeholders, perspective, knowledge, communication, the project, the approach, and activities).

The creation of a valid maturity grid is one element in the creation of TE Index and the operationalisation of transdisciplinary working with industry. However, it is recognised that the design of a maturity grid is an iterative process. This is especially true here where there is a lack of prior understanding of the dimensions which are fundamental to the success of transdisciplinary working. To this end future verification and validation studies will adopt a TD approach in which the perspectives of industry who will use the grid are captured and incorporated.

Acknowledgements

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References

[1] C. Rhodes, *Briefing Paper Number 01942. Manufacturing: statistics and policy*, The House of Commons Library research service, UK, 2020.

[2] UKRI. *Manufacturing the future*. 2021 [cited 2021 24 February]; Available from: https://epsrc.ukri.org/research/ourportfolio/themes/manufacturingthefuture/.

[3] The University of Bath. *TRansdisciplinary Engineering Design (TREND)*. 2021 [cited 2021 24 February]; Available from: https://www.bath.ac.uk/projects/transdisciplinary-engineering-design-trend/.

[4] L. Newnes, et al., TRansdisciplinary ENgineering Design (TREND): Towards a Transdisciplinary Engineering Index. *Advances in Transdisciplinary Engineering*, 2020, Vol. 12, pp. 42-49.
[5] L. Apostel, *Interdisciplinarity: Problems of teaching and research in Universities*, OECD, 1972.
[6] S, Lattanzio, et al., Concepts of Transdisciplinary Engineering: A Transdisciplinary Landscape, *The International Journal of Agile Systems and Management*, Accepted 2021.
[7] C. Pohl, From Transdisciplinarity to Transdisciplinary Research. *Transdisciplinary Journal of Engineering & Science*, 2010, Vol. 1, pp. 65-73.
[8] C. Pohl and G.H. Hadorn, *Principles for Desigining Transdisciplinary Research*, Swiss Academies of Arts and Sciences, Bern, 2007.
[9] B. Tress, G. Tress, and G. Fry, Clarifying integrative research concepts in landscape ecology*, Landscape Ecology*, 2004, pp. 479–493.
[10] F. Wickson, A.L. Carew, and A.W. Russell, Transdisciplinary research: characteristics, quandaries and quality*, Futures*, 2006, Vol. 38(9), pp. 1046-1059.
[11] T. Augsburg, Becoming Transdisciplinary: The Emergence of the Transdisciplinary Individual. *World Futures*, 2014, Vol. 70(3-4), pp. 233-247.
[12] J.H. Bernstein, Transdisciplinarity: A Review of Its Origins, Development, and Current Issues. *Journal of Research Practice*, 2015, Vol. 11, Article R1.
[13] S. Lattanzio, et al., Transdisciplinarity Within the Academic Engineering Literature*, International Journal of Agile Systems and Management*, 2020, Vol. 13(2), pp. 213-232.
[14] R.W. Scholz and G. Steiner, Transdisciplinarity at the crossroads. *Sustainability Science*, 2015, Vol. 10(4), pp. 521-526.
[15] E. Carey, et al., Foraging for Transdisciplinary Challenges: Emergent Industrial Themes, in *Advances in Transdisciplainry Engineering,* 2021, in press.
[16] R. Lawrence, Deciphering interdisciplinary and transdisciplinary contributions. *Transdisciplinary Journal of Engineering and Science*, 2010, Vol. 1(1), pp. 125-130.
[17] C, Pohl, What is progress in transdisciplinary research? *Futures*, 2011, Vol. 43(6), pp. 618-626.
[18] Swiss Academies of Arts and Sciences. *td-net Network for Transdisciplinary Research*. 2018 27th July 2020]; Available from: http://www.transdisciplinarity.ch/en/td-net/Transdisziplinarit-t/Definitionen.html.
[19] T. Mettler, *A design science research perspective on maturity models in information systems*. Institute of Information Management, Universtiy of St. Gallen, 2009.
[20] A.M. Maier, J. Moultrie, and P.J. Clarkson, Assessing organizational capabilities: Reviewing and guiding the development of maturity grids. *IEEE Transactions on Engineering Management*, 2012, Vol. 59(1), pp. 138-159.
[21] P. Fraser J. Moultrie, and M. Gregory. The use of maturity models/grids as a tool in assessing product development capability. *IEEE International Engineering Management Conference*, 2002.
[22] J. Becker, R. Knackstedt, and J. Pöppelbuß, Developing maturity models for it management - A procedure model and its application. *Business and Information Systems Engineering*, 2009. Vol. 51(3), pp. 249-260.
[23] T. de Bruin, et al. Understanding the main phases of developing a maturity assessment model. *ACIS 2005 Proceedings - 16th Australasian Conference on Information Systems*. 2005.
[24] J.C.R. Hauck, et al., Proposing an ISO/IEC 15504-2 compliant method for process capability/maturity models customization, *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2011, pp. 44-58.
[25] A. Maier, J. Moultrie, and J. Clarkson, Developing maturity grids for assessing organizational capabilities: practitioner guide, *4th international conference on management consulting, Academy of Management (MCD 2009)*, 2009, Vienna. pp. 1-29.
[26] C.F. Salviano, et al., A method framework for engineering process capability models, *EuroSPI 2009*. 2009, pp. 625-636.
[27] M. Van Steenbergen, et al. *The design of focus area maturity models*. In: R. Winter et al. (eds.) *Global Perspectives on Design Science Research*, 2010, pp. 317-332.
[28] C.G. Von Wangenheim, et al., Creating software process capability/maturity models. *IEEE Software*, 2010, Vol. 27(4), pp. 92-94.
[29] G.A García-Mireles, M.Á. Moraga, and F. García. Development of maturity models: A systematic literature review. *16th International Conference on Evaluation & Assessment in Software Engineering (EASE 2012)*, 2012, 10.1049/ic.2012.0036.
[30] The Carbon Trust. *Energy management self-assessment tool*. 2021 [cited 2021 24 February]; Available from: https://www.carbontrust.com/resources/energy-management-self-assessment-tool.
[31] R. Ørngreen and K. Levinsen, Workshops as a research methodology. *Electronic Journal of e-Learning*, 2017, Vol. 15(1), pp. 70-81.
[32] T. Mettler, Maturity Assessment Models: A Design Science Research Approach. *International Journal of Society Systems Science*, 2011, Vol. 3(1/2), pp. 81-98.

Appendix 1: Disciplinary Maturity Grid

	Cluster 1: Situation / stakeholders	Cluster 2: Perspective	Cluster 3: Knowledge	Cluster 4: Communication	Cluster 5: The project	Cluster 6: Approach	Cluster 7: Activities
Level 1	Siloed working in isolation on a task	No overarching statement of strategy, disparate views held and no evidence of any mechanism(s) to resolve and develop a shared	You don't know what disciplines need to be involved, the methods and how you might integrate and transcend them. (You don't know what you don't	Siloed working. Little or no communication between organisational functions and/or stakeholders.	An approach* unique to function of a single person/team/discipline.	Lack of systematic approach but no attention to TD.	No activity
Level 2	Multiple teams working towards a common goal, but with limited co-operation and coordination	Understanding of the need for a clear mission statement, value management and shared understanding. But no	You know what disciplines are required but do not know the relationships and how to integrate and transcend them.	Some evidence to support that communication is occurring across organisational functions. Limited to particular tasks	Collaborative approach* that enables working on a common goal, but with limited co-operation and coordination	Aware of the need for a systematic approach(es) but roadmap (plan, timescale and resources) not identified. No evidence	Some activity but no appreciation of what people/teams are doing and how it contributes to the whole.
Level 3	Multiple teams with a common goal, sharing functions and co-operating, but without shared values and governance	Evidence of mechanisms to develop a clear mission statement, manage value management and the need for holistic understanding. Limited evidence of shared understanding and common perspective /	You know what disciplines are required and know the relationships but you do not know how integrate and transcend them. (You know what you don't know.)	Extensive evidence supporting that communication across organisational functions does occur. Processes and policies exist which embed this working within the culture of the company.	Collaborative approach* that enables working on a common goal, sharing functions and co-operating, but without shared values and governance	Approach defined and adoption roadmap (resources, plan, integration) developed. underway. Evidence business buy-in.	Some activity and appreciate what people/teams are doing and how it contributes to the whole but do not their progress.
Level 4	Multiple teams with a common goal, co-operating, sharing functions and governance, but not values	Evidence of a clear mission statement, operationalisation of a value management framework and holistic understanding. Some evidence of shared understanding and shared	Well aware of what they need to know and the disciplines that need to involved. And the methods that transcend it.	Some evidence supporting that communication across organisational functions and stakeholders occurs. Limited to particular tasks or specific areas within the company.	Collaborative approach* that enables working on a common goal, co-operating, sharing functions and governance, but not values	Approach being implemented but not fully operationalised. Emerging evidence of coordination and holistic approach.	Extensive co-ordinated activities with shared understanding of the activities being performed and their progress to date
Level 5	Fully integrated teams working across and between functions, with shared values and governance	Evidence of a clear mission statement, operationalisation of a value management framework and holistic understanding. Evidence of shared understanding and shared	Well aware of what they need to know and the disciplines that need to involved. And the methods that transcend it. And you know your future needs and how to get there.	Extensive evidence supporting that communication across organisational functions and stakeholders occurs. Processes and policies exist which embed this within the culture of the company.	Collaborative approach* that enables working across and between functions, with shared values and governance	Approach implemented and fully operationalised. Clear evidence of coordination and holistic approach.	Extensive co-ordinated activities with shared understanding of the activities being performed and their progress to date. Are able to contribute positively to other activities and have a good
Level 6		This a TD Blackbelt!				Clear evidence of thought leadership and evolution of toolset and approaches.	

Part 2

Transdisciplinary Engineering Education and Training

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A Transdisciplinary Approach for the Design Optimization of Medical Simulations

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Abstract. Simulation in healthcare is rapidly replacing more traditional educational methods, becoming a fundamental step in the medical training path. Medical simulations have a remarkable impact not only on learners' competencies and skills but also on their attitudes, behaviors, and emotions such as anxiety, stress, mental effort, and frustration. All these aspects are transferred to the real practice and reflected on patients' safety and outcomes.
The design of medical simulations passes through a careful analysis of learning objectives, technology to be used, instructor's and learners' roles, performance assessment, and so on. However, an overall methodology for the simulation assessment and consequent optimization is still lacking.
The present work proposes a transdisciplinary framework for the analysis of simulation effectiveness in terms of learners' performance, ergonomics conditions, and emotional states. It involves collaboration among different professional figures such as engineers, clinicians, specialized trainers, and human factors specialists. The aim is to define specific guidelines for the simulation optimization, to obtain enhanced learners' performance, improved ergonomics, and consequently positively affect the patient treatment, leading to cost savings for the healthcare system. The proposed framework has been tested on a low-fidelity simulation for the training of rachicentesis and has allowed the definition of general rules for its enhancement.

Keywords. Transdisciplinary design, Design optimization, Simulation-based training, Human Factors, User experience.

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Introduction

For some decades, simulation has been used for educational purposes in several fields. It is defined as an imitation of a real system, able to mimic the real situation both in practical and behavioral contents. Indeed, its main advantage is the opportunity to involve the participants in a very immersive experience, avoiding the risks that would arise in real situations. For this reason, simulation is considered an excellent tool to reduce errors in high-risk industries such as aviation, defense, the nuclear energy field, and even healthcare.

The healthcare industry has begun to use simulation because it allows repeatedly practicing on simulated complications without putting the patient at risk, and thus, as a consequence, reducing the chance of bad outcomes in the real practice [1]. Moreover, beyond the learning of practical procedure and technical skills, simulations also offer the healthcare staff the opportunity to learn several non-technical skills such as clinical decision-making, situation awareness, team working, communication skills. For this reason, simulation-based training is considered an optimal solution for preparing and assessing human responses to real-life problems: it provides the opportunity to experience realistic training in terms of both clinical practice and stress management.

The stress role in the simulation context is crucially important together with the cognitive load. Indeed, during simulations, the participant is simultaneously exposed to the realism of the event, and to the demand to execute the correct intervention. Concerning the stress, while its feeling should be similar to that one felt in real practice, in the meantime, it should be maintained within certain limits, avoiding acute stress, which can compromise the performance, and post-traumatic stress disorders.
Regarding the mental effort, it should be balanced to avoid, on one side, low levels of attention, and, on the other side, cognitive overload which may compromise the learning path and the acquisition of new skills. In this context, the importance of a transdisciplinary approach to analyze the impact of medical simulations on trainees' stress, cognitive load, perceptions, workload, and performance is undeniable. Indeed, only with a comprehensive and transdisciplinary methodology, it would be possible to study the effectiveness of the simulation from the students' perspective.

Several definitions of transdisciplinarity exist, but all agree on the necessity to go beyond the scientific disciplines and interact with non-scientific expertise [2]. Ergonomics, which is indispensable in this context, is a classical transdisciplinary discipline because it blends technical and social aspects. Indeed, it concerns the design of systems, machines, or interfaces, based on the users' needs and requirements [3].

Several studies in the scientific literature analyzed the user experience, physical, and cognitive ergonomics with transdisciplinary approaches in the simulation context, but they are mainly applied to the aviation [4], and automotive [5] domains. Therefore, it emerges the need to apply such kind of transdisciplinary analysis also to the medical simulation training [6]. It would be extremely useful for the optimization and re-design of simulators and simulations, from a user-centered design perspective, and thus for the improvement of learners' performance, avoiding cognitive overloads and excessive stress. Only effective medical training can lead to improved clinical performance, patient safety, and, consequently, quality of care.

The paper focuses on defining a transdisciplinary framework for the analysis of simulation effectiveness in healthcare applications. It aims at measuring the quality of training in terms of performance as well as user experience (UX) considering the users' cognitive and emotional states of the trainees and defining specific guidelines to optimize the simulation-based training process.

1. Research Background

Nowadays, a standard definition and classification of simulations still do not exist. It can be classified into human (i.e. a role-play among students) or non-human simulation (e.g. using a manikin or computer), or according to the used educational tool [7]: standardized patients (with actors), screen-based computer (with interactive software), skill trainers (with partial manikins), high-fidelity manikins (with anatomical full-sized, computer-controlled simulators). It may be also classified according to fidelity [8], which is a multidimensional construct, related to the perception of how real or lifelike a simulator/simulation is for the user.

Different authors referred to various levels of fidelity. All agree in distinguishing between “engineering/physical fidelity” and “psychological fidelity” referring to the realistic look of the simulators in the first case, and to the demand of specific behaviors to complete the task in the second case [9]. Curtis et al. [10] considered also the “functional fidelity” involving actions, responses, and instrument accuracy. Vincent-Lambert et al. [11] added three other dimensions: social, the culture of the group, and degree of openness or trust.

Psychological fidelity is considered very critical and more important for learning and transfer than the other dimensions [9]. Accurately reproducing stressful conditions is one of the most fundamental and challenging aspects of simulation design. During the design of simulations and simulators, great attention must be placed on the realism and feeling of immersion; for this reason, a close collaboration between physicians and engineers who design the simulator is always needed. Also, the inclusion of pedagogical and psychological expertise into the design and development of educational devices is essential [12].

To have successful simulation-based training, above the simulated scenario, also briefing and debriefing must be carefully considered during the design. The briefing takes place before the simulation; in this period the teacher explains the objectives of the simulation and how it will be conducted. The debriefing occurs after the simulation and is an active retrospective assessment in which students appraise their technical and cognitive performance, highlighting the importance of human factors [13]. For its nature, it is considered the most important phase of the simulation. Debriefing is developed as a therapeutic practice for people experiencing traumatic and stressful events. Discussing shared experiences in terms of practical performance, potential wrong approaches, and related feelings is a strategy to minimize the chance of post-traumatic stress disorders [14].

Therefore, simulation-based training is characterized by a pedagogical framework that allows the students to experiment with the same workflow and workload that they would experience in real clinical cases [8]. The design of medical simulations passes through a careful analysis of learning objectives, technology to be used, instructor role, performance assessment, and so on.

However, a series of issues need further research: among these, the development and use of transdisciplinary assessment tools for the evaluation of technical and behavioral competencies [15, 16, 17] arise.

Human Factors (HF) and Ergonomics have been introduced in engineering to add the physical, psychological, social, and cultural needs of human beings, to the mechanical, electrical, manufacturing requirements considered during the product/system design [18]. Moreover, HF is fundamental also in the evaluation of the human-machine interaction and the evaluation of the UX, helping in the improvement of human performance, the optimization of physical and mental workload, comfort, and perceived effort, and the reduction of the risks associated with user errors.
However, even if education in healthcare focuses on high-stakes environments and the acquisition of complex manual and cognitive skills, human factors are not well integrated and adopted into medical training [19]. Indeed, the number of successful implementation and development of medical simulations is relatively small compared with the manufacturing industry.

In this context, the adoption of a human-centered, transdisciplinary approach is compulsory for the creation of successful training paths and simulators, and their optimization and re-design.

2. Research Approach

2.1. Transdisciplinary Framework

To assess medical simulation effectiveness, several transdisciplinary aspects have to be analyzed before, during, and after the simulation itself (Figure 1). Based on this accurate and extensive assessment, it is then possible to outline the recommendations to re-design and optimize the simulation.

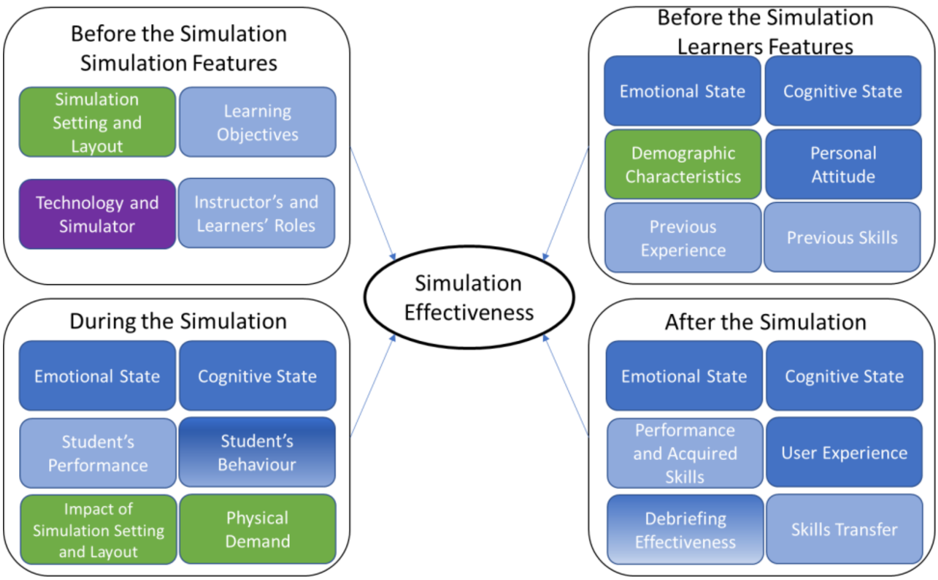

Figure 1: Transdisciplinary Framework for the assessment of medical simulation effectiveness. Included expertise: technical / engineering (purple), ergonomics (green), pedagogical (light blue), psychological (blue), or a blend of both (blue/light blue)

Before the accomplishment of the simulation, the engineering, pedagogical, and social aspects must be considered. The first ones relate for example to the technical aspects of the used simulator, the second ones to the predefined learning goals, the roles of learners and instructor during the simulation, and the third ones to the demographic, and personal characteristics of learners (such as previous experiences, skills, attitude, …).

The cognitive conditions and emotional states (such as stress, anxiety, frustration, effort,..) of learners must be considered before, during, and after the simulation, to understand its effect on such conditions. According to ISO 10075-3, 2004 [20], the mental workload can be measured through performance assessment methods, self-assessment methods, and physiological measurements methods. Among the three different assessment techniques, the self-assessment method is the most applied in the healthcare simulation field [21]. However, subjective user ratings can be misleading metrics of simulation effectiveness [10]. Examples of the application of physiological measurements exist in the literature [22], but they are not widespread. For this reason, it is evident the need of including a multi-dimensional assessment.

Also, for the detection of psychological stress four main criteria are used [20]: psychological, physiological, behavioral, and biochemical. The most common analyses typically include the subjective assessment based on self-report and physiological assessment based on heart rate, and skin conductivity monitoring.

Moreover, even the ergonomics of the simulation room and instruments' layout must be considered both in relation to the cognitive and physical demands for learners.

After the end of the simulation, it is important to acquire information about the user experience, the acquired skills and performance, and the effectiveness of the debriefing phase on the learners' stress and cognitive conditions.

2.2. Data Analysis

Several assessment measures can be exploited to analyze the different research areas included in the transdisciplinary framework:

- Technical area (which includes the technical aspects of the used simulator and technology): in a user-centered perspective, the usability and user experience related to the use of the simulator and/or advanced technologies (e.g. extended reality devices) should be assessed through ad-hoc questionnaires and usability tests;
- Ergonomics area (which comprehends simulation setting and layout, physical demand, and demographic characteristics): the physical ergonomics should be analyzed by using wearable sensors (e.g. for the acquisitions of the EMG signal, motions, etc.) or virtually through different digital human models. Also, the learners' demographic characteristics (i.e. age, weight, height, etc.) should be collected and studied through statistical regression models to understand their effect on the simulation execution.
- Pedagogical area (that includes learning objectives, instructor's and learners' roles, previous experience and skills, performance, acquired skills, and skill transfer): the performance should be evaluated during the simulation by using specific checklists and recording times, errors, attempts, etc. The acquisition of skills should be assessed both with a comparison between the pre- and post-simulation and then in the clinical field with real medical cases.

- Psychological area (which comprehends emotional and cognitive states and personal attitude): feelings such as frustration, anxiety, effort, etc. could be assessed through self-assessment, comparing the learners' perception before and after the simulation, and then through statistical analysis. The cognitive load and the stress could be monitored in real-time using smart wearable devices for the acquisition of physiological parameters. In this way, it is possible to discern between perceived and physiological cognitive/emotional states and understand the variables that most affect the simulation effectiveness.

Therefore, thanks to the application of this multi-dimensional analysis and the use of different assessment methods, it is possible to study:

- Perceived stress, anxiety, frustration, mental effort through the self-assessment questionnaires: variation between pre- and post- simulation.
- Objective stress and cognitive load based on the continuous physiological monitoring (e.g. heart rate, heart rate variability, breathing rate, electrodermal activity, …) before, during, and after the simulation (i.e. comparison between stressful and restful tasks or simulation phases).
- Differences in learners' opinions about the usefulness of simulation-based training.
- Usability of the simulator and/or other technologies and user experience of the learners (in relation to the simulation layout too).
- Performance and skills evaluation for the single tasks or the overall simulation.
- Standard central trend measures for the description of the demographic characteristics, the performance, the biometric indices, as well as for the analysis of the responses to the self-assessment questionnaires.
- Statistical single and multiple linear regression analysis to discover the variables that affect students' performance, stress, cognitive load, during the simulation-based training.

Based on these relationships among variables, it is possible to define specific guidelines for the optimization and re-design of the simulations, to improve the simulation effectiveness and balance the levels of stress and cognitive load.

3. Use Case

3.1. Analysis

This study considered the low-fidelity simulation for the training of rachicentesis, which is a specific lumbar puncture for the collection of the liquor, for diagnostic purposes. The goal of the simulation is to learn how to perform the puncture and become able to let the liquor spilling out. Indeed, if the needle is non-inserted in the right place and with the right depth, the liquor would not come out.

The simulation duration varies from a few minutes to half an hour, according to the learner's skills and ability. All the variables related to the simulation setting, used technology, simulation tasks, learners' characteristics have been recorded. The room layout included a desk with the skill trainer for the lumbar puncture and, on its right, all the needed instrumentation for the procedure.

In this case study, the standard simulation workflow (i.e. briefing, simulation, and debriefing) was not followed. Indeed the simulation was preceded by the theory explanation, the teacher briefing, and demonstration, but it was not followed by the debriefing. This work focused on the assessment of learners' performance, cognitive and emotional conditions, following the workflow in Figure 2.

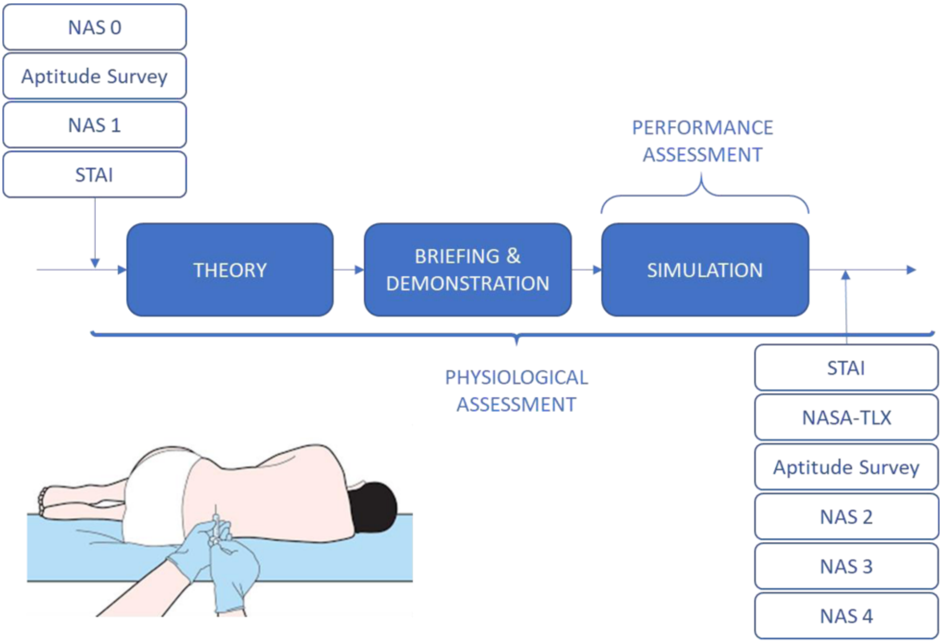

Figure 2: Simulation assessment workflow

The physiological parameters have been collected from the arrival in the classroom until the end of the simulation, through non-invasive wearable devices, to assess the objective levels of stress and cognitive load experienced by the learners, before, during, and after the training.

Several questionnaires were administered before and after the simulation to assess the subjective stress, cognitive load, anxiety, frustration, effort, and workload perceived by the learners, and to distinguish their variations due to the training.

The Numerical Analogue Scale (NAS) was administered at the arrival in the classroom, ten minutes later, and ten, twenty, and thirty minutes after the end of the simulation, to study the trend of the perceived stress.

The double-module State-Trait Anxiety Inventory (STAI) was administered to evaluate the anxious trait of learners in their lives (only before the simulation) and the perceived level of anxiety in those precise moments (before and after the training).

The NASA Task Load Index (NASA-TLX) was administered after the simulation to record the learners' opinions about the perceived mental, physical, temporal demands, effort, performance, and frustration.

The aptitude survey was administered before and after the training to understand the learners' aptitude and familiarity with simulations and advanced technologies.

Moreover, the performance was analyzed for each task of the entire procedure, in terms of committed errors, the number of attempts, consultations with the instructor, times, task correctly/incorrectly performed, or not performed. Also, a skill questionnaire was administered before and after the simulation, to verify the learning.

3.2. Results

The self-assessment questionnaires and the physiological signals were singularly analyzed, as well as the performance. All these variables were then assessed through several models of multiple linear regression analysis. The statistical analysis highlighted that learners' performance is not influenced by perceived and physiological stress. Cognitive load and stress levels are well balanced during the simulation and they turn back to basal levels after the end of the training (suggesting that the debriefing is not indispensable in low-stressful simulations).

However, some issues emerged. Table 1 proposes some basic guidelines to solve the principal simulation's issues (related to learners' performance, cognitive and emotional conditions) highlighted by the multiple linear regression analysis.

Table 1. Possible solutions to simulation issues.

	Solutions to issues
Performance	
(Too) high cognitive load causes: • Increment of simulation time • Increment of errors	Feedback about the tasks' sequence and execution could be provided during the simulation
Success is not reached if the instructor practically assists the learner	The instructor should only assist the learner with advice, without interrupting his/her simulation execution
Performance is worse in the afternoon	Lesson contents could be divided into two sessions: theory in the morning and simulation in the afternoon (real cases could happen every time of the day)
Cognitive and Emotional States	
Anxiety before the simulation compromises performance and learning	The instructor should calm down the learners during the briefing
Stress is higher when more errors are committed	If too many errors are committed, the instructor should give theoretical help
For a long simulation duration: • Stress increases • Frustration increases • Effort increases	The simulation duration could be reduced (and consequently even stress, effort, and frustration) by providing feedback that could help the learners in the correct execution of the tasks
The effort is higher for tall subjects	Physical ergonomics should be studied and adjusted

Therefore, from this transdisciplinary effectiveness analysis, the necessity of optimizing the simulation from pedagogical, psychological, ergonomic perspectives arises.

4. Conclusions

This work underlined the relevance of the application of transdisciplinary approaches for the design and optimization of simulation-based medical training. Indeed, in the simulation context, all the pedagogical, technical, ergonomic, and psychological dimensions assume a great weight. As it is important to achieve high performance through a valuable pedagogical path, it is also fundamental to assure a good stress balance: simulation should bring learners to a stress level similar to that one in the real practice, and, at the same time, it should not provoke excessive stress which may damages performance, consequently resulting in increased risk for the patient.

The same reasoning should be done for the cognitive load. Indeed, to guarantee better performance and the best skills memorization, the mental effort should not be too low, and, at the same time, cognitive overload must be avoided. Also, the physical domain must be considered: the learners should feel physically comfortable during the simulation.

Moreover, beyond the aspects treated in this work, even the technical features of the simulators and the level of fidelity should be taken into account, both from the psychological and engineering points of view.

References

[1] S. L. Dawson and J. A. Kaufman, The imperative for medical simulation, In: *Proceedings of the IEEE*, Vol. 86, pp. 479-483, 1998.

[2] M. Goudswaard, B. Hicks, and L. Newnes, An Appraisal and Classification of the Transdisciplinarity of Existing Design Tools, *Advances in Transdisciplinary Engineering,* Vol 12, pp. 50 – 59, 2020.

[3] F. Grandi, M. Peruzzini, C. E. Campanella, M. Pellicciari, Application of Innovative Tools to Design Ergonomic Control Dashboards, *Advances in Transdisciplinary Engineering,* Vol. 12, pp. 193-200, 2020.

[4] A.R. Hidalgo-Muñoz, D. Mouratille, N. Matton, M. Causse, Y. Rouillard, R. El-Yagoubi. Cardiovascular correlates of emotional state, cognitive workload and time-on-task effect during a realistic flight simulation. *International Journal of Psychophysiology,* Vol. 128, pp.62-69, 2018.

[5] F. Grandi, M. Peruzzini, R. Raffaeli, And M. Pellicciari, Transdisciplinary Assessment Matrix to Design Human-Machine Interaction, *Advances in Transdisciplinary Engineering*, Vol. 12, pp. 183-192. 2020.

[6] A. Brunzini, A. Papetti, E. Brandoni Serrani, M. Scafà, M. Germani, How to Improve Medical Simulation Training: A New Methodology Based on Ergonomic Evaluation, In: *International Conference on Applied Human Factors and Ergonomics (AHFE 2019), AISC 96,* pp. 145–155, 2020.

[7] S. Sahu and I. Lata, Simulation in resuscitation teaching and training: an evidence-based practice review, *Journal of Emergencies, Trauma and Shock*, Vol. 3, pp. 378–384, 2010.

[8] S.S. Elshama, How to apply Simulation-Based Learning in Medical Education? *IberoAmerican Journal of Medicine*, Vol. 02, pp. 79-86, 2020.

[9] G. Norman, K. Dore and L. Grierson, The minimal relationship between simulation fidelity and transfer of learning, *Medical Education,* Vol. 46, pp. 636–647, 2012.

[10] M.T. Curtis, D. Granados, and M. Feldman, Judicious Use of Simulation Technology in Continuing Medical Education, *Journal of Continuing Education in the Health Professions,* Vol. 32, pp. 255-260, 2012.

[11] C. Vincent-Lambert and F. Bogossian F, A guide for the assessment of clinical competence using simulation, *U21 Health Sciences Group*, 2017.

[12] A. Holzinger, M.D. Kickmeier-Rust, S. Wassertheurer, M. Hessinger, Learning performance with interactive simulations in medical education: Lessons learned from results of learning complex physiological models with the HAEMOdynamics SIMulator, *Computers & Education*, Vol. 52, pp. 292–301, 2009.

[13] S.J. Mercer, Using full immersive simulation to prepare trauma teams to work in a major trauma centre, *Trauma*, Vol. 19, pp. 277–285, 2017.

[14] S. D. AL Sabei and K. Lasater, Simulation debriefing for clinical judgment development: A concept analysis, *Nurse Education Today*, Vol. 45, pp. 42-47, 2016.

[15] W.F. Bond, R.L. Lammers, L.L. Spillane, R. Smith-Coggins, R. Fernandez, M.A. Reznek, J.A. Vozenilek, J.A. Gordon, Society for Academic Emergency Medicine Simulation Task Force, The Use of Simulation in Emergency Medicine: A Research Agenda, *Academic Emergency Medicine*, Vol. 14, pp. 353-364, 2007.

[16] T. Sawyer and M.M. Gray, Procedural training and assessment of competency utilizing simulation, *Seminars in Perinatology*, Vol. 40, pp. 438-446, 2016.

[17] S.L. Hanshaw and S.S. Dic, High fidelity simulation evaluation studies in nursing education: A review of the literature, *Nurse Education in Practice*, Vol. 46, 2020.

[18] ISO 9241-210, Ergonomics of human system interaction - Part 210: Human-centered design for interactive systems, 2010.

[19] F.J. Seagull, Human Factors Tools For Improving Simulation Activities In Continuing Medical Education, *Journal Of Continuing Education In The Health Professions*, Vol. 32, pp. 261–268, 2012.

[20] ISO 10075-3, Ergonomic principles related to mental workload // Part 3: Principles and requirements concerning methods for measuring and assessing mental workload, 2004.

[21] M. Scafà, E. Brandoni Serrani, A. Papetti, A. Brunzini, M. Germani, Assessment of Students' Cognitive Conditions in Medical Simulation Training: A Review Study, In: *International Conference on Applied Human Factors and Ergonomics (AHFE 2019), Advances in Intelligent Systems and Computing,* Vol. 958, pp. 224–233, 2020.

[22] A. Brunzini, A. Papetti, L. Formenti, A. Luciani, D. Messi, E. Adrario, P. Barbadoro, Cognitive Load and Stress Assessment of Medical High-Fidelity Simulations for Emergency Management, In: *International Conference on Applied Human Factors and Ergonomics (AHFE 2020),* pp. 343–350, 2021.

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Fostering Design Thinking in Transdisciplinary Engineering Education

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Abstract. Disruptive technologies such as 3D printing, artificial intelligence (AI), and robotics have changed how people think, learn, and work fundamentally. Engineering education must adapt to this digital transformation. There has been increasing interest in integrating design in the engineering curriculum around the world. While traditional problem solving is a linear and structured approach, design thinking is set by a human-centered innovation process which leads to better products and services. This concept is well aligned with the educational vision of transdisciplinary engineering. However, it is challenging to teach the mindset of design thinking for people with various domain knowledge. In this paper, the differences in how industrial designers and design engineers tackle a design project are explained. We intend to share a few successful examples regarding how design methodology captures customer requirements and explores creative solutions in the product development lifecycle within the current engineering curriculum. Also, the user experience research in response to the trend of cyberphysical integration is discussed. Finally, we conclude with the need for a holistic curriculum design in digital manufacturing as a case study to illustrate the role of design thinking for future transdisciplinary engineering education.

Keywords. Design thinking, engineering education, transdisciplinary, design methodology, 3D printing, digital manufacturing

Introduction

Disruptive technologies such as 3D printing, artificial intelligence (AI), and robotics have changed the way people think, learn, and work fundamentally. The education curriculum needs to be developed and reformed progressively in order to train and upskill the current workforce to embrace this digital transformation. There are many educational philosophies such as undeclared major and STEM (science, technology, engineering, mathematics) for different levels of school and higher education [1]. One main consensus is the emphasis on cross-discipline competence. It is also known as a T-shaped skill. The vertical bar of ‘T’ is your domain knowledge in a single field. The horizontal bar of ‘T’ is your ability to collaborate across disciplines. Thus, a good curriculum structure should centralize the importance of a broad base of general skills and knowledge that support one’s domain knowledge. This concept is well aligned with the vision of transdisciplinary engineering [2].

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At the same time, the use of design thinking strategies has been gaining a lot of traction in academia and various industries. The term ‘design’ is generic and abstract, leading to a wide audience. Fashion designers and design engineers are both considered as design professionals while the former works towards beautiful visual artworks, and the latter is more analytical. Inevitably, there seem to be inconsistent definitions of ‘design thinking’ in different disciplines. Nowadays this buzz term is coming mostly from business innovation seminars while it shares a common ground with the heuristics principles in engineering ideation [3]. To our understanding, in general, design thinking helps to make sense of the complex connections between diverse perspectives. For that reason, design thinking encourages collaborations and cross-disciplinary teamwork. Therefore, it has become one of the required skills that foster engineering innovations. The question is how to integrate the ideology of design thinking into curriculum development so the students can be exposed to this designer-ly strategy.

The remainder of this paper adapted the format of design thinking proposed by Brenner, et al. [4]. The first section elaborates on the difference in curriculum approach between engineering schools and design schools. It states the ‘Why’ of the paper’s agenda and considers design thinking as a mindset within transdisciplinary engineering education. The second section focuses on ‘How’ incorporating design thinking as a method has benefited engineering and manufacturing innovations by presenting examples within a current engineering curriculum. Lastly, we posit that design thinking can continue to augment engineering education in the cyberphysical age.

1. WHY: Perspectives from engineering schools and design schools

Historically, engineers and designers used to be segregated in different schools and trained with distinct abilities. Mechanical Engineering (ME) is an academic discipline with a long history. Over time, new academic disciplines appeared to cater to the trend of real-world problems. During the Bauhaus movement, Industrial Design (ID) emerged as a new discipline in response to the industrialization of consumer products and mass-production techniques. These disciplines intertwined gradually which has been reflected in the title of school programs (e.g., mechanical engineering design stream, industrial design engineering). This phenomenon seems to imply a good indication that industrial designers and mechanical engineers would make a great team to solve complex problems. However, interdisciplinary collaboration only succeeds based on a shared understanding of the domain knowledge. This is challenging not only for the practitioner but also the educator. To bring the gap closer, it is beneficial to glimpse the core curriculum developed by the respective schools.

Here, we use an example to illustrate the main differences between engineering education and design education. The two schools explore the design space differently. Imagine a task is assigned to design a 3D printer. The ME school emphasizes achieving functionality and feasible technical solutions. The design space would inform the technical restrictions for heating and extruding or the strength test of the filament. On the other hand, the ID school emphasizes capturing human-centered requirements. The first few questions that come to their mind could be: Is the printer designed for a kid or a professional? Is it ergonomically friendly for the user to replace the filament? In other words, ME students are taught to manage risk, and ID students are trained to manage human uncertainty. The level of uncertainty can extend to personal preferences and experiences. Hence, compared to ME students, ID students tend to pay more attention to the product appearance.

The traditional linear and structured way of thinking is excellent and efficient when solving simple problems. A simple usage problem of a 3D printer can be: why is my printer not working? This problem can be resolved step by step in the troubleshooting process. The users pinpoint the known problem, list the viable options, evaluate them then select the best outcome. Nevertheless, this problem-solving approach is not ideal for ill-defined problems such as 'why users choose printer A over printer B.' People from a strong engineering background may be unfamiliar working around problems with less technical constraints, resulting in difficulties thinking out of the box. This is where design thinking comes into play. Design thinking is an iterative process to relook into our problems from as many different perspectives as possible. During this abductive thinking process, the original problems are reframed to yield more creative solutions.

The integration of experts' domain knowledge enhanced by design thinking enables both designers and engineers to solve problems, considering perspectives from both design and engineering disciplines (see Figure 1). For example, an industrial design engineering curriculum can evolve from a design curriculum augmented by essential engineering knowledge. Similarly, a mechanical engineering design curriculum possess the foundations of a robust engineering curriculum, supplemented by modules and projects that require students to implement design thinking. Introducing design thinking into the traditional engineering curriculum can enhance the core domain knowledge of engineers. Hence, improving the core curriculum developed by the respective schools allows both practitioners and educators to reap the benefits of a true transdisciplinary design engineering education.

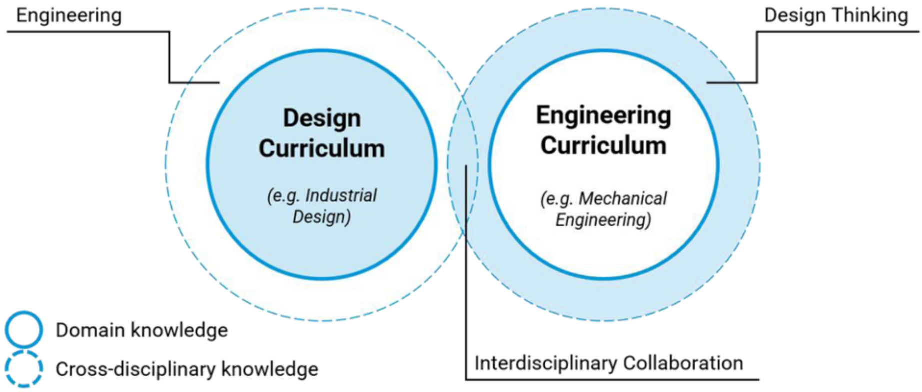

Figure 1. Transdisciplinary design and engineering education.

The rise of 3D printing and digital manufacturing necessitates design thinking within a holistic engineering curriculum. The most wildly used 3D printing process, known as fused deposition modeling (FDM) melts and extrudes the thermoplastic filament through a nozzle layer by layer. This process is fairly slow and often needs to deal with overhangs. In this sense, the next generation of printers may be inspired to minimize the additional support structures so as to reduce the printing time. If one applies linear thinking to solve this problem, he/she might jump to the simple conclusion that we need a more advanced process such as powder bed techniques. Alternatively, following the design thinking approach, the design space can be expanded by having additional degrees of freedom in motion to fabricate the 3D model. In a study by Dai, et al. [5], they used a multi-directional deposition method to optimize the toolpath in two steps: first decomposing the volume into sequences of curved surface layers, and then decomposing each surface into the curved toolpath. Their results achieve better precision and surface quality of spatial toolpath generation over the conventional slicer. This appears to be a fine example of design thinking implementation on an engineering problem.

Accordingly, it is not surprising that design thinking has been applied to support the innovations in engineering education [6]. For example, Coleman, et al. [7] developed an instrument based on the similarities between engineers and designers to assess the students' perceived design thinking ability. In an environmental engineering course, Clark, et al. [8] found a positive association between design thinking and the students' perceived creativity and sustainable career practices. Palacin-Silva, et al. [9] reported the lessons learned from the perspectives of teachers and students on running a software engineering capstone project with design thinking. Tomita, et al. [10] proposed a structured framework to guide and trace the exploratory nature of design thinking for complex societal problems in the context of systems engineering. In this paper, we intend to apply design thinking to the curriculum design of an emerging transdisciplinary engineering program for digital manufacturing.

2. HOW: Design methodology within the current engineering curricula

Design methodology is defined as a set of design methods/tools that augment design thinking. The engineering schools and design schools both claim to utilize design methodology in their practices. The roots are slightly different. In a full picture of the product development lifecycle that covers from the demand side to the supply side, stakeholders get involved in various stages about design, development, part production, assembly, and maintenance support. There has been widely recognized design methodology such as function analysis, quality function deployment and Boothroyd-Dewhurst's design for manufacturing and assembly. They consider single or multiple stages of the product development lifecycle. Some focus on reducing part counts and assembly operations to minimize the production cost, and others attempt to identify implicit requirements and needs for greater customer satisfaction. Regardless of qualitative or quantitative approaches, design methodology facilitates the desirable design outcome for efficiency, sustainability, creativity etc. Next, we would like to highlight a few examples of how design thinking (as a method) has benefited engineering innovations within the current engineering curriculum.

2.1. Sketches, drawings, and design thinking workshop

Sketching is one of the most intuitive design methodologies. It can convey conceptual ideas, visualize the product functionality and human interaction. Unlike engineering drawings, which is more detailed on actual geometry and proportional dimension, sketching is handy for exploring the form. Therefore, this method is still relevant and crucial in today's practice of individual designers. On the other hand, design thinking workshops built upon a collaborative mindset, similar to the concept of co-design and participatory design. A design thinking workshop is held to gather insights by putting a diverse variety of people together to address the given topic. Everyone will brainstorm to reframe the problem statement collectively and broaden the innovative ideas. The classical design thinking exercises sometimes are criticized for ending with just a room full of Post-Its. It is important to note that the inquiry nature of design thinking brings in the creation of systems.

2.2. Knowledge-based design systems

When scientists begin to discuss the possibility of AI for design, a research stream on knowledge-based design systems rises. It is a computer-aided program that supports decision-making for complex problems. Specifically, the design procedures are captured as a set of algorithms and design rules. Take a golf club design for example. Once we computerize the correlations between design performance requirement (wind resistance) and product properties (curve), numerous 3D model variations can be generated automatically [11]. Such systems realize a seamless integrated approach to reduce time-to-market from digital design to manufacturing.

In addition to the improvement in engineering performance (e.g., weight, strength), we can leverage generative design algorithms to explore complex geometric forms. For instance, it brings the potential of biomimicry to produce organic shapes inspired by nature. The fabrication of these cellular and lattice structures becomes possible due to the additive manufacturing (AM) process. After hundreds of thousands of conceptual designs are generated, some of them may have comparable functional performance. In this case, what are the final selection criteria to go into the production phase? Can AI make the products appeal more to the customers?

Considering that emotional design add value to products and services, we can build a knowledge-based design system for users' psychological needs. Kansei engineering is a philosophy that aims at translating subjective feelings into product specifications [12]. Kansei is a Japanese term meaning human emotions, feelings and impressions towards a product or service. Kansei can be quantified in either the physiological level (eye movement, facial expression) or the semantic level (semantic differential scale). In this regard, researchers have developed a Kansei engineering system (KES) from different perspectives.

Li, et al. [13] applied multi-objective optimization to satisfy user's affective responses for vase forms. Although beauty is in the eyes of the beholder, there are some ground rules for visual perceptions such as most people prefer symmetry. In light of this, Lugo, et al. [14] exploited the gestalt principles to generate the design of wheel rims. Lastly, it worth noting that the visually appealing style is just one application of users' feelings. Knowledge-based KES can push further to enable user experience study such as building trust in autonomous vehicle safety [15].

3. Design for transdisciplinary engineering education

With the advancement in information technology, the impact of design thinking is visible in many digital engineering tools. Modern devices connect to the Internet, generate, and collect usage activity data continuously. Engineers can now employ AI to understand users, machines, systems, and organizations in a bid to assist real-time decision-making. On the whole, the trend of design informatics is an embodiment of design thinking and data science. Relevant machine learning techniques have been proposed to manage such heterogeneous data, make them informative, then acquire contextual knowledge.

3.1. Trend in the cyberphysical age

Design thinking has driven the evolution of design methodology research. The early mobile phones have various forms, colorful buttons, and even flip-style designs [16]. Today, those mechanical features have been replaced by the touch screen [17]. The increasing screen size indicates that users spend a great amount of time on the digital interface. The digitalization of design methodology, therefore, thrives under the umbrella term of user experience (UX). Moreover, the focus of design development shifts from product to service. While everything is going virtual, it is of importance to consider cyberphysical interactions in the real world. One seminal example of human-machine interaction is the hand gestures that adjust the size of the digital photo on the touch screen. Think about how we used to interact with the TV. At first, you must press the button on a physical TV box before the remote controls were invented. Now, one device can communicate to all home appliances at once and is even accessible using voice control. In short, disruptive technologies are clearly changing our everyday experience.

As AI continues to advance, machines are getting smarter. They can make recommendations after learning your behavior patterns such as your most frequent routes when travelling via taxi and the items you are likely to purchase based on your activities. These models are trained and perform best to predict events based on the data you feed in. However, we argue that AI for design may not be able to think out of the ‘cyber box’ nor stress enough the importance of physical domains to create an impactful user experience. In the cyberphysical age, design thinking does not necessarily demand sophisticated technology. For instance, the Wii was popular at a time because the designers relooked into simple motion sensors then proposed an intuitive way to interact with digital games. It is evident that an emphasis on UX is warranted in this era of cyberphysical interactions.

3.2. Holistic curriculum design for digital manufacturing

Digital manufacturing is an adequate example of this cyberphysical integration [18]. However, the current educational coursework materials in the mainstream engineering curricula mainly focus on scientific principles and rules in one domain. They are not ready for providing a holistic perspective to the students via a system-of-system approach for an interdisciplinary engineering concept. To the best of our knowledge, this paper is the first to explore the application of design thinking in an engineering curriculum for digital manufacturing. This curriculum should prepare the future workforce for the latest challenges of the manufacturing landscape, and train them to innovatively devise better UX in this cyberphysical age. With that goal, we propose a comprehensive book series that breakdown digital manufacturing into three aspects: design, device, and digital factory.

The first volume will look at the design aspect from digital design to part manufacturing in the context of 3D printing. The design methodologies will be adopted to exploit the full potentials of additive manufacturing. The second volume focuses on the devices and agents at the factory level such as industrial Internet of things, digital twins, and cyberphysical security. These applications inform a complex multi-input multi-output system for predictive modeling. The second book also presents new business models working towards a sustainable net zero operations and economy. The digital architecture enables greater resilience for supply chain management such as the unexpected demand shifts during the COVID-19 pandemic.

Indeed, there are already many existing textbooks on the market for the above-mentioned individual topics. The main contribution of our curriculum is to put leading experts from various fields together to tell one cohesive story. It will incorporate the major aspects of 3D printing with immense depth in science and engineering fundamentals, and breadth in a range of technologies. This enables the readers to have a bigger picture knowing how different disciplines work together to fulfill the vision of advancing towards digital manufacturing. In this sense, design thinking is an overall method to describe our approach in designing an engineering curriculum for digital manufacturing. We believe a holistic curriculum design is essential for the future of transdisciplinary engineering education.

4. Conclusion

This paper aims to discuss the application of design thinking in transdisciplinary engineering education. Rather than debating on its vague definition, we used explicit examples to depict the role of design thinking in current engineering schools and design schools. Evidence from knowledge-based design systems has demonstrated the advantages and limitations of AI design methodology in engineering innovations. Therefore, we expect that design thinking skills will remain pivotal when it comes to creativity and curriculum development. Moving towards the cyberphysical age, the workforce of the future must obtain a broad base of general skills and knowledge that enhance collaborations across the disciplines. Consequently, a creative curriculum that lay the ground for digital manufacturing in the engineering school is warranted.

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References

[1] Y. Li, A. H. Schoenfeld, A. C. Graesser, L. C. Benson, L. D. English, and R. A. Duschl, Design and Design Thinking in STEM Education, *Journal for STEM Education Research,* 2019, Vol. 2, pp. 93-104,.

[2] N. Wognum, J. Mo and J. Stjepandić, Transdisciplinary Engineering Systems, R. S. Kenett, R. S. Swarz, and A. Zonnenshain (Eds.) *Systems engineering in the fourth industrial revolution: Big data, novel technologies, and modern systems engineering*, John Wiley & Sons, 2019, pp 483-510.

[3] C. M. Gray, C. M. Seifert, S. Yilmaz, S. R. Daly and R. Gonzalez, What is the content of "design thinking"? Design heuristics as conceptual repertoire, *International Journal of Engineering Education,* 2016, Vol. 32, no. 3B, pp. 1349-1355.

[4] W. Brenner, F. Uebernickel and T. Abrell, Design thinking as mindset, process, and toolbox, in W. Brenner, F. Uebernickel, *Design thinking for innovation*: *Research and Practice*, Springer Nature Switzerland , 2016, pp. 3-21.

[5] C. Dai, C. C. Wang, C. Wu, S. Lefebvre, G. Fang, and Y.-J. Liu, Support-free volume printing by multi-axis motion, *ACM Transactions on Graphics (TOG)*, 2018, Vol. 37, No. 4, pp. 1-14.

[6] C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey and L. J. Leifer, Engineering design thinking, teaching, and learning, *Journal of engineering education*, 2005, Vol. 94, No. 1, pp. 103-120.

[7] E. Coleman, T. Shealy, J. Grohs, and A. Godwin, Design thinking among first-year and senior engineering students: A cross-sectional, national study measuring perceived ability, *Journal of Engineering Education*, 2020, Vol. 109, No. 1, pp. 72-87.

[8] R. M. Clark, L. M. Stabryla, and L. M. Gilbertson, Sustainability coursework: student perspectives and reflections on design thinking, *International Journal of Sustainability in Higher Education*, 2020, Vol. 21, No. 3, pp. 593-611.

[9] M. Palacin-Silva, J. Khakurel, A. Happonen, T. Hynninen, and J. Porras, Infusing design thinking into a software engineering capstone course, *2017 IEEE 30th Conference on Software Engineering Education and Training (CSEE&T)*, 2017: IEEE, pp. 212-221.

[10] Y. Tomita, K. Watanabe, S. Shirasaka, and T. Maeno, Applying design thinking in systems engineering process as an extended version of DIKW model, *INCOSE International Symposium*, 2017, Vol. 27, No. 1, pp. 858-870.

[11] D. Chang and C.-H. Chen, Digital design and manufacturing of wood head golf club in a cyber physical environment, *Industrial Management & Data Systems*, 2017, Vol. 117, No. 4, pp. 648-671.

[12] M. Nagamachi and A. M. Lokman, *Innovations of Kansei engineering*. CRC Press, Boca Raton, 2016.

[13] Y. Li, M.-D. Shieh, and C.-C. Yang, A posterior preference articulation approach to Kansei engineering system for product form design, *Research in Engineering Design*, 2019, Vol. 30, No. 1, pp. 3-19.

[14] J. E. Lugo, J. P. Schmiedeler, S. M. Batill, and L. Carlson, Relationship between product aesthetic subject preference and quantified Gestalt principles in automobile wheel rims, *Journal of Mechanical Design*, 2016, Vol. 138, No. 5, 051101.

[15] K. Kaur and G. Rampersad, Trust in driverless cars: Investigating key factors influencing the adoption of driverless cars, *Journal of Engineering and Technology Management,* 2018, Vol. 48, pp. 87-96.

[16] J. R. Jiao, Y. Zhang, and M. Helander, A Kansei mining system for affective design, *Expert Systems with Applications*, 2006, Vol. 30, No. 4, pp. 658-673.

[17] K. Y. Chan, C. Kwong, T. Dillon, and K. Fung, An intelligent fuzzy regression approach for affective product design that captures nonlinearity and fuzziness, *Journal of Engineering Design*, 2011, Vol. 22, No. 8, pp. 523-542.

[18] C. D. Patel, Cyberphysical Integration, *The Bridge*, 2020, Vol. 50, No. 4, pp. 21-23.

Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Design and Production Automation for Mass Customisation – An Initial Framework Proposal Evaluated in Engineering Education and SME Contexts

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Abstract. Maintaining high product quality while reducing cost is essential for mass-customised products, requiring continuous improvement of the product development process. To this end, design automation should be utilised in all stages of a product's develop process and lay the foundation for automation of repetitive tasks throughout the process from interaction with the customer to design and production in order to mitigate errors and minimise costs. In this paper, a design automation and production preparation framework is proposed that can facilitate automation from initial stages via CAD to production. Examples of the framework are shown in the shape of proof-of-concepts systems developed by master students in the context of a course in design automation at Linköping University. Included disciplines such as automated planning of robot assembly paths, CNC manufacturing files and production drawings are described, based on design automation, Knowledge-Based Engineering, and design optimisation. Additionally, variations of the framework are implemented at three SMEs, and the results thereof are presented. The proposed frameworks enable interaction and connection between the "softer", human centred, aspects of customer interaction within sales, with more traditional "harder" engineering disciplines in design and manufacturing.

Keywords. Design Automation, Mass Customisation, Product Configuration, Production Preparation, Transdisciplinary Engineering Education

Introduction

A competitive market combined with complex products and requirements has directed companies to manage complexity by continuously rationalising their product development process, aiming to minimise costs and increase quality. For this, automation is highly applicable in both design and manufacturing.

Mass customisation of complex products requires an engineer-to-order (ETO) approach, which allows for a high level of customisation by including the customer in early design stages [1]. Due to the high variation between products and the uniqueness of customer requirements, one-off parts are required in addition to standardised parts. Errors are more likely to occur during design and production due to the uniqueness of these parts than in the case of more traditionally mass-produced or even configured-to-order (CTO) products built solely from standardised parts. For mass-customised products

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it is thus of utmost importance to mitigate errors in initial stages, as error-related costs incurred increase the further the development process progresses. Additionally, design and production of mass-customised products will incur increased time and costs as design- as well as production tasks must be repeated for alterations and variations. While the notion of cost varies depending on whom is affected and how, it is in this context primarily seen from the industry's point of view as a financial loss, either directly due to loss of materialistic or time resources or indirectly due to loss of reputation and customer trust in the company. Additional types of costs, ranging from environmental costs to the wellbeing of personnel, may however require attention during a product's development and remainder of its lifecycle.

Repetitive tasks are naturally fit for automation. Automation in manufacturing is well proven in industry and widely used within various fields, such as mechanical and electrical engineering. To accomplish mass customisation, the literature suggests different approaches such as modularisation [2], product families and platform design [3], which can be supported by methods such as Design Automation (DA) [4], product optimisation [5] and Knowledge-Based Engineering (KBE) [6].

When opting for DA the goal is to capture a wide range of the design rationale in a DA-tool. Advanced tools are able to produce both the geometric representation of the product i.e., the CAD model, and production data needed to automate the process from customer order to delivery. DA and KBE techniques are core to the development of product configurators, aimed at aiding product development in the (conceptual) design of product variants [7]. In combination with product optimisation, powerful design tools can be developed capable of sustaining mass customisation. A further aim with the introduction of DA configuration frameworks is to alleviate engineers from their non-creative and mundane tasks, and to intertwines actors from multiple disciplines including colleagues from both upstream and downstream of the product development process as well as with end-customers. This requires application of inter- or even transdisciplinary engineering methods to fully succeed. While successful examples of the implementation and use of DA in industry exist, companies continue to show a strong need for employees with skills and knowledge of how DA and KBE can be used together with product configurators to speed up their ETO-processes. Therefore, this paper describes how the proposed framework is implemented in a master's course, so that newly graduated engineers can bring this knowledge to industry. Additionally, implementations of the framework are discussed based on case studies in collaboration with three SMEs.

The remainder of this paper is structured as follows. After an initial state-of-the-art description, a general automation framework for design and production preparation of mass-customized products is proposed. Proof-of-concept implementations frameworks in the shape of results from a Masters' course in DA taught at Linköping University are described. Additionally, implementations of the framework are showcased from case studies in collaborations with Swedish industries before a discussion and concluding remarks.

1. State of the Art

According to Stokes [8], 80% of (CAD) design tasks are routine-like and repetitive. These tasks are often time-costly and error-prone and are therefore suitably subject to DA [4]. Willner et. al. [9] confirm this, stating that "design automation based on integrating product configurators and CAD systems may result in a reduction of the engineering time by up to 90%". One method of achieving DA is the application of KBE, applied in the form of knowledge-based systems (KBS), allowing existing knowledge to be utilised in order to create new products or product variants. Thus, repetitive tasks can be automated, supporting reuse of product knowledge as well as multidisciplinary optimisation throughout the entire design process [10].

Amadori & Tarkian et al. [11] propose High Level CAD templates (HLCt) as a method for geometry automation with the aim of DA. Building on both morphological and topological geometry automation, the concept of HLCt is that each template contains attributes necessary in order to visualise the 3D geometry and provide contextual references for other templates. Additionally, the templates provide geometric and non-geometric attributes required for downstream tools such as simulation models, production files and Enterprise Resource Planning (ERP) and Product Lifecycle Management (PLM) integration. HLCt have been successfully applied in contexts such as rapid design of train carriages [12], robotic grippers [13] and spiral staircases [14], decreasing time, costs, and errors in design processes.

Highly customised designs can be produced by means of additive manufacturing due to the inherent geometrical freedom of the manufacturing process, as numerous methods supporting DA in design for additive manufacturing exist [15]. Mass-customised products are however often dependent on more traditional types of manufacturing due to functional, material, or other requirements. In these cases, production data such as drawings, NC machine code, and robot control programmes are required. CAM software can be utilised to automatically produce the CNC code needed to manufacture the virtual model in a physical setting. While such CAM systems are meant to be plug-and-play for CNC code generation, the reality is that extensive manual operations continue to be required. Therefore, works such as [16] are presented to fill the need reported in the industry. This is the case for many process planning systems, where lack of flexibility in handling varying inputs hinders complete automation [17].

The inclusion of sales in the engineering design process requires designers of a DA framework to consider the human elements involved and ease transdisciplinary communication to fully understand "soft" customer requirements, in addition to "hard" technical requirements, and thus solve an ill-defined problem. This requires not only technological integration but a common language between disciplines to break communicational barriers. [18]. This integration of disciplines within a large process requires a transdisciplinary engineering approach [19]. The education in engineering master programmes at Linköping University is conducted based on the educational framework CDIO (Conceive-Design-Implement-Operate) [20] and builds on a combination of disciplinary and interdisciplinary courses, with project courses looking towards transdisciplinary inclusion of human-focused aspects in engineering. Key points for transdisciplinary approaches include ill-defined and open-ended problems relevant for both academia and industrial practitioners [19]. The course presented in this paper attempts to addresses these issues in a project-based learning environment.

2. Proposed Framework

With the aim of achieving DA throughout the design process from conceptual design stages to production preparation, a framework incorporating HLCt-powered CAD configurators and auxiliary production preparation automation modules is proposed. The nature of such modules depends entirely on the production method these aim to support but will inevitably build on data introduced in earlier development stages, included in the templates with which the entire product model is built.

The DA implemented is based on the HLCt principle as outlined by [11]. Following chapters describe the additional improvements added to the principles of HLCt in order to enable automation of downstream models. HLCt allows the design space to be divided into smaller building blocks that can be easily modified, added, and removed. The addition of downstream logic does not affect existing design logic and can in itself be modified at any point in time without upstream complications, a strategy preferrable from a maintenance point-of-view.

Figure 1 illustrates the proposed framework including DA activities and examples of product preparation automation modules. To the left, a visualisation of the DA facet of the framework, where a CAD configurator is utilised to configure a customised product resulting in a configured model, based on user input. The CAD Configurator builds the model from a library of HLCt building blocks. Logic concerning the compatibility and required contextual and parametric inputs of the HLCt is drawn from a knowledgebase, which is compiled from the entire library beforehand. To the right of Figure 1, a set of production preparation automation methods, where information embedded in the model drawn from the HLCt in previous steps is utilised to automatically generate production documents and data, illustrated by the "Drawing Module", "Layout Optimisation" and "Product Simulation". Naturally, in a generic case the production preparation automation will include many more modules depending on the product and its manufacturing. In the forthcoming chapters, however, a subset of these models is described for illustrative purposes.

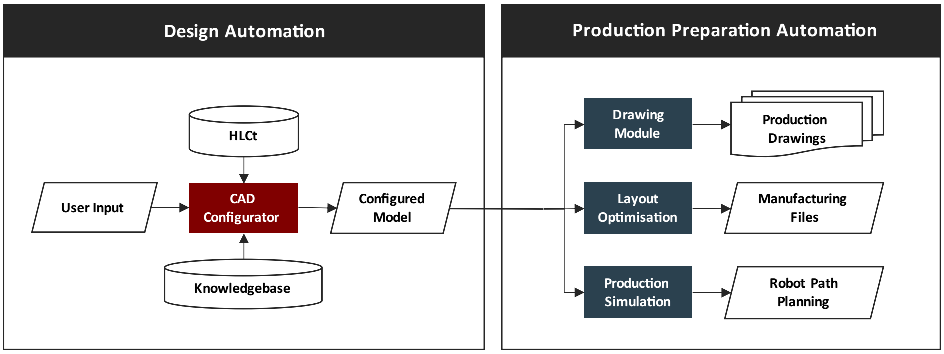

Figure 1. Proposed framework including Design Automation and Product Preparation Automation

2.1. Design Automation and Product Configuration

The framework builds on input models, modelled by the user from scratch or based on imported shapes, such as the resulting surfaces from a 3D scan. The user input will form the base on which HLCt are instantiated through the CAD configurator, thereby creating the detailed model required for the product development process to advance.

HLCt templates include the parametrisation and contextual links required for both morphological and topological adaptation of the template geometry within the context into which it is instantiated. Information required for production preparation of the final product is embedded in the HLCt templates, the nature of which depending on the type of feature the template contains and the method of manufacturing/production it requires. As the detailed features are instantiated from the templates, a complete blueprint is formed from which production data can be generated.

2.2. Production Preparation Automation

Often encountered production data ranges from traditional formats such as production drawings for both manufacturing and assembly to machine-specific CNC code. Creation of production drawings continue to cost large amounts of money, up to a third of total engineering costs according to the US Department of Defense, with 60% of the drawings containing errors and inconsistencies [21]. Due to the repetitive nature of included tasks and all required data being readily available in CAD models, these are prime candidates for automation. Similarly, manufacturing data can be extracted based on the geometry of the CAD model and encoded to fit the application in question.
The proposed framework illustrates modules for generation of drawings and path files for CNC manufacturing as 2D representations, automatically recognised by the machine's operating system or line-by-line generated code. In the CAD environment, the drafting API is utilised to this end similarly to the generation of production drawings, albeit with the exclusion of humanly legible annotations. Production-specific datum geometry is included in the HLCt, instantiated within the 3D model. From these, (sectional) 2D views can be generated ready to be included in a drafting document and positioned based information included in the template. Positioning of multiple parts to be manufactured from the same specimen of material, requires an experienced user or optimisation algorithms in order to minimise manufacturing time and material costs. This can be achieved by optimising the position and rotation of each part upon a common plane, with a goal function towards a minimum area of the resulting bounding box of all parts constrained by the material's and/or machine's limitations.

In order to define a robot assembly programme a set of operations need to be defined in a robot program. Depending on the geometry of the parts of a product (represented in the CAD models) the number, size, position, and rotation of these operations will be different. In this study DELMIA is utilised as the robot offline programming software. By utilising HLCt, product assemblies are never pre-configured, yet information needed to automatically setup any given configuration can be embedded. All HLCt contain contextual information concerning their compatibility and geometric interaction with each other. The same technique is used to automatically generate, i.e., configure, the production cell. Every geometry is predefined in a template, including the information necessary to be instantiated correctly in context. This includes robots, components to be processed and any additional tools that may be required. Once the production cell has been populated, the robot paths can be generated.

For any given production process, tasks can be defined with Robot Operations in DELMIA, requiring user-defined start, end, and way points. These are defined as coordinate systems to describe the position and orientation of the robot gripper in various steps of the operation. Options include operations such as Motion, Delay, Pick, or Place. Definitions of operation-specific objects and parameters are embedded in the HLCt, rendering complete automation of robot path generation possible.

3. Student Course Results

The framework is put into context in the course *TMKU01 Design Automation of Customized Products* taught at Linköping University as part of the master's programmes in Mechanical Engineering and Design and Product Development. Conducted towards the end of the programmes, pre-requisite disciplinary knowledge includes parametric CAD modelling and DA as well as multidisciplinary design optimization. Intended learning outcomes include understanding of the correlation of digital models with reality, the use of customer data to drive development of customised products and the suitability of different digitalisation methods depending on the type of product. Run in project-form with the application or product to be chosen by the students, and thus without pre-defined answers, the course builds on open-ended problems. Projects are selected based on level of complexity and realism, in order to appropriately simulate industrial cases. Focus in the course lies on applying knowledge of multiple disciplines and learn through a practical example to combine these in a process from early customer and human centred interaction to detailed technical design and production.

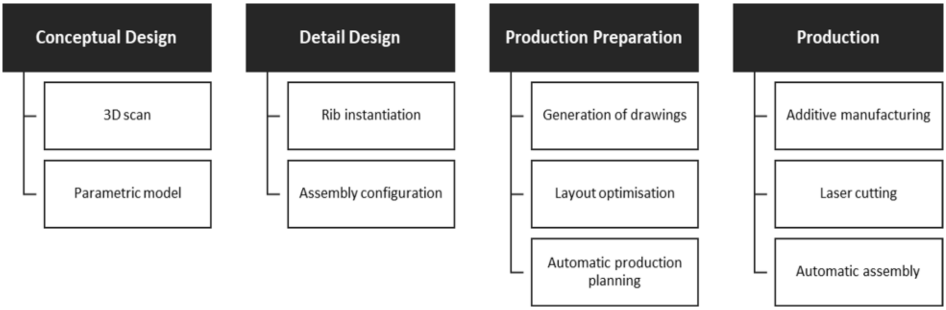

Figure 2. Automation tasks undertaken in the course *Design Automation of Customized Products.*

Students are required to design a product of their choice utilising DA, while allowing the product to be configurable and customisable. Scale models are produced using a CNC controlled laser-cutter machine and assembled using an industrial robot. The entire process from concept to assembly is simulated through steps incorporating conceptual design, detail design, production preparation and production, as shown in Figure 2. Between each step, DA is achieved through the use of KBE as described above. Hence the complete framework is simulated and tested in a simplified educational setting.

All modelling and drafting is undertaken in CATIA V5. Physical mock-ups are digitised by means of 3D scanning, and a parametric model of the conceptual shape is generated from the scan with HLCt. Detailed parts are instantiated from HLCt templates and adapted to the input model. In the case of for example an aerocraft, structural rib members are instantiated to fit the model as the entire assembled product model takes shape. With all required information included in the assembled model, production preparation steps are taken before a physical scale model is produced.

As part of the production preparation automation, students produce a framework capable of generating technical drawings for manufacturing and assembly based on the products configured using the CAD configurator. Based on vertices in the model measurements are added, while adhering to the commonly agreed upon rules for technical drawings. An example of generated drawing features can be seen in Figure 3.

Generation of manufacturing files is accomplished as described in previous sections utilising the drafting workbench. The result is essentially a bare technical drawing sans annotation, exported in the form of a vector image for input to the CNC controlled laser-cutting machine functioning as the main manufacturing tool. Prior to generating robot paths, the layout of the parts to be manufactured within the material's limitations is optimised using the optimisation software ModeFRONTIER, which is directly linked to parameters in the CATIA model as well as an Excel worksheet functioning as graphical user interface and user data storage. Constraints are set in ModeFRONTIER based on the material's limitations read from user data. During optimisation, values of parameters controlling the parts' locations are controlled by the algorithm and custom functions incorporating CATIA API calls are executed for each iteration. These functions execute clash analyses within the CAD environment, of which the results are returned to the algorithm for evaluation. The optimisation algorithm utilised in this process is the genetic algorithm NSGA-II [23].

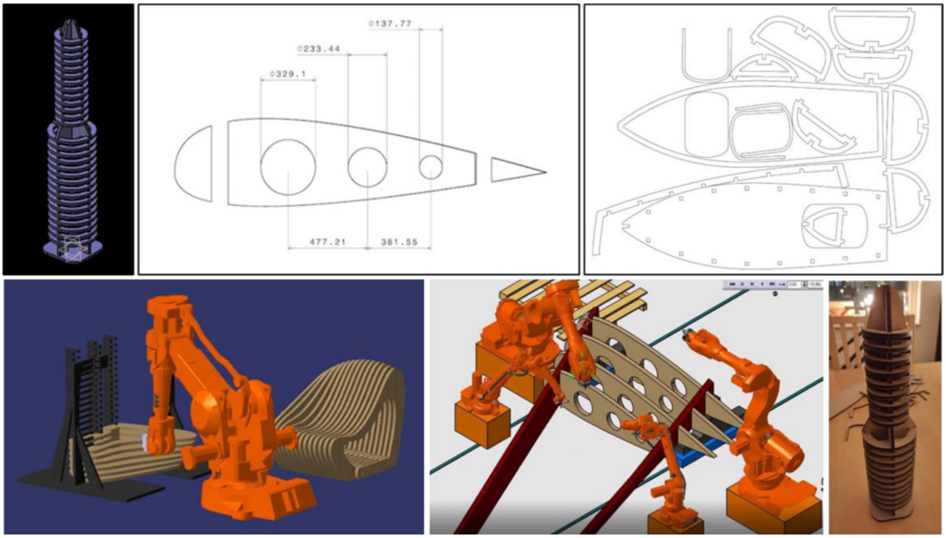

Figure 3. A selection of project results in various stages of the framework. From top left to bottom right: A configured model, generated drawing features, generated CNC paths, robot assembly in simulation, and an assembled scale model. Models depict, in order, a residential tower, structural members of an aerocraft's wing, structural members of a sailboat, and modular furniture.

The production preparation process for laser-cut parts is entirely automated and requires no user interaction other than specifying limitations and a 3D model of the product to be manufactured. The process takes, optimisation included, approximately one hour on a workstation running Windows 10 on a quadcore CPU at 3.5GHz with 16 GB RAM. Examples of layouts, CNC paths, and assembled scale model are shown in figure 3.

In order to fulfil the automation requirements, the framework includes a module for generation of robot paths based on positions rendered from the 3D model itself. Creation and simulation of paths is achieved in DELMIA utilising the production planning software's API. To perform a complete assembly of the product, a sequence of robot operations is generated as described in section 2.3. Generic functions for creation of operations and tags are required, which control the DELMIA functions within the CATIA environment through the API. The manner in which parts, robot(s), fixtures, and other manufacturing details are positioned is encoded specifically for each application. The benefit of this approach stems from the opportunity to alter the design of the

product’s morphology and topology in its entirety while still being able to utilise the existing robot planning script to regenerate the robot’s offline code.
Figure 3 shows still images of automatically planned robot assembly simulations created during the course. Both images show the required models for robots, fixtures, and parts to be assembled. In this case structural rib members for sections of a park bench and rib structures of an aircraft wing. In both cases, the ribs shown are a direct result of the described DA and production preparation methods.

Knowledge transfer is confirmed throughout the project through continuously dialogue between students and teachers. Examination is conducted in a seminar setting where the project results are presented. Students are required to provide proof of adequate knowledge by discussing the suitability of different methods, and the impact their results could have on a product development process and personal involved therein in an industrial setting.

4. Industrial Implementations

The proposed framework demonstrated in the student course has been implemented in an industrial setting within the context of the research project e-FACTORY. Due to confidentiality agreements, the details of those implementations cannot be disclosed. However, a summary of their outcome is given below. Within the research project the proposed automation framework has been implemented at three companies, including a unique CAD-configurator for each, as well as product-specific HLCt and exclusive knowledgebases. In three distinctive settings various configurators were applied for three of the partner companies. The type of product and CAD and configuration software for each case can be seen in Table 1.

Table 1. Company case details

Company	Product	CAD Software	Configuration Software
A	Industrial staircases	SolidWorks	XperDi CAD Configurator
B	Industrial staircases	Inventor	Developed in-house
C	Conveyor belts	SolidWorks	DriveWorks

Each company has been able to automate a large portion of previously manually undertaken repetitive CAD processes. By storing information for downstream tasks within configured models, all three companies were able to automatically generate 2D-drawings and manufacturing files. Apart from time savings, the most appreciated advantage of configurator-based DA is the mitigation of errors in the process. To verify the effect of the developed frameworks, workshops and interviews have been conducted with engineers and salespersons at each company, with representatives stating that the implementation has meant huge time savings in administrative work on the models. Company C estimates that they can save up to 90% of administrative time from quotation via order registration, purchasing, and control of stock balance to technical documentation. Respondents have stated the expectancy that the framework will provide improved sales support and handling of existing customer relations, while being able to increase the number of quotes generated for new customers as online configurator are to be released. In this context, the configurators’ ability to provide customers direct access to offers and drawings at any time is seen as a considerable advantage.

5. Discussion & Conclusion

A successful implementation of a DA framework enables interaction and connection between the “softer”, human-centred, aspects of customer interaction within sales, with more traditional “harder” engineering disciplines in design and manufacturing. Inclusion of salespersons in the engineers’ process, and vice versa, requires designers of a DA framework to consider the human elements involved and ease transdisciplinary communication. Education in transdisciplinary engineering is of utmost importance, with movements such as Industry 4.0 pushing towards greater integration between disciplines and industries’ increasing focus on mass customisation. The course described is one step towards a wide-spread understanding of the importance and means of coupling deeply technical with surrounding disciplines.

Based on observations in relation to the introduction of the described framework in industrial settings, it is apparent that the industry is in need of versatile engineers capable of understanding both technical and human factors in the product development process. Results from the industrial implementations have both verified the need for and improved the described course. While this particular course merely ticks part of the CDIO checklist for complete TE education, it is its position in a master’s programme that fosters its students’ understanding of interdisciplinary methods by combining topics from several disciplinary courses and applying these in a simulated industrial setting, preparing the students for their eventual thesis projects and careers. To enhance the impact of the course’s teachings and its link to reality, future course projects are to include close contact with industrial actors acting as product owners.

The framework proposed in this paper is highly dependent on the use of HLCt, being the building block and information carrier for the majority of the information required for design and production preparation, chosen due to the flexibility and maintainability it provides the user over centrally stored, hardcoded product knowledge.

While modern production methods relying on automation may lessen the requirement for traditional drawings during production, human-readable documentation will undoubtedly continue to be required for quality assessment, testing, maintenance, non-automatable production methods and other human interactions with a product throughout its lifecycle. Provided the HLCT includes the appropriate information, any such documentation can be generated for mass-customised products from the configured model with specialised framework. Similarly, existing stand-alone programs such as process-specific CAD/CAM software can be incorporated, requiring such software to be accessible through an API and flexible enough for true mass customisation, as the tool itself should not limit upstream design freedom. The framework may be implemented in different stages of the product development process, be it variant design of well-defined product families or conceptual design of individual parts or indeed entirely new product families, enabling the user to rapidly iterate through concepts and assess their feasibility.

A modular DA approach based on the concept of HLCt provides a flexible yet robust configuration process and enables automated production preparation by efficient reuse of knowledge. Implementation in the production of existing products in SME contexts has shown both the need for and potential effectiveness of the framework proposed, easing communication between disciplines. Initial results from both student projects and industrial cases call for further verification of the included production preparation methods as well as exploration of more advanced application in realistic settings and inclusion of additional engineering disciplines.

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References

[1] C. E. Levandowski, J. R. Jiao, and H. Johannesson, A two-stage model of adaptable product platform for engineering-to-order configuration design, *J. Eng. Des.*, 2015, Vol. 26, No. 7–9, pp. 220–235.
[2] A. Ericsson and G. Erixon, *Controlling Design Variants: Modular Product Platforms*, Society of Manufacturing Engineers, Dearborn, 1999.
[3] J. Jiao, T. W. Simpson, and Z. Siddique, Product family design and platform-based product development: a state-of-the-art review, *Journal of Intelligent Manufacturing*, 2007, Vol. 18, No. 1, pp. 5–29.
[4] M. Tarkian, *Design Automation for Multidisciplinary Optimization: A High Level CAD Template Approach*, PhD dissertation, Linköping University Electronic Press, Linköping, 2012.
[5] J. Andersson, *Multiobjective Optimization in Engineering Design: Applications to Fluid Power Systems*, PhD dissertation, Linköpings universitet, Linköping, 2001.
[6] G. La Rocca and M. van Tooren, Knowledge based engineering to support complex product design, *Advanced Engineering Informatics*, 2012, Vol. 26, No. 2, pp. 157–158.
[7] A. Trentin, E. Perin, and C. Forza, Product Configurator Impact on Product Quality, *Int. J. Prod. Econ.*, 2012*,* Vol. 135, No. 2, pp. 850–859.
[8] M. Stokes, *Managing Engineering Knowledge: MOKA: Methodology for Knowledge Based Engineering Applications*, Professional Eng. Pub., London, 2001.
[9] O. Willner, J. Gosling, and P. Schönsleben, Establishing a maturity model for design automation in sales-delivery processes of ETO products, *Computers in Industry*, 2016, Vol. 82, pp. 57–68.
[10] G. La Rocca, Knowledge based engineering: between AI and CAD. Review of a language based technology to support engineering design, *Advanced Eng. Inform.*, 2012, Vol. 26, No. 2, pp. 159–179.
[11] K. Amadori, M. Tarkian, J. Ölvander, and P. Krus, Flexible and robust CAD models for design automation, *Advanced Engineering Informatics*, 2012, Vol. 26, No. 2, pp. 180–195.
[12] V. Gopinath, M. Tarkian, J. Ölvander, and W. Gaziza, Template driven conceptual design of high speed trains, *Proc. of the ASME 2014 IDETC/CIE, Vol. 2A: 40th Des. Autom. Conf.,* 2014.
[13] M. Honarpardaz, J. Ölvander, and M. Tarkian, Fast finger design automation for industrial robots, *Robot. Auton. Syst*, 2019, Vol. 113, pp. 120–131.
[14] L. P. Poot, C. Wehlin, M. Tarkian, and J. Ölvander, Integrating sales and design: applying CAD configurators in the product development process, *Proc. Des. Soc. Des. Conf.*, 2020, Vol. 1, pp. 345–354.
[15] A. Wiberg, J. Persson, and J. Ölvander, Design for additive manufacturing – a review of available design methods and software, *Rapid Prototyping J.*, 2019, Vol. 25, No. 6., pp. 1080–1094.
[16] J. Braumann and S. Brell-Cokcan, Parametric robot control: Integrated CAD/CAM for architectural design, *Integr. Through Comput. - Proc. 31st Annu. Conf. Assoc. Comp. Aided Des. Arc. ACADIA*, 2011.
[17] M. Al-wswasi, A. Ivanov, and H. Makatsoris, A survey on smart automated computer-aided process planning (ACAPP) techniques, *Int. J. Adv. Manuf. Technol.*, 2018*,* Vol. 97, No. 1–4, pp. 809–832.
[18] M. Butt, A. Sharunova, M. Storga, Y. I. Khan, and A. J. Qureshi, Transdisciplinary Engineering Design Education: Ontology for a Generic Product Design Process, *Procedia CIRP*, 2018, Vol. 70, pp. 338–343.
[19] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, and W. J. C. Verhagen, Transdisciplinary systems engineering: Implications, challenges and research agenda, *International Journal of Agile Systems and Management*, 2019, Vol. 12, No. 1, pp. 58–89.
[20] E. F. Crawley, J. Malmqvist, S. Östlund, D. R. Brodeur, and K. Edström, *Rethinking engineering education: The CDIO approach, second edition*. Springer International Publishing, 2014.
[21] B. Boehm, J. Bayuk, A. Desmukh, R. Graybill, J. Lane, A. Levin, M. Azad, M. McGrath, A. Pyster, S. Tarchalski, R. Turner, and J. Wade, *Systems 2020:Strategic Initiative. (report SERC-2010-TR-009), 2010.*
[22] M. Honarpardaz, M. Tarkian, J. Ölvander, and X. Feng, Finger design automation for industrial robot grippers: A review, *Rob. Auton. Syst.*, 2017, Vol. 87, pp. 104–119.
[23] K. Deb, S. Agrawal, A. Pratap, and T. Meyarivan, A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II, *IEEE Trans. Evol. Comput.*, vol. 6, no. 2, pp. 182-197, 2002.

Part 3

PD Methods and Digital TE

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Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Incremental Update of a Digital Twin of a Production System by Using Scan and Object Recognition

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Abstract. While production plants are subjects of frequent change, for instance due to changed processes, new products or new machine tools, the process plans must be subsequently updated. This generally affects all planning processes for production management and thus in particular also modern planning methods such as the Digital Twin of a production system. The simulation of production processes using a Digital Twin is a promising means for prospective planning, analysis of existing systems or process-parallel monitoring. However, many companies, especially small and medium-sized enterprises, do not apply the technology, because the generation of a Digital Twin is cost-, time- and resource-intensive and IT expertise is required. Supposed that the process of generation of the Digital Twin was completed once using scans and deep learning applied to a point cloud of a production system, this paper describes a conceptual approach to provide an incremental update of this Digital Twin, as often as necessary. The solution alternatives are presented and discussed, in particular the use of flexible devices (360°-camera) for the object acquisition. A particular attention is given to the integration of the entire change process for updating an existing Digital Twin.

Keywords. Digital Twin, Digital Factory, Object Recognition, Indoor Object Acquisition, Simulation, Transdisciplinary Engineering

Introduction

The Digital Twin is the surrogate of a physical object or system, which can be a product, a production system, but also a company or a process. As a frequently used buzzword which connects research and commercial applications, Digital Twin can be found also in further, non-technical domains such as medicine, economy or society [1]. The Digital Twin connects virtual planning and development models with the real world of products and production systems in order to obtain insight of the system and its state as well as behavior. A vision in the sense of Industry 4.0 is that technically complex systems can control themselves autonomously and behave more intelligently using digital algorithms, virtual models and status information [2]. Therefore, the virtual representation of the Digital Twin enables in the realisation of this vision by providing the real system with a digital operational layer on which the autonomous and intelligent algorithms can execute.

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The mutual functional relationships of products or production systems are determined based on customer requirements and taking into account a large number of legal requirements in product planning and development. Without knowledge of these relationships, the operating data that the real asset records in its later product life cannot be interpreted correctly. If it is not known how a machine or system should actually work, it is not possible to unequivocally identify the causes of deviations from this desired state or behavior and enforce appropriate countermeasures. Knowing the history of its origins is also important in order to be able to assess the reason, for example, of a bearing failure and which other machines could also be affected by the problem [2]. With such information, the behavior of a technical system can be easily predicted.

One of the distinctive dimensions of Digital Twin is the time of creation. The approach to create the virtual model first or synchronouosly with the physical counterpart is sufficiently supported by modern software tools. The opposite way which consists of digitalization or reverse engineering of an existing environment is not that well covered by methods and tools, and therefore subject of various research activities. In previous research of these authors, an approach for generation of Digital Twin of manufacturing in a built environment was developed which addresses the entire factory hall [3]. With fast scans of the shop floor and subsequent object recognition, the production layout (e. g. size and location of the objects) and the production semantic (e. g. machine types, transport routes) can be recorded as automated as possible and visualized true to scale in digital models [4]. This allows a Digital Twin of an already existing production system to be set up quickly and thus cost-effectively. It should be emphasised at this point that the Digital Twin is built up initially and the structure is thus fixed [5].

Production systems are constantly being rescheduled and rebuilt to increase their productivity or to use them to produce other products [6]. There are therefore many good reasons for operators to precisely record the current status of their plant and production system. This actual status never exactly corresponds to the planning status, because there are often deviations during the construction of the system or many details are not planned at all. That is why many operators try to bundle the information on their existing systems in a Digital Twin [7]. However, the operators are faced with the question of how they can set up this digital surrogate with a reasonable expenditure of time and money [8].

This need is in particular supported by the process simulation as a core element of the digital factory and is becoming increasingly important for small-and-medium enterprises as a result of developments in the area of digitisation [3]. Nevertheless, current studies prove that the use of simulation models for production systems in small and medium-sized enterprises is still not standard [4]. This is particularly due to the fact that the costs for setting up and operating the Digital Twin are not transparent and tend to be estimated as too high. IT knowledge is also lacking, so that the benefits cannot be correctly estimated or there is a reluctance to implement the Digital Twin [5]. At this point, it is also often critical that a one-off investment in a Digital Twin is seen as unsafe, as companies are aware that a continuous updating process is necessary to keep the Digital Twin up to date and valid [6]. Small companies have small tasks, e.g. replacement of a machine by a new one, which do not require the acquisition of the entire hall. Thus, a flexible solution for a intermediate, iterative update of the Digital Twin is necessary.

The remainder of this paper is structured as follows: In Section 1, the problem statement is expressed. Section 2 illustrates the importance and options in the data acquisition. Section 3 presents the solution concept for iterative update which is further detailled and structured in Section 4. Finally, Section 5 summarizes the conclusions and outlook.

1. Problem statement

In general, different processes are conceivable for setting up a Digital Twin. Often, a Digital Twin is built by people with the expertise of the corresponding software tools manually. For this purpose, these people must be provided with the relevant information on the production system to be mapped so that they can create the Digital Twin. However, the authors of this article have developed and researched a procedure for efficient generation of a Digital Twin over the last two years, so that this will be presented here as a feasible alternative [8]. The further explanations are also oriented towards this procedure and based on it. The efficient, generic approach for generation of the Digital Twin of an existing production system is depicted in Figure 1. During the initial setup, the operator of a plant provides his facility (1) which is being scanned (2) by a commercial device [3]. The resulting point cloud is transferred to CAD modeling which creates a CAD assembly of the production system or the entire plant based on the point cloud. The most challenging task in this process is the object recognition in the cloud based on a CAD library [9]. The equipment characteristics are collected by a different way to provide the initial setup. This setup means that a Digital Twin can be created once with the method with no possibility for further adjustment of the Digital Twin is carried out after the method has been completed.

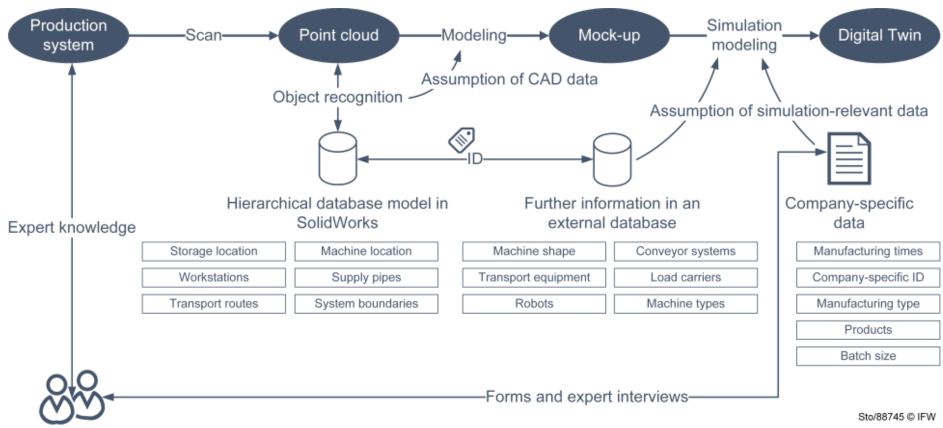

Fig. 1. Approach for generation of the Digital Twin of production system

The exploitation of the Digital Twin can take place from this point on, but production systems often change during its lifecycle [10]. The (digital) twinning implies an immediate, instant change of the digital surrogate in case of change of the corresponding physical part and vice versa. The following constraints are especially important, although further modifications to the production system are possible:

- Adjustment activities change the production sequences, which in turn changes processing times, for example. This is caused by the inherent mission of production management to continuously increase productivity through minor adjustments.
- The production schedule may change over time. This input variable for the production system, meaning which product is to be produced at which time, is usually subject to constant alterations.

- New products or product variants impose various adjustments to be made to the production processes or new ones to be developed.
- Besides products, new machines or new transport equipment may be added to the production system or old machines may be removed from the production system.
- The layout of the production system can change by repositioning objects in the production hall.
- Often are such modifications cummulated.

The aforementioned changes mean that the resulting Digital Twin must be updated whenever necessary [10]. However, updating the Digital Twin is as important as a change relevant for the simulation results can occur. Three general cases are explained here as illustration of this change and update, which pose different levels of complexity and effort for updating and should therefore be considered as separate cases. In ascending order of complexity, these cases are shown in the Table 1.

Table 1. Cases of update of the Digital Twin.

Case	Description/Content
Parameter-based	The changes in the real system lead to the requirement that the Digital Twin can remain in its current form, but that single parameters have to be updated. It can be provided remotely. No additional object acquisition is necessary.
Structural partial	The changes in the real system require an adjustment of the Digital Twin, but the general structure can be preserved so that a new scan is not necessary or only isolated areas have to be re-recorded.
Structural full	The changes in the real production system are so extensive that a new recording is required and the Digital Twin has to be completely recreated.

A parameter-based and (entire) structural updates suppose re-use or repeat of the generation of the Digital Twin with the already developed method [4]. For the partial update, the same metod can be re-used too, but with regard to a significantly reduced scope. It implies an appropriate object acquisition method for a reduced space which considers the specific local circumstances (accessability, impact of darkness, dirt, dust, occlusion).

2. Object acquisition

The flexibility and speed how the production system is being acquired has the particular importance on the affordability of this approach. The most used acquisition devices are the scanners which can be used as either fixed or mobile devices. However, new approaches becomes known just recently which use end-user commercial camera for shape acquisition [11].

The comparison between the terrestrical laser scanner and the 360°-camera is shown in Table 2. As a mature technology, the scanner discovers advantages in accuracy and availability of rough data. The comparison of the whole range of criteria shows that the alternative with the 360°-camera is the superior option [12].

Table 2. Comparison between terestrical laser scanner and 360°-camera.

Characteristic	Terestrical Laser Scanner	360°-Camera
Scan duration (e. q. 300 qm)	One hour (six scans)	Three minutes
Invest costs	80,000 €	500 €
Qualification of the scan operator	Expert	Everybody
Traveling expenses	Yes	No
Availability of the point cloud	0.5 hour	One day
Accuracy	One millimeter per ten meters	Ten millimeters per ten meters

In comparison with a scanner, a commercial 360°-camera acquires the video of a scene. This video must be translated into the point cloud in a subsequent process which can be performed offline. The 3D-reconstruction pipeline is shown in Figure 2. After the 360°-video is uploaded in the cloud, a process starts which extracts the singular images from the video and translates these in a point cloud. The particular challenge lies in the registration (the mutual localisation of singular images in the space) and the handling of light reflections on the bright surfaces.

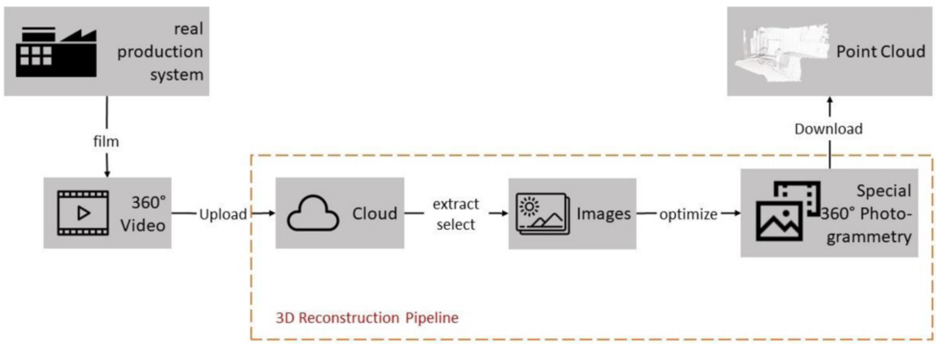

Fig. 2. 3D reconstruction pipeline based on 360° video

This methods is conventient especially for smaller rooms and tasks which occuring during a update.

3. Parameter-based update

The implementation of the updates described in Table 1 primarily relies on the extent of the required change. The first case mentioned in Table 1 is for example when, as mentioned above, the production schedule is changed or adjustments to the production system lead to altered processing times. Moreover, new products that do not lead to structural modifications of the production system can also be addressed with this case. It is therefore a matter of adjusting parameters of the Digital Twin, such as processing or set-up times.

A useful addition for this case is the connection of the Digital Twin to the existing IT systems, especially Enterprise Resource Planning (ERP) or Manufacturing Execution Systems (MES). However, a connection to machine or operating data is also reasonable at this point, as for example explained by Donhauser et al. [13]. With this interface connection to ERP or MES, information about products, production schedules, work plans, machining and set-up times, or similar can be transmitted directly to the Digital Twin [14]. The updating of the Digital Twin is carried out automatically here, so that this process does not require any further handling and thus provides a natural practical extension to the basis method a a kind of living Digital Twin.

The simplest update process described here, which only involves parameter adjustment, is thus achievable in the next development steps. The basic functionalities are considered in the current method. However, it should be noted at this point that due to the large number of different MES and ERP, a generic solution can only be achieved with standardised transfer protocols.

4. Structural partial update of the Digital Twin

A much more far-reaching updating process occurs when, in addition to the parameters of the Digital Twin, the structure must also be adapted. This is always the case when objects, such as machines or material handling, are added, removed or displaced in the real production system. That is a typical case in the real life business [10]. However, this case can also arise in the case of comprehensive changes to products or the production schedule, if this results in major modifications to the production system that cannot be mapped with a pure parameter adjustment of the Digital Twin (Figure 3).

A structural update can of course be carried out by people who have expertise in the simulation software. However, this manual process would be costly as well as fault-prone and the corresponding IT expertise must be available. A gap between the model of factory and the simulation model would arise. In terms of the basis method used here, an efficient method would therefore lead to a better result, since again no IT expertise is needed, the effort is low, and the costs for the update are predictable.

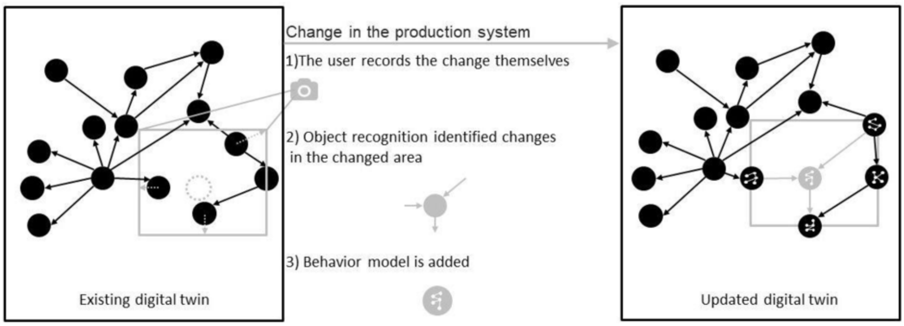

Fig. 3. Approach for the structural update of the Digital Twin

In order to conduct a real update of the Digital Twin, an extension of the method is necessary for the next development steps. This method has its particular workflow and consider a significant change in the object acquisition. Figure 3 provides an overview of the research approach.

The approach consists of three key characteristics, shown in the Figure 3, which are needed to proceed from a current Digital Twin (left hand side of the figure) to an updated Digital Twin (right hand side of the figure).

At first, the change in the real system should be preferably recorded by the customer himself which is particularly beneficial if the customer is located far abroad. This means that if, for example, a machine is moved to a different location in production hall or a new machine is added to the production system, only this area of particular interst is acquired. In this way, the overall effort is being reduced to a few objects of interests. To be able to do this by a customer, a simple process with a simple easy-to-use device is needed. Here, an application for consumer camera or common smartphones is developed with which a production area can be recorded as a 360°-video (Figure 2). Photogrammetry is used to generate the required point cloud. During the recording, the customer receives augmented reality feedback on whether the respective area has been correctly recorded by displaying objects in green on the mobile phone display if they have been captured. Finally, the recording can be sent directly to the offices that will further process the recording. For this purpose, the secure data transfer must be used [20]. The volume of data which is being generated and transferred here is significantly lower than for scan of the entire production system. If the initial result is not sufficient, this procedure can be repeated as often as necessary. Accordingly, a simple application for a consumer camera or a smartphone is created here that enables the client to take the scan of the changed areas himself. The service offered here is a lean process that can be carried out quickly without the need to work on the customer's premise.

At second, the basis method for the object recognition based on Convolutional Neural Networks should be applied in the changed areas and the adaptation of the Digital Twin. It belongs the entire process which must be adapted so that single areas from the Digital Twin can be segmented and modified. This poses a particular challenge because the edges between the existing and the modified areas have to be designed to fit each other. This issue must be resolved by an additional registration. In addition, however, this new updating method is quite similar to the method already explained for the initial creation of the Digital Twin. Here, too, a point cloud is first created from the scan (but here with a changed role by the customer). Subsequently, object recognition identifies new objects and inserts them into the CAD model, which in a further step is transferred to the simulation software to adjust the Digital Twin.

At third, if the method is able to deal with small sections of the production systems (e. g. discrete Digital Twin), it can be extended in that matter that the Digital Twin is being enriched by behavioural models as an advanced stage of the parameter-based updating of the Digital Twin. The core idea is that behavioural models are stored for the single objects, especially machine tools. These behavioural models represent the functions and capabilities of the objects, so that changed conditions, such as new products, wear, malfunctions, etc., are directly represented by the models and do not require any further updating process for the Digital Twin. Accordingly, this aspect prevents few further requirement for updating processes for the Digital Twin.

With the three characteristics presented, there is therefore an efficient incremental updating process that represents a sensible extension of the existing method. A scalable Digital Twin of manufacturing is created in short time with low effort, in which behavioural models of machines are embedded. Easy update facilitates the simulation of much more variants, making the production planning and control of industrial companies more reliable, efficient and comprehensive [15]. The resulting Digital Twin becomes more accurate through parameterisation from the machine level and requires fewer updating processes.

5. Structural update of the Digital Twin

For the last case of an update process, it is assumed that the changes in the production system are so comprehensive that partial updates of single areas cannot be carried out with a reasonable effort. Such cases occur in the context of fundamental organisational changes to the production system or when a far-reaching restructuring of the system is carried out [16].

The partial update process described in the previous section would then be too costly, as the additional effort required to assemble existing and updated parts of the Digital Twin exceeds the savings. Accordingly, in such a case, a renewed application of the basis method for the entire hall or plant as a new case would be recommended. This means that the complete process would be repeated: Scan of the factory floor and re-creation of the Digital Twin with the upstream object recognition.

It should be emphasised at this point, however, that most steps can be shortened here, since an initial creation process already exists. Accordingly, company-specific data on products, for example, no longer needs to be fundamentally re-entered, but can be taken over from previous processes. Another useful extension is the integration of the machine models. This additional aspect then prevents the requirement for further updates [17]. The accuracy of object recognition would be higher based on more trainings performed.

6. Discussion

As presented in this paper, the Digital Twin of production system could be improved further in term of flexibility, availability and timeliness [18]. Based on technological improvements in basis disciplines (camera hardware, computer vision, deep learning, localization algorithms), the vision of a real-time recognition, localization, and simulation of complex processes in a factory is moving even closer, although a mobile all-in-one application is not achievable at this time.

A tremendous move to the mobile acquisition devices, in particular to the spherical camera, becomes obvious. Its handling is easy for untrained personal too and three-dimensional reconstruction from videos and images is robust. The commercial spherical cameras achieve even higher resolutions and already meet the demand for sufficient resolution of homogeneous structures. Apart of localization, which is an inherent issue for all mobile devices, cameras struggle with a higher level of noise which become visible quickly on white walls or other homogenous surfaces [12]. In the reconstruction, these are not a straight but sinusoidal waves become visible [19].

With a spherical camera and a suitable image processing pipeline, a 3D-model can be created fast and efficiently by simple means, if the the highest accuracy of the model is not required. A further step would be the reconstruction of gaps within the 3D model at a later stage. This would simplify the merge with the basis model [20].

Object recognition is subject of intensive research in field of computer vision with remarkable advancements. Objects with distinctive features can be recognized timely, easily and reliably. The current challenge is more to select and adapt an appropriate, fast and reliable approach for object recognition rather than to develop a new one. The affordability of the recognition could be dramatically improved by further publicly available object databases [21].

The moment can be hardly predicted when 3D recognition methods become available on real-time applications, including mobile devices. Majority of deep learning libraries are designed for desktop operating systems, but some libraries also provide support for mobile operating systems. It heavily depends on further development on deep learning, in particular to accelerate the training procedure which is a limitation factor at this time [21].

The proposed method for update is the basis for an incremental, semi-automatic model setup for simulations of production systems. With this approach, it is possible to maintain a generic method with which any production system can be transferred into a simulation model [22]. This procedure allows the required information to be stored in the simulation software and to be accessed in the model construction with an almost instant actuality.

7. Conclusions and outlook

This paper describes a conceptual approach for the incremental update of the Digital Twin of an existing production system which is a step ahead for the frequent implementation of the Digital Twin. Digital Twins are a powerful means to optimize the processes in the manufacturing industry using its high-fidelity digital surrogate. This paper contributes a concept how to resolve the frequent issue of intermediate disparity between the virtual model and the physical part. With support of deep learning, the twinning becomes almost continuous.

Digital Twin is an encompassing approach of digitization for tackling complex, real-world problems. Digital Twin poses a huge potential which up to now was primarily recognized in the manufacturing industry but also in healthcare, society, and economics [1]. The Digital Twin is also an important approach in overarching earlier approaches. In essence, multiple disciplines, multiple functional roles, and multiple stakeholders need to collaborate in the processes making up the engineering, healthcare, societal, or economic systems.

The synchronous availability of the digital and the physical product alone brings interoperability into play as an indispensable prerequisite. It is enforced by dynamic interaction between technical and social characteristics of new product, process, and service development. Considering the human factor, e. g. human-machine interaction, a Digital Twin becomes part of a social-technical system. This moves the scope of Digital Twin in the area of transdisciplinary engineering [23].

While data are the fuel of Digital Twin, the main challenge lies in a seamless integration of methods and tools that are suitable to support the dynamic and evolving nature of the modern production system that need to be developed including the development system itself. The lack of standardization is particularly significant because it is unlikely that a complex system will come from a single source in a challenging environment. As a tool which can have many sub-components spread across collaborators and industry partners, developing regulations and security mechanisms is imperative for widespread of adoption of Digital Twin to overcome the concerns regarding data sharing.

References

[1] C.K. Lo, C.H. Chen, R.Y. Zhong, A review of digital twin in product design and development, *Advanced Engineering Informatics*, Vol. 48, 2021, 101297.
[2] L. Wagner, Kein Digital Twin ohne digitale Durchgängigkeit. *Zeitschrift für den wirtschaftlichen Fabrikbetrieb*, 2020, Band 115, pp. 43-45, DOI: 10.3139/104.112315.
[3] M. Sommer, J. Stjepandić, S. Stobrawa and M. von Soden, Automatic Generation of Digital Twin Based on Scanning and Object Recognition, *Adv. in Transdisciplinary Engineering*, Vol. 10, 2019, pp. 645-654.
[4] M. Sommer, J. Stjepandić, S. Stobrawa and M. von Soden, Automated generation of a digital twin of a manufacturing system by using scan and convolutional neural networks, *Advances in Transdisciplinary Engineering*, 2020, 12, pp. 363-372.
[5] B. Denkena, M.-A. Dittrich, S. Stobrawa, J. Stjepandić, Efficient generation of a digital twin using object detection for data acquisition and XML-interface for model creation, *Procedia CIRP*, 2020, 93, 274-279.
[6] R. Wallis, J. Stjepandic, S. Rulhoff, F. Stromberger, J. Deuse, Intelligent utilization of digital manufacturing data in modern product emergence processes, *Advances in Transdisciplinary Engineering*, Vol. 1, 2014, pp. 261-270.
[7] S. Wenzel, T. Peter, Prozess-Simulation in kleinen und mittleren Unternehmen mittels des Bausteinkastensystems KMUSimMetall. In: Wenzel, S.; Peter, T. (Eds.): *Simulation in Produktion und Logistik*. Kassel: university press 2017, pp. 433-442.
[8] M. Sommer, J. Stjepandić, S. Stobrawa and M. von Soden, Improvement of factory planning by automated generation of a digital twin, *Advances in Transdisciplinary Engineering*, Vol. 12, 2020, pp. 453-462.
[9] E. Ostrosi, J. Stjepandić, S. Fukuda and M. Kurth, Modularity: New trends for product platform strategy support in concurrent engineering, *Advances in Transdisciplinary Engineering*, 2014, Vol. 1, pp. 414-423.
[10] J. Stjepandić, M. Sommer, S. Stobrawa, Digital Twin: Conclusion and Future Perspectives, in J. Stjepandić et al. (eds.) *DigiTwin: An Approach for Production Process Optimization in a Built Environment*, 2021, Springer Nature, in press.
[11] D. Moon, S. Chung, S. Kwon, J. Seo, J. Shin, Comparison and utilization of point cloud generated from photogrammetry and laser scanning: 3D world model for smart heavy equipment planning, *Automation in Construction*, Vol. 98, 2019, pp. 322–331.
[12] M. Sommer, K. Seiffert, Scan Methods and Tools for Reconstruction of Built Environments as Basis for Digital Twins, in J. Stjepandić et al. (eds.) *DigiTwin: An Approach for Production Process Optimization in a Built Environment*, 2021, Springer Nature, in press.
[13] T. Donhauser, U. Endter, T. Schmidt, L. Baier, P. Schuderer, J. Franke, Echtzeitabbild der Produktion. wt werkstattstechnik, 110 (2020) 4, pp. 214-219.
[14] O. Kuhn, H. Liese and J. Stjepandic, Methodology for knowledge-based engineering template update, *IFIP Advances in Information and Communication Technology,* Vol. 355, Springer, Berlin Heidelberg, 2011, pp. 178-191.
[15] B. Denkena, K. Doreth, M. Köller, S. Wilmsmeier, F. Winter, F.: Simulationsbasierte kombinierte Instandhaltungs- und Produktionsplanung, G. Mayer, C. Pöge, S. Spieckermann, S. Wenzel, (eds.) *Ablaufsimulation in der Automobilindustrie*, Springer Vieweg, 2020, pp. 261-273.
[16] B. Denkena, S. Stobrawa, M. Sommer, J. Stjepandic, M. Von Soden, Production planning using the digital twin | [Effiziente Erstellung eines digitalen Zwillings zur Verwendung im Produktionsmanagement; Produktionsplanung mit dem digitalen Zwilling] , *WT Werkstattstechnik*, 2020, 110(10), pp. 661-665.
[17] B. Denkena, S. Wilmsmeier, S. Hauck, Adaptive Simulationsmodelle - Integration von Maschinendaten in Materialflusssimulationen. *ProductivITy*, 22 (2017) 3, pp. 37-39.
[18] B. Denkena, M.-A. Dittrich, S. Stobrawa and J. Stjepandić, Automated Generation of a Digital Twin Using Scan and Object Detection for Data Acquisition, in: M. Putz and A. Schlegel (Hrsg.) *Simulation in Produktion und Logistik 2019*, Wissenschaftliche Scripten, Auerbach, 2019, pp. 49-60.
[19] Z. Ma, S. Liu, A review of 3D reconstruction techniques in civil engineering and their applications, *Advanced Engineering Informatics*, Vol. 37, 2018, pp. 163–174.
[20] F. Xue, W. Lu, K. Chen, C.J. Webster, BIM reconstruction from 3D point clouds: A semantic registration approach based on multimodal optimization and architectural design knowledge, *Advanced Engineering Informatics*, Vol. 42, October 2019, Article number 100965.
[21] B. Salem, J. Stjepandić and S. Stobrawa, Assessment of Methods for Industrial Indoor Object Recognition, *Advances in Transdisciplinary Engineering*, Vol. 10, 2019, pp. 390-399.
[22] G. da Silva Serapião Leal, W. Guédria, and H. Panetto, An ontology for interoperability assessment: A systemic approach, *Journal of Industrial Information Integration*, Vol. 16, 2019, 100100.
[23] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić and W.J.C. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 753-762.

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Automated Generation of a Digital Twin of a Process Plant by Using 3D Scan and Artificial Intelligence

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Abstract. The simulation of production processes using a Digital Twin is a promising tool for predictive planning, analysis of existing systems or process-parallel monitoring. In the process industry, the concept of Digital Twin provides significant support for process optimization. The generation of the Digital Twin of an already existing plant is a major challenge – in particular for small and medium-sized enterprises. In this sense, the twinning of the existing physical environment has got a particular importance due to high effort. Shape segmentation from unstructured (e.g. point cloud data) is a core step of the digital twinning process for industrial facilities. This is an inherent issue of Product Lifecycle Management how to acquire data of existing goods. The practice of Digital Twin is described based on object recognition by using methods of Machine Learning. The exploration of the pipeline semantics presents a particular challenge. The highly automated procedure for the generation of Digital Twin is described based on a use case of a biogas plant. Commercial deployment, pitfalls, drawbacks and potential for further developments are further explored.

Keywords. Digital Twin, Process Plant, Object Recognition, Indoor Object Acquisition, Simulation, Transdisciplinary Engineering

Introduction

The concept of Digital Twin consists of generation, maintenance and use of the virtual surrogate of an object or system during its entire lifecycle. The aim of this approach is to achieve a highly reliable product/system definition, verification, and validation including the modes of failure. By gathering and processing real-time data, the real system can be monitored with its Digital Twin, while (potential) problems can be detected, communicated with the real system, and dealt with [1]. The concept has been applied in the manufacturing domain originally, but is increasingly used in other domains like process industry and became a pillar of Product Lifecycle Management (PLM). It is a concept that requires a transdisciplinary approach for its creation, implementation, and use. Even when applied in the manufacturing domain predominantly, business knowledge as well as human behavior knowledge are needed, next to the technical knowledge. Without collaboration between people from these different disciplines, the Digital Twin concept cannot fully be exploited [2].

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From the early beginning, Industry 4.0 has facilitated digital achievements as the pillars of its development [3]. Due to fact that all data are available in digital format, and sensors are inbuilt into the industrial spaces, the main pre-requisites for Digital Twin in the area of manufacturing are fulfilled. A mirroring or twinning of systems between what existed in real space to what existed in virtual space and vice versa becomes possible and meaningful. Using the emerging extensive simulation capabilities, it became feasible to perform realistic tests in a virtual environment. Furthermore, the overwhelming rise of artificial intelligence, primarily expressed by techniques such as Machine Learning, made a significant contribution to the further progress of the Digital Twin [4].

Following these technical advancements, manufacturing industry has broadly implemented Digital Twins in the past few years for specific tasks, for example, the monitoring and the predictive maintenance of long-lasting goods in service [5]. In this sense, the twinning of the existing physical environment has got a particular importance. This is an inherent issue of PLM how to acquire data of existing goods.

To acquire the necessary data of industrial or process plant, three approaches can be considered: (i) manual measurement and manual remastering, (ii) acquisition of geometry by a device (e.g., 3D scanner) followed by manual remastering, and (iii) acquisition of geometry by a device (e.g., 3D scanner, 360 degree camera) with a subsequent object recognition [6]. The latter provides the foundation of this paper.

The outline of the paper is as follows. In section 1, the background of the generation of a Digital Twin is introduced. In section 2, the process definition for object recognition in a process plant is explained. Results for a process plant are presented in section 3. Discussion of the challenges that still exist in the process domain is presented in section 4. The paper ends with a brief conclusion and outlook.

1. Background

Process engineering facilities are constantly being rescheduled and rebuilt in order to increase their productivity or to produce other products with them. They need regular maintenance. In addition, when carrying out incident analyzes, the authorities check whether they can be operated safely and evacuated.

Facilities are often bought and sold again without the entire know-how being handed over to the new owner. In many cases, the know-how is stored as expert knowledge in the heads of the operating and maintenance staff. It is lost when the staff retire or are replaced by employees from outside the companies who are not very familiar with the operation of the facility.

Therefore, there are many good reasons for operators to precisely record the actual status of their facilities. This actual status never exactly corresponds to the planning status. Already during the construction of the facility deviations appear and / or many details are not planned at all [7]. Therefore, many operators try to bundle the information on their existing facilities in a Digital Twin.

The Digital Twin is a virtual representation of a real existing facility. It can contain different information and have different users, depending on whether it is to support development, planning, assembly, production or service. The operators are faced with the question of how they can set up this digital substitute with a reasonable expenditure of time and money.

Driven by a tremendous development in area related to computer vision, a plethora of object recognition approaches and methods were developed recently for different purposes. Although photogrammetry still plays an important role, a trend to point cloud-based approaches is obvious which is the basis for object recognition algorithms. For industrial application with rough environmental conditions (dirt, smoke, darkness, dust, vibration), it looks like the best compromise between costs, accuracy, acquisition speed and robustness. A scanner can be used as a terrestrial and mobile device (carried by human, car, drone) [6]. More recently, promising approaches for use of consumer 360 degree cameras were developed. In order to prepare the point cloud for a feature-based process of planning and simulation, the objects it contains must first be recognized and a CAD-based structure must be created.

Here, the challenge is how to embed the object recognition in the process of virtual 3D layout planning in a built environment as well as which findings and results can be expected. Realistic 3D layout models need to be created using point clouds acquired by commercial devices and prepared for object recognition with methods of Artificial Intelligence (AI) considering the strict data quality requirements. The generic procedure, the assessment of the available object recognition frameworks and the solution approaches are described in the previous reports [8][9]. Seamless, robust, (semi-) automatic workflow of primarily standard, modular components with low user assistance is of particular interest in order to achieve high efficiency. A proper quality assessment and error handling is necessary to facilitate automation of the entire process [10]. Once a highly reliable CAD model of a plant is created, there are several options to transform and export it to further tools in order to generate a Digital Twin.

Due to their functional importance, pipelines are crucial structures in process plants. They consist of branched structures organized in dense and complex cylinder configurations. Although pipes are merely cylindrical primitives which can be easily defined by their axis and radius, they are often combined with additional components such as flanges, valves, inlets, elbows, tees, etc. 3D scanning and recognition of pipelines is challenging due to small pipe surfaces and their intricate structure causing large self-occlusions, missing parts and insufficient sampling [11].

2. Process definition

Complex procedures as described in previous research [8][9] usually are being controlled by appropriate workflow software. Prior of such an implementation, it must be defined how the process steps scan, object recognition and generation of Digital Twin (Figure 1) interact with each other [12]. Basically, that are tasks for different user profiles because the present technology does not provide the performance to collect entire functionality for generation of Digital Twin in one device (e. g. portable computer). The tasks scan, object recognition, design engineering (to provide the requested change) and process planning (generation of Digital Twin) can be seen functionally independently of each other; with data exchange among singular steps [13].

The object acquisition must be provided at the plant site by a device (scanner or camera, terrestrial or mobile) [14] and the raw data are transferred by a secure web connection or disk to the next instance which provides data processing (object recognition, feature recognition, translation). After the full data model of the plant was created, it is sent to the design and engineering which complete the required change of the process system. Finally, the data set ca be sent to the plant engineering to conclude simulation, adaption and optimization (Figure 1) [15].

While some steps must be done manually (point cloud preparation, noise filtering, outlier removal, feature extraction, and almost the entire training), the workflow has to ensure an automated execution of all remaining steps. This is in particular true for the most time-consuming steps: execution of segmentation and execution of object recognition. The flexible, modular handling of the object recognition framework must also be provided [16].

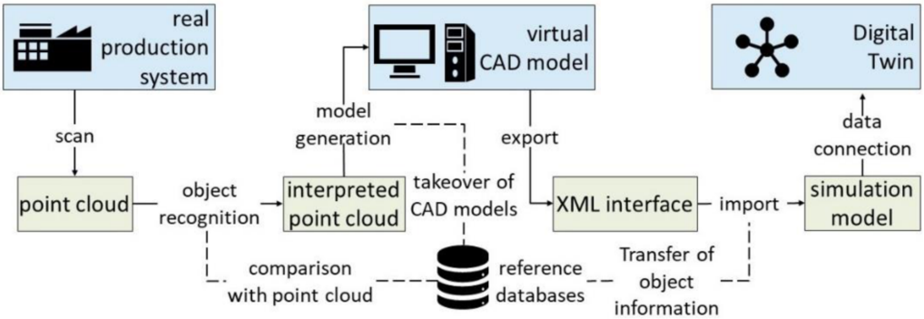

Figure 1. Workflow generation of Digital Twin [15].

The most manual work is expected on the segmentation of complex scenes which promises the highest rationalization potential, although no support from public directories can be expected [17]. A successful segmentation anticipated a reduction in data volume of point clouds with a factor of 1.000 and more between the rough point cloud and the segmented point cloud focused on segments for further processing can be achieved. During these manual steps, the model clean-up, the noise filtering and the outlier removal are conducted. The extraction of models and portions for training of recognition respectively segmentation occurs at this point of time. Finally, the point cloud must be exported in the desired format (e. g. e57) [18].

From this point on, the process runs automatically apart of training which is not mandatory for each data set [19]. Training is necessary in a sufficient extent to provide the test base for the later testing [20]. Mesh reconstruction and point cloud segmentation are implemented as separate utilities for the object recognition framework. To collect all automatic running steps, a user front-end was built. It controls the semantic segmentation, cluster extraction and cluster classification (recognition of singular objects). A viewer is included which allows the visualization of each intermediate result [21].

Segmentation is conducted manually or by supervised training which is preferred for complex scenes. The first issue is the preselection of smaller agglomerations in the entire point cloud which are assumed to contain an object. Such clusters can be covered by a bounding box like a packing box for a product in the right position and orientation. It helps in the assessment of results, too. The segmentation module is being trained to subdivide the entire scene in nine categories: roof, wall, floor, pipelines, structure, vessels, transport, auxiliary, and noise. For a process pant, pipelines, apparatus and connected devices are of a particular interest and can be considered separately [15].

Before the object recognition can start, the objects of interest must be available in the system library. Since they are usually not included in the standard database such as ModelNet, an additional reference library must be set up that contains the objects of interest. This is performed in two ways: either by using CAD models with a good data quality [22](e.g., vendor library) or exemplary point cloud models. To ensure the similar properties of both model types, CAD models are transformed in point clouds using a virtual scanner which is stochastically moved around the object.

Singular point clouds models must be further transformed in order to prepare an adequate input for object recognition procedures, depending on the object recognition framework used [9]. In case of the voxel-oriented framework, the point cloud must be translated into a corresponding voxel model. The side length of a voxel plays a significant role here. Tests have shown that a variable length which is related to the object shape provides the best results. Although the start model already has been simplified, a further simplification occurs during the translation to a voxel model which hardly can be prevented. If the simplification dilutes a local feature (e. g. an auxiliary device), then sufficient recognition results cannot be expected. Rather, it is to be feared that a wrong object will be recognized. Therefore, when building the sample models, care must be taken to ensure that the distinctive features are considered. In case of a pipe, the centerline and the radius are such distinctive features.

An exemplary procedure in three steps (segmentation, clustering, recognition of object in singular clusters) has been trained with up to 1000 epochs, the developed framework can be tested using real-life data extracted from the process plant.

3. Results

After the new integral DigiTwin tool was previously used for the generation of the Digital Twin in manufacturing [8], it was recently tested for a biogas plant located in north of Germany (Figure 2). In first case, an optimization of material flow was performed with the output of object recognition. The data of an existing biogas plant were necessary for training, operation, maintenance, and reconstruction.

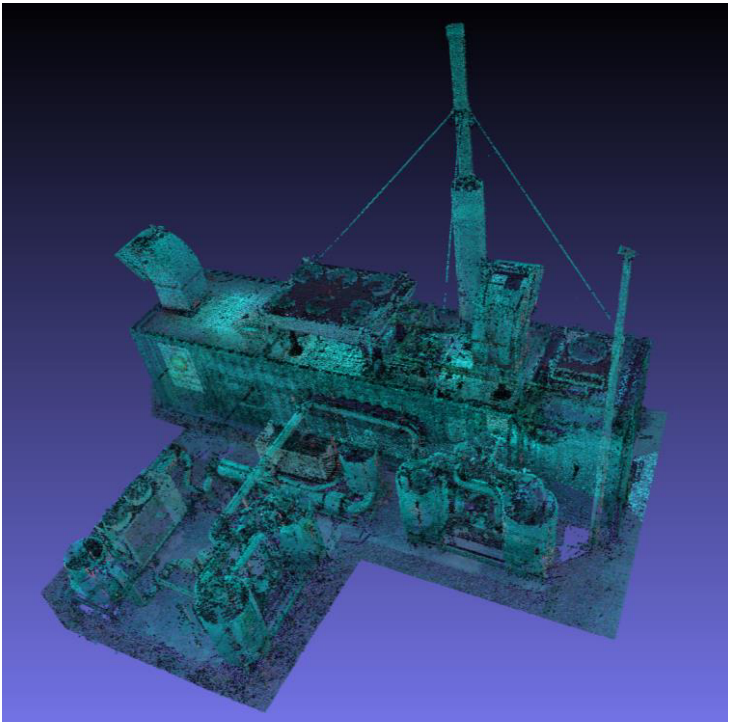

Figure 2. Biogas plant scanned with different devices.

With regard to virtual training, maintenance or operation of a system, the topic of virtual reality becomes decisive. It must be concurrently fed by data. This is usually not a problem for new systems, as a later virtual operation can be included in the planning of the system. The as-designed models can be linked with piping diagrams and then enriched with sensor data from the system. For already existing systems, 3D models, if available, are often obsolete due to maintenance work, repairs or modernization activities and can no longer be used for the use of virtual applications. The effort to create a suitable 3D model is associated with great effort and correspondingly cost-intensive.

In all industrial cases, the object recognition of objects available in the library was of the particular importance. The models were manually prepared and put in the tool chain as described in the previous section. The overall recognition rate is high, although the environmental impact often was negative. As a rule, more than 75 percent of all objects can be truly recognized. However, the recognition procedure is sensitive and needs to be stabilized. Provision of bounding boxes for singular objects of interest is helpful for repair of missing and wrong oriented objects.

In order to verify this approach for the recognition of pipelines, experiments with the point cloud from the plant construction (biogas plant) have been conducted. This method is only based on the registered industrial point cloud itself regardless of the varying point densities [13]. Such industrial point clouds may contain defects such as occlusions and sparseness. In total, the results were acceptable, but disparate in detail. Good results were achieved in the segmentation phase automatically and robustly. Pipeline easily can be separated from the remaining components of a plant. In highly dense industrial spaces, class segmentation of cylinders, I-beams and valves that have easily distinguishable geometric patterns in the processing unit, warehouse and cranes work well.

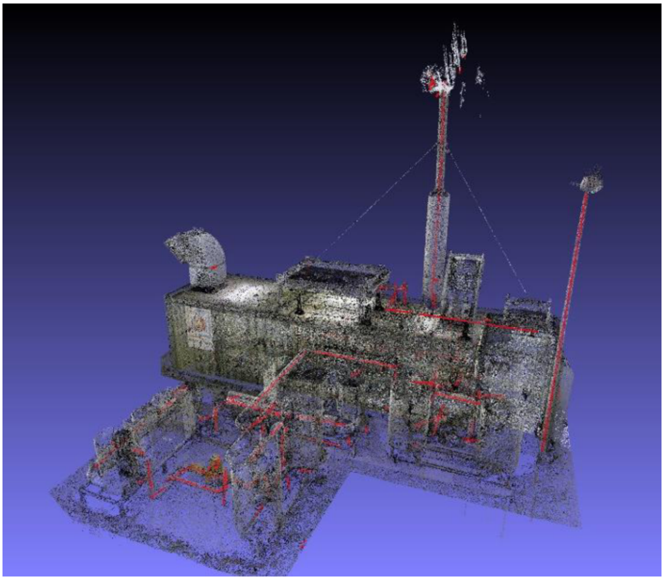

Figure 3. Results of the object recognition in a biogas plant.

The focus of a biogas plant lies in the recognition of the pipelines including their semantics (Figure 3). For this task, a specific extension of the object recognition framework was developed. The process step segmentation runs as previously described.

The step clustering consists of the identification of the singular pipe segments which are subsequently added to pipelines. By detection of the corresponding pipe radius, the centerline of the pipeline can be derived. If all segments and control elements (flanges, valves, inlets, elbows, tees etc.) can be found, the pipeline can be completed. The integration of PI&D diagram which is a pre-requisite for a operating license is not performed in this stage yet.

Figure 2 shows the point cloud model of the entire biogas plant which was obtained by scans from different devices with a total volume of 57 GB for the entire scan project. Such package is difficult to handle and cannot be used as an active environment in the conventional CAD systems. Portions of such point cloud can be imported as passive environment.

Figure 3 shows the extracted pipeline with its recognized centerlines and pipe radius respectively which would be subject of redesign and optimization. Worth to note, that the entire data volume was reduced from 57 GB for the entire plant to only 22 MB for the pipeline. These intermediate results provide a good basis for design work on reconstruction and optimization since leading CAD systems can easily handle a smaller amount of point cloud models. This outcome is obtained in a neutral format and can be exported to each proprietary CAD format for further design work. Most issues occur on elbows which are often recognized in a false orientation. Therefore, the additional object recognition algorithms were necessary.

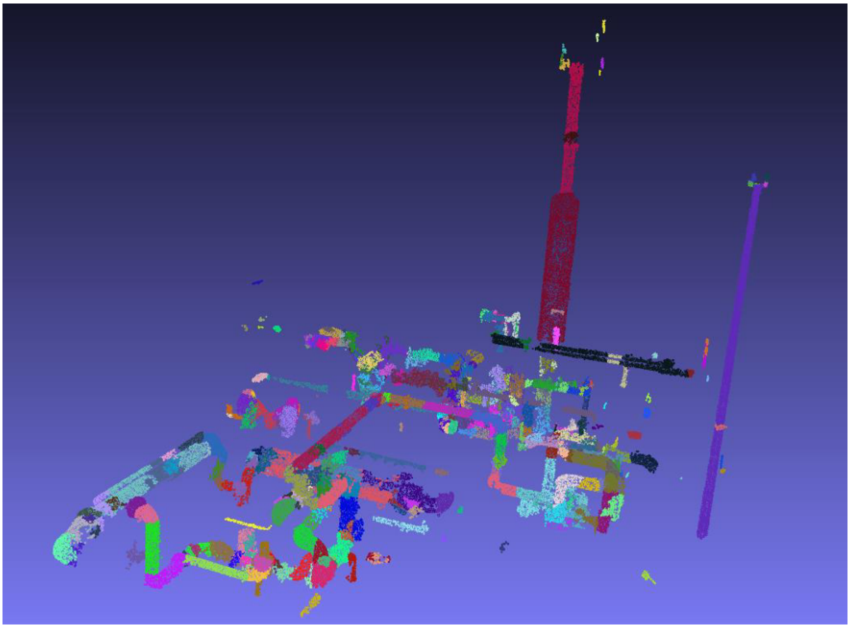

Figure 4. Recognition of singular pipeline segments.

Figure 4 sets the focus on sigular pipe segments which are marked in distinctive colors. However, a principal distinction between a pipe and an apparatus which can have an identical cylindrical shape must be done in a specific case. The recognition of all segments, devices and apparatus is the pre-requisite for the recognition of the pipeline semantics.

4. Discussion

The successful generation of Digital Twin paves the way for a full digitalization of the process plants. Although there is still no legal requirement in many countries, a 3D model of the plant is an important aid in development, production and operation of a plant. The approach presented here is capable to deal with complex real-world industrial facilities, such as highly dense biogas plant. Assuming that a searched object is known, either in the publicly available or in the private library, there is a high probability that it will be recognized in the correct position and orientation. The distance deviation of the absolute position in space is acceptable for this purpose since it remains in the tolerance range known from literature [13]. Manual rework in a small extent can be always expected for each data set, indeed.

Based on these tests, several improvements must be taken into account for the next development steps:

- The huge amount of input data could be significantly reduced by a better scanning procedure, if constructional domain knowledge can be used for this purpose. That could be achieved by a pre-scan of objects of interest as known from autonomous driving. The camera-based approach is especially promising [6].
- By using low-cost devices (e. g. augmented reality glasses, 360-degree camera), the usability and the acquisition speed could be improved and the costs reduced. This would prevent the impact of occlusion. However, the concern of the low position accuracy still remains [6].
- The final results could be improved by extension of the object library, for example by a blend with further libraries (CAD standard part libraries). Industry circles and associations could provide their data.
- The recognition of pipelines in fully variety needs to be considered. The pipe classification is noisy and should be reinforced by robust clustering and graph-based aggregation techniques to compute a coherent pipe model [23].
- While the training requires so much effort, its automation would drastically reduce the processing time and increase the overall efficiency.
- Integration of P&ID drawings and non-geometrical information would improve the confidence and the acceptance by the regulatory bodies.
- While the object recognition basically is a probability calculation, it needs an extensive and quantitative comparative performance evaluation in order to meet the requirements from the industry.

The commercial use of the described procedure and tool for generation of Digital Twin is provided by the portal OpenDESC.com which is in service for 23 years. It provides service for transfer and translation of the auxiliary data (primarily CAD) in the industrial supply chains. It offers services globally and is used by more of 100 customers located worldwide [24].

A deployment schema for generation of Digital Twin is depicted in Figure 5 as a collaborative procedure where the tasks scan, object recognition and process planning/layout design are undertaken by different teams. The scan is conducted on the customer's premise, either by customer or a service provider. Then point cloud data are sent to OpenDESC.com where object recognition is done as described in section 2. Results can be transmitted to the plant engineering / process planning where the Digital Twin will be finally completed.

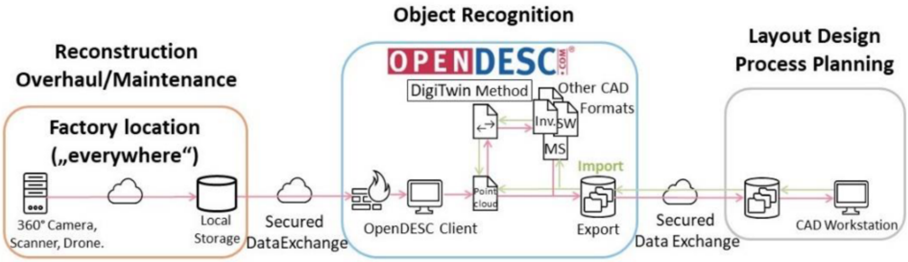

Figure 5. Workflow for generation of Digital Twin as a service.

5. Conclusions and outlook

The affordability of object reconstruction with semantic enrichment needs to be primarily justified in terms of cost-benefit [25] in comparison with the manual acquisition. If the object recognition as shown here in an use case from the biochemical industry is successful, the justification is easy. However, the drawbacks must be considered to prevent a use case with no recognition (e. g., on significant occlusion which cannot be compensated). Theoretically, in highly dense industrial spaces data acquisition could be made impossible both by a missing accessibility though the acquisition device and the poor recognition caused by incomplete point cloud and occlusion [26]. Therefore, such obstacles can only be resolved by an incremental scanning (e. g. by a highly flexible mobile device which can access each segment of a plant) [27].

Because the Digital Twin is subject to frequent changes, the question arises of how its consecutive updates (e. g. replacement for an apparatus in a larger hall) can be conducted without restraint to repeat the entire process described above [28]. A simple procedure need to be developed in which the user company is enabled to undertake the initial part of the update process itself. For this purpose, an application is being developed with which the partial spaces of the hall to be updated in the Digital Twin can be scanned using the camera of a standard smartphone. The application will guide the user during the recording process, so that handling can be carried out quickly and easily. The scan recorded with the application is further processed automatically to a high degree and the Digital Twin is updated. With the extension of the object recognition for the part of a model to be developed, the existing Digital Twin is analysed and changes are automatically overlayed.

References

[1] C.K. Lo, C.H. Chen, R.Y. Zhong, A review of digital twin in product design and development, *Advanced Engineering Informatics*, Vol. 48, 2021, 101297.

[2] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, W. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, Vol. 7, 2018, pp. 753-762.

[3] C. Zhang, Y. Chen, A Review of Research Relevant to the Emerging Industry Trends: Industry 4.0, IoT, Blockchain, and Business Analytics, *Journal of Industrial Integration and Management*, 2020, Vol. 5, No. 1, pp. 165–180.

[4] R. Wallis, J. Stjepandić, S. Rulhoff, F. Stromberger, J. Deuse, Intelligent utilization of digital manufacturing data in modern product emergence processes, *Advances in Transdisciplinary Engineering*, Vol. 1, 2014, pp. 261-270.

[5] Y. Wang, S. Wang, B. Yang, L. Zhu, F. Liu, Big data driven Hierarchical Digital Twin Predictive Remanufacturing paradigm: Architecture, control mechanism, application scenario and benefits, *Journal of Cleaner Production*, 2020, Vol. 248, 119299.
[6] M. Sommer, K. Seiffert, Scan Methods and Tools for Reconstruction of Built Environments as Basis for Digital Twins, in J. Stjepandić et al. (eds.) *DigiTwin: An Approach for Production Process Optimization in a Built Environment*, Springer Nature, 2021, in press.
[7] Z. Pučko, N. Šuman, D. Rebolj, Automated continuous construction progress monitoring using multiple workplace real time 3D scans, *Advanced Engineering Informatics*, Vol. 38, 2018, pp. 28–40.
[8] M. Sommer, J. Stjepandić, S. Stobrawa and M. von Soden, Automatic Generation of Digital Twin Based on Scanning and Object Recognition, *Advances in Transdisciplinary Engineering*, Vol. 10, 2019, pp. 645-654.
[9] B. Salem, J. Stjepandić and S. Stobrawa, Assessment of Methods for Industrial Indoor Object Recognition, *Advances in Transdisciplinary Engineering*, Vol. 10, 2019, pp. 390-399.
[10] L. Wagner, Kein Digital Twin ohne digitale Durchgängigkeit. *Zeitschrift für den wirtschaftlichen Fabrikbetrieb*, 2020, Band 115, pp. 43-45, DOI: 10.3139/104.112315.
[11] L. Cheng, Z. Wei, M. Sun, S. Xin, A. Sharf, Y. Li, B. Chen, C. Tu, DeepPipes: Learning 3D pipelines reconstruction from point clouds, *Graphical Models*, 2020, Vol. 111, 101079.
[12] O. Kuhn, H. Liese and J. Stjepandic, Methodology for knowledge-based engineering template update, *IFIP Advances in Information and Communication Technology,* Vol. 355, Springer, Berlin Heidelberg, 2011, pp. 178-191.
[13] Z. Ma, S. Liu, A review of 3D reconstruction techniques in civil engineering and their applications, *Advanced Engineering Informatics*, Vol. 37, 2018, pp. 163–174.
[14] D. Moon, S. Chung, S. Kwon, J. Seo, J. Shin, Comparison and utilization of point cloud generated from photogrammetry and laser scanning: 3D world model for smart heavy equipment planning, *Automation in Construction*, Vol. 98, 2019, pp. 322–331.
[15] J. Stjepandić, M. Sommer, Object Recognition Methods in a Built Environment, in J. Stjepandić et al. (eds.) *DigiTwin: An Approach for Production Process Optimization in a Built Environment*, Springer Nature, 2021, in press.
[16] E. Ostrosi, J. Stjepandić, S. Fukuda and M. Kurth, Modularity: New trends for product platform strategy support in concurrent engineering, *Adv. in Transdisciplinary Engineering*, 2014, Vol. 1, pp. 414-423.
[17] E. Agapaki, I. Brilakis, CLOI-NET: Class segmentation of industrial facilities' point cloud datasets, *Advanced Engineering Informatics*, 2020, Vol. 45, 101121.
[18] J. Stjepandić, S. Bondar, W. Korol, Object Recognition Findings in a Built Environment, in J. Stjepandić et al. (eds.) *DigiTwin: An Approach for Production Process Optimization in a Built Environment*, Springer Nature, 2021, in press.
[19] K. Kawashima, S. Kanai and H. Date, As-built modeling of piping system from terrestrial laser-scanned point clouds using normal-based region growing, *Journal of Computational Design and Engineering*, Vol. 1, 2013, pp. 13-26.
[20] T. Czerniawski, F. Leite, Automated digital modeling of existing buildings: A review of visual object recognition methods, *Automation in Construction*, 2020, Vol. 113, 103131.
[21] C. Emmer, A. Fröhlich and J. Stjepandić, Advanced engineering visualization with standardized 3D formats, *IFIP Advances in Information and Communication Technology*, Vol. 409, Springer, Berlin Heidelberg, 2013, pp. 584-595.
[22] S. Bondar, C. Ruppert, J. Stjepandić, Ensuring data quality beyond change management in virtual enterprise, *International Journal of Agile Systems and Management*, 2014, Vol. 7, Nos. 3/4, pp. 304–323.
[23] R. Maalek, D.D. Lichti, R. Walker, A. Bhavnani, J.Y. Ruwanpura, Extraction of pipes and flanges from point clouds for automated verification of pre-fabricated modules in oil and gas refinery projects, *Automation in Construction*, 2019, Vol. 103, pp. 150–167
[24] S. Bondar, L. Potjewijd, J. Stjepandić, Globalized OEM and tier-1 processes at SKF, in: J. Stjepandić et al. (eds.) *Advanced Concurrent Engineering*, Springer-Verlag, London, 2012, pp. 789-800.
[25] C.T. Li, J.C.P. Cheng, K. Chen, Top 10 technologies for indoor positioning on construction sites, *Automation in Construction*, 2020, Vol. 118, 103309.
[26] A. Garcia-Garcia, J. Garcia-Rodriguez, S. Orts-Escolano, S. Oprea, F. Gomez-Donoso, M. Cazorla, A study of the effect of noise and occlusion on the accuracy of convolutional neural networks applied to 3D object recognition, *Computer Vision and Image Understanding*, 164, 2017, pp. 124-134.
[27] S. Bondar, B. Salem, J. Stjepandić, Indoor Object Reconstruction based on Acquisition by Low-cost Devices, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 113-122.
[28] Stjepandić, J., Sommer, M., Stobrawa, S.: Digital Twin: Conclusion and Future Perspectives, in J. Stjepandić et al. (eds.) *DigiTwin: An Approach for Production Process Optimization in a Built Environment*, Springer Nature, 2021, in press.

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Logo Image Retrievals Using Deep Embedding Learning

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Abstract. A logo is s graphical emblem or mark used as an identification for a company and its products and services. Logos are legally protected as intellectual properties (IPs) if registered as trademarks (TMs). Logos™ are widely distributed online nowadays in the digital economy. Due to their wide distributions online, the constant checking of TM legal usages becomes extremely challenging in the TM registration and protection system. The fact that users can easily imitate the registered TM logo designs casts serious IP legal issue, which highlights the importance of developing an automatic logo image retrieval system. Considering the complexity of TM visual semantics, this research proposes a deep embedding learning for logo image similarity analysis using triplet-network. We propose the optimization of sampling parameters to improve the TM image retrieval performance with robust model. The research aims to reduce discrepancy between human visual interpretation. This transdisciplinary engineering research incorporates deep learning (DL) modeling and TM legal analysis for image-centric TM protection. To demonstrate the model performance, more than 10,000 images for model training and 3000 images for model testing are adopted from Logo-2K+ database. Image retrieval performance shows excellent results with recall@10 exceeding 93%.

Keywords. Image retrieval, triplet network, deep embedding learning, trademark similarity analysis, trademark infringement, transdisciplinary engineering

Introduction

With well exceeding 10 million global TM registrations per year [1], TM management and protection become challenging tasks for all IP authorities world-wide. Nowadays, although with some computer supporting systems, the world intellectual property organization (WIPO) and individual country IP offices still relies on TM examiners to check Vienna classifications to ensure no duplicated or deceptively similar TMs are registered in the IP legal system [2]. Thus, it takes a long time for the examiners to complete the registration review. TM examiners spend most of their time searching for similar TMs through the system. The examination of TM patterns tends to be subjective and can lead to inconsistencies of similarity judgement based on different subjective

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views of the examiners [3][4]. Thus, computer-supported (or automatic) TM image retrieval systems become vital and indispensable.

Nowadays, machine learning (ML) methods show remarkable performances in the field of smart image retrievals, image classifications, and picturesque feature detections. However, there are still many challenges and issues while solving problems with transdisciplinary nature, e.g., the needs of TM legal/law knowledge for the ML modeling of logo^{TM} image retrievals. When the ML predictive modeling without taking TM legal characteristics into consideration, the performance of the TM similarity analysis will be largely weakened [5]. Thus, the logo^{TM} image retrieval system can fully support the accurate analysis of both TM registration/examination and TM fair use (law) judgement.

The logo^{TM} retrieval system is based on the geometric figures and visual semantics of logo designs, which can provide key information on the similarity matching of logo images, especially during the initial TM examination [6] and, also, the online logo^{TM} infringement investigation. To enhance model training efficiency and accuracy, this research adopts the pre-trained convolution neural network on the large-scale dataset and then perform fine-tuning on the small TM logo dataset. In this research, we use the VGG19 pre-trained model as the backbone from the Keras application which uses the training data from ImageNet [7]. During the model training, we construct a triplet network and improve the algorithm for selecting samples to form triplet samples. Triplet loss function is used to measure the different between the target and the predicted scalar. The model can use the loss function for back-propagating the gradient calculations. Finally, gradient descent approach is used to update the parameters of the model classifiers. In addition to the high accuracy of the logo image retrieval results, the similarity analysis can also be performed at different semantic levels.

In section 1, we discuss the literature review of image retrieval technology in recent years. Section 2 introduces the logo similarity analysis (deep learning) modeling framework and the model fine-tuning methodology. Section 3 presents the neural model verification and shows the experimental performance of the model application. Section 4 draws the conclusions.

1. Literature review

Nowadays, search engines commonly used on Internet platforms are based on keywords. In the process of keywords searching, the retrieval system uses text-based to retrieve some images or files in the database that are already labeled with specific text or some descriptions [8]. The retrieval algorithm uses text mining to analyze the similarity between keywords and tagged text. However, text-based image retrieval is not based on image features to match but uses manual labeling methods to match [9].

With the growth of ML methods in recent years, many studies focused on Content-based image retrieval (CBIR). CBIR is a method of extracting image features and transforming these visual features into specific mathematical vectors or matrices for further analysis. In the CBIR system architecture, query image is mainly used for image retrieval tasks. The system converts the query image input by the user into feature vectors that can express visual meaning and analyzes the similarity between these feature vectors and the images in the database. This study summarized the literature review of image retrieval technology in recent years into two main parts. The first part is traditional ML methods, which focuses on the low-level features of the image in the retrieval image features, including color, shape, texture or spatial layout. The other part of image retrieval technology uses DL methods to extract image features. Some studies have shown that DL methods can extract more semantic visual concepts and save more time in algorithm performance than traditional ML methods [10][11]. In section 1.1, we introduce the application of traditional ML algorithms in the field of image retrieval. Section 1.2 introduces the development of DL in image retrieval technology.

1.1 Traditional machine learning methods

In traditional ML methods, the low-level features of images are mainly captured such as color, shape and texture. This subsection introduces the image retrieval performance of different specific mathematical models in the image retrieval literature.

Color histogram is based on statistical analysis method to measure the similarity analysis of images. Using a histogram to represent the color feature distribution in the overall image, this method can effectively represent the multi-type feature distribution but has the limitation of rotation invariance [12]. Since color information is less sensitive to changes in directionality and size, the use of color histogram analysis is relatively lacking in the local feature analysis of the image [13]. Color is an important feature information for image similarity analysis. Some studies have successfully used color distribution to extract image features for matching, which can extract image color distribution, image contrast and pixel brightness distribution [14].

Texture features can also convey important image information in image feature retrieval. Local binary patterns (LBP) are proposed by Ojala of Oulu University in Finland, which is a feature description method using regional texture changes [15]. In many practices, the advantage of the local binary pattern algorithm is that it can effectively extract image texture information. Liu et al. pointed out that LBP algorithm is weak in color feature extraction in image retrieval tasks. Therefore, a method of fusing LBP and color information feature (CIF) method is proposed to solve the problem of image classification and retrieval problem [16]. LBP was first used for texture analysis and is very effective for face recognition, expression recognition, multimedia searches, and motion analysis.

Zhou et al. purposed a collaborative index embedding to unifying index of SIFT feature and the deep convolution neural network for IR task. To show the neighborhood embedding with integrated SIFT feature and CNN feature, the index embedding algorithm will continue to update the index file of CNN and SIFT features. The indexes that are close in the SIFT space will be pulled closer in the CNN feature space. The improved CNN index output shows a significant improvement in retrieval accuracy, which is more than 10% higher than the original CNN and SIFT index [17].

1.2 Few-shot learning

Few-shot learning is a method of making predictions based on a limited number of samples. Different from standard supervised learning, few-shot learning can recognize a category that is not included in the training set [18]. In this research scope, we introduce two popular network architectures: Siamese network and Triplet network. These two simple networks can calculate similarities or distances between images in the feature space and thereby solve few-shot learning task.

Siamese Network is mainly constructed by two CNN networks. Siamese network uses paired samples to create similar and dissimilar image pairs through the binary labels and fine-tuning the model parameters through contrastive loss [19]. Some studies are focus on improving the architecture of SNN and the method of selecting training samples

[19][20]. Appalaraju et al. proposed an improvement in the method of selecting negative samples in the training model [21]. In the initial stage of model training, the easy negative sample that are easy to learn from the model should be selected, and as the training epoch increases, the hard-negative samples that are difficult to learn from the model will increase.

Triplet neural network is mainly constructed by three CNN networks. Through the Triplet loss function, images feature in the vector space strive to reduce the distance between the similar images and increase the distance between dissimilar images [22]. Wu et al. research team pointed out the importance of sampling methods in deep embedding learning and improved the original triplet loss function. In the sampling method, distance weighted sampling is proposed, which considers that each sample point in the feature space is uniformly distributed in a hypersphere space. At the same time, the distance-weighted sampling method is used to improve the effective samples for training [23]. Lan et al. research mainly compares the performance of traditional ML methods and deep learning-based methods on TM feature learning. The experimental results show that the DL method has a good performance in TM retrieval, and also shows the Triplet neural network has a better performance [24]. Min et al. constructs more complex Triplet network architecture and trained it via simultaneously optimizing the triplet loss and softmax loss during model training [25]. Veit et al. constructs Conditional Similarity Networks to learn semantic features defined by human concept during machine training [26]. Embed different semantic features into different subspaces for model similarity learning.

Compared with traditional ML methods, few-shot learning with deep embedding learning is no longer restricted to the color, shape and texture of the picture, and it can extract more semantic features in the deep neural network architecture. This research adopts the architecture of triplet network as the original logo similarity analysis DL model framework. By reorganizing data samples and improved sample selection algorithm, different visual concepts can be used to analyze the model when analysis the similarity of different logos.

2. Research methodology

Figure 1 shows the architecture diagram of the system constructed in this research. In the framework, it can be divided into three stages: pre-processing stage, training stage, testing stage and the process of model similarity analysis. The framework process at each stage will be introduced in detail in the following sections.

2.1 The pre-processing stage

In the pre-processing stage, this research includes two parts, the first part is to introduce the pre-training backbone of the neural model, and the second is how this research pre-process the TM dataset for model fine-tuning. This research imports the pre-trained CNN model from the Keras application which uses the training data from ImageNet [7]. In the CNN model architecture, three new classifiers are added, including a flatten layer, one dense layer with 512 units and output shape 512 units with L2 Norm regularizer. To improve the performance of model convergence, we add kernel initialization and regularization parameters in dense layer.

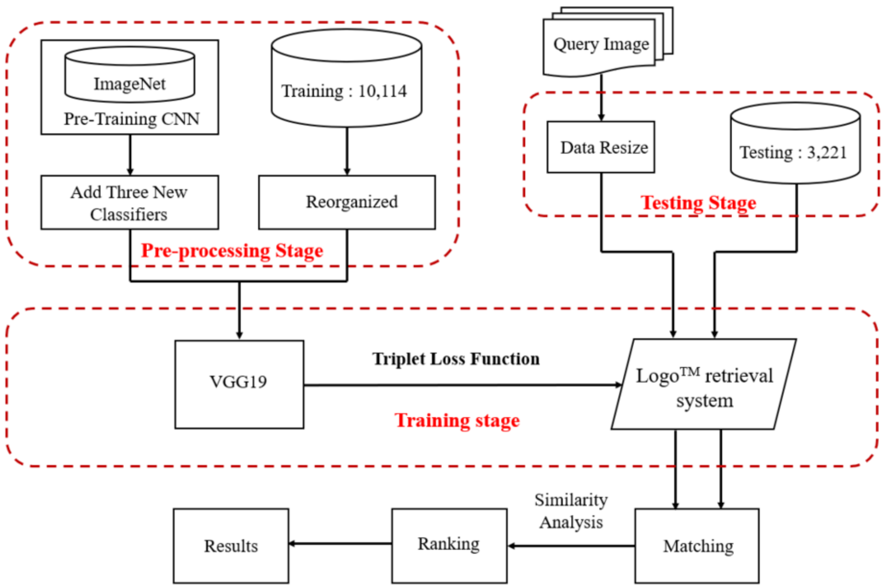

Figure 1. The framework of logo similarity prediction system.

We adopted the Logo 2K+ dataset as this research training and testing dataset. The Logo 2K+ contains 167,140 images with 10 root categories, which further sub-classified onto 2,341 company logo categories [27]. Since this research focuses on the similarity learning of geometric pattern features, we select some suitable data from Logo 2K+ as the model training and testing data set. We select TM logos with obvious similar features and clean backgrounds in the Logo 2K+ dataset as the reorganize dataset for this study. In the Logo 2K+ dataset, even in the same category, there are still some mixed company TM logos. This research follows several rules in selecting and excluding each category of TMs: (1) We choose a clean background with obvious characteristics (Figure 2). (2) Delete distortion, blur, and patterns that are too small. (3) Delete pictures with the same letters but different fonts or styles (Figure 3). (4) Select geometrically similar TM patterns in each category. The total number of TM logo reorganized in this study is 13,335 (10,114 for training, and 3,221 for testing).

Figure 2. Logos in the same category must be able to clearly show the main geometric features.

Figure 3. The TM logos belong to the same category in Logo 2K+ dataset, their geometric characteristics may be different.

2.2 Training stage of the similarity prediction model

In the training stage, this study adopts a triple network training model to learn the similarities between TM logo features. In the triple network architecture, the input channels of the model are anchor, positive, and negative three logos, in which anchor and positive are logos of the same category, and negative are the logos of different categories. The image extracts feature vectors through a pre-trained model and output the feature vectors from three new classifiers. The feature vectors of these three outputs are expressed in the feature space R^d with nonlinear f(x). Having three feature vectors, including f(a) (Anchor), f(p) (Positive) and f(n) (Negative), we can further calculate the Euclidean distance between each vector. The algorithm calculates the Euclidean distance between the two feature vectors f(a) and f(p) shown in D (f(a), f(p)) = $\|f(a) - f(p)\|_2^2$. Another distance between the two feature vectors f(a) and f(n) is shown in D (f(a), f(n)) = $\|f(a) - f(n)\|_2^2$. Further, we can use these distance values to calculate the triplet loss function (Eqn. 1). The model implements the triplet loss function to back propagation for calculating the gradients. Finally, use gradient descent to update the model parameters. Triplet loss function is to encourage the distance between feature vectors of the same category in the feature vector space to be minimized and maximizing the distance between images of different categories. Finally, the hyperparameter "Margin" is set to determine whether the positive sample and the negative sample can be distinguished in the feature vector space.

$$\mathrm{L} = \mathrm{Max}\{D\ (\mathrm{f(a)}, \mathrm{f(p)}) + \mathrm{Margin} - \ \mathrm{D}\ (\mathrm{f(a)}, \mathrm{f(n)}), 0\} \qquad (1)$$

2.3 Triplet sampling strategy for model fine-tuning

Selecting valid triplet samples will improve the performance of the training model. In this research positive sampling, we select the sample with semi-hard positive which the distance between anchor and positive is greater than the average distance of the same category. The positive sampling satisfies Eqn. 2's condition, where "p" is the number of positive samples, M(a) as the dataset with the same category as anchor "a" and f(a) and i(a) denote feature vectors.

$$D(\mathrm{f(a)}, \mathrm{f(p)}) > \frac{\sum_{i \epsilon M(a)} \|f(a) - i(a)\|_2}{p} \qquad (2)$$

In negative sampling, it can be divided it into three cases including easy negative, hard negative and semi-hard negative. In easy negative situation, the model can easily distinguish between positive and negative samples, which is less helpful for model training. Hard negative sample is also difficult for the human visual to distinguish the difference between negative and anchor, and it is more difficult for model training. Selecting too many "hard negative" samples will make the model's generalization ability poor and cause the loss function difficult to converge. "Semi-hard negative" is a better interval for model training and more stable in the similarity learning. In the negative sampling strategy, first select the semi-hard negative that satisfies Eqn. 3's condition. If the first condition is not met, then we select the hard negative that satisfies Eqn. 4's condition. In Eqn. 3 and Eqn. 4, "margin" is a positive value, which defines the distance boundary between the anchor and samples.

$$D(f(a), f(p)) < D(\mathrm{f(a)}, \mathrm{f(n)}) < D(f(a), f(p)) + margin \quad (3)$$

$$D(\mathrm{f(a)}, \mathrm{f(n)}) < D(f(a), f(p)) < D(f(a), f(p)) + margin \quad (4)$$

This research sets the margin value based on the selected sample category. In the setting of the "margin", the study found that the similarity distance between the mini batch (each category) and the anchor category will be different for different categories. Therefore, the margin settings of different categories are dynamically adjusted during the negative sampling. The margin setting is the average distance of negative sample categories minus the average distance of positive samples, which show in Eqn. 5. Where "n" is the number of negative samples, "p" is the number of positive samples and N(a) is the dataset that the mini batch from anchor's category. In section 3.1, we present the performance of different sampling strategies on the triplet network model. The experimental results show that the positive sample and negative sample selection methods designed by this research perform best for TM pattern similarity learning.

$$Margin = \frac{\sum_{j \epsilon N(a)} \|f(a) - j(a)\|_2}{n} - \frac{\sum_{i \epsilon M(a)} \|f(a) - i(a)\|_2}{p} \quad (5)$$

3. Experiments

In this study, the standard Recall@K [28] metric is used to measure the logo^{TM} image retrieval system performance. Recall@K can be defined as: According to Top-K ranking results based on the similarity of a given query image, if at least one image of the same category is retrieved by the model, the recall value is 1. Otherwise, the recall value is 0.

This research constructs the neural model using Tensorflow environment [29]. The hyperparameters of the model include: batch-size (256), number of training epochs (100), input image resolution (224 × 224 pixels), triplet loss margin threshold (1.0). ADAM is the solver for optimization [30]. In the learning rate, we adopted a learning schedule. The learning rate is 0.01 in the first 15 epochs, and then the learning rate is multiplied by 0.1 every ten epochs.

3.1 Sampling strategies

In the experiment of the negative sample margin setting, there are two settings including constant margin (first three rows) and a "average margin" (last three rows) for comparison which is shown in Table 1. In positive sampling, we compare three strategies: Easy Positive, Semi Hard Positive, and Hard Positive. Easy Positive (EP) is to select the positive sample that is closest to the anchor in the feature vector space among the same category. The margin setting of the Semi-hard Positive (SP) sampling strategy depends on the average distance of the same category. The SP sampling condition is defined as Eqn. 2 which is shown in Section 2.3. In hard positive (HP) sampling strategy, the algorithm selects the farthest sample as the positive sample in the same category. In the HP strategy, the samples for model training are focused on samples that are difficult to identify, and it will increase the difficulty of model convergence. Three sampling methods can be listed as "Easy positive and Semi-hard Negative" (EPSN), "Semi-hard Positive and Semi-hard Negative" (SPSN), "Hard Positive and Semi-hard Negative" (HPSN). And we also compare with semi-hard negative sampling with constant margin which the constant value is 0.5. Three constant margin methods can be listed as "Easy positive and Constant negative" (EPCN), "Semi-hard Positive and Constant Negative" (SPCN), "Hard Positive and Constant Negative" (HPCN).

Table 1. Model verification in positive sampling margin settings.

	Top-1		Top-5		Top-10	
Sampling Methods	mAP	Recall@1	mAP	Recall@5	mAP	Recall@10
EPCN	0.77	0.80	0.72	0.85	0.69	0.83
SPCN	0.76	0.79	0.75	0.85	0.73	0.88
HPCN	0.70	0.75	0.69	0.77	0.72	0.86
EPSN	0.79	0.81	0.74	0.85	0.73	0.89
SPSN	**0.82**	**0.84**	**0.81**	**0.89**	**0.77**	**0.93**
HPSN	0.70	0.73	0.70	0.83	0.67	0.87

From the experimental data results in Table 1, the SHSN sampling algorithm has well performance in all the retrieving results. This study proposes methods for optimizing positive and negative sample selection strategies and observes the changes in model effects in different strategies.

3.2 Evaluation results

Table 2 presents the results of the logo similarity predictions. The first column in Table 2 is query image, and the following five columns are the retrieval results of the model and the distance similarity presented above each TM logo. We can see that when the similarity distance calculated by the model is less than 0.5, it can be said that it is directly similar to the overall appearance of the query image. For the case where the similarity distance is greater than 0.5, it can be known that some features are indirectly similar to the query image. Some factors that can cause bias in the logo^{TM} image retrieval system results are: color changes, background noise, and image clarity.

4. Conclusion

Based on the triplet network architecture, we built a deep neural network model focusing on the learning of multi-concept similarity of TM patterns. The contribution of the logo^{TM} image retrieval system in this research is to optimize the network parameters and improve the sampling strategy based on the similarity learning of TM features in the existing triplet network architecture. In the verification, the parameter optimization, based on SPSN, yields the best performance in learning the similarity of TM features. In addition to improving the retrieval accuracy of the model, the distance analyzed in the logo^{TM} image retrieval system can also be used to determine whether there is visual semantic similarity. The model trained and tested in this research provides the computer supported inspection for accurate and efficient TM registration and protection processes.

Table 2. The logo™ image retrieval system experiment results.

0.0	0.5	0.591	0.596	0.62	0.63
0.0	0.64	0.65	0.69	0.71	0.73
0.0	0.39	0.51	0.61	0.67	0.67
0.0	0.11	0.39	0.68	0.71	0.73
0.0	0.38	0.50	0.55	0.58	0.63

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References

[1] WIPO, 2019, *World Intellectual Property Indicators 2019: World Intellectual Property Organization.* [Online]. Available: https://www.wipo.int/publications/en/details.jsp?id=4464/

[2] J. Schietse, J.P. Eakins and R.C. Veltkamp, Practice and challenges in trademark image retrieval, *Proceedings of the 6th ACM international conference on Image and video retrieval*, 2007, pp. 518-524.

[3] M.D. Frakes and M.F. Wasserman, Are There as Many Trademark Offices as Trademark Examiners? 2020, *Duke Law Journal,* 69, 1807-1853.

[4] J.T. McCarthy, *McCarthy on Trademarks and Unfair Competition*, 5th ed, Thomson West, Deerfield, 2020.

[5] S. McJohn and I. McJohn, Fair Use and Machine Learning, *Northeastern University Law Review, Forthcoming*, 2019, https://ssrn.com/abstract=3406283, Accessed: July, 3 2021.

[6] Kinney and Lange, P. A., *Intellectual Property Law for Business Lawyers,* Thomson West, Eagan, 2020.

[7] C. François, Keras, 2019, Accessed: 30.05.2019. [Online]. *Avaiable: https://keras.io/*

[8] S. Yang, L. Li, S. Wang, W. Zhang, Q. Huang, and Q. Tian, Skeletonnet: A hybrid network with a skeleton-embedding process for multi-view image representation learning, *IEEE Transactions on Multimedia,* 2019, 21(11), pp. 2916-2929.

[9] A. Amelio, A new axiomatic methodology for the image similarity, *Applied Soft Computing*, 2019, Vol. 81, 105474.

[10] U. Markowska-Kaczmar and H. Kwaśnicka, Deep Learning—A New Era in Bridging the Semantic Gap, In: H. Kwaśnicka, L.C. Jain (eds.) *Bridging the Semantic Gap in Image and Video Analysis*, Springer Nature Switzerland, 2018, pp. 123-159.

[11] G. Qi, H. Wang, M. Haner, C. Weng, S. Chen and Z. Zhu, Convolutional neural network based detection and judgement of environmental obstacle in vehicle operation, *CAAI Transactions on Intelligence Technology,* 2019, 4(2), pp. 80-91.

[12] K. Roy and J. Mukherjee, Image similarity measure using color histogram, color coherence vector, and sobel method, *International Journal of Science and Research (IJSR),* 2013, 2(1), pp. 538-543.

[13] R. Chakravarti and X. Meng, A study of color histogram based image retrieval, *2009 Sixth International Conference on Information Technology: New Generations,* 2009, pp. 1323-1328.

[14] J.-M. Guo, H. Prasetyo and J.-H. Chen, Content-based image retrieval using error diffusion block truncation coding features, *IEEE Transactions on Circuits and Systems for Video Technology,* 2014, 25(3), pp. 466-481.

[15] T. Ojala, M. Pietikainen and T. Maenpaa, Multiresolution gray-scale and rotation invariant texture classification with local binary patterns, *IEEE Transactions on pattern analysis and machine intelligence,* 2002, Vol. 24(7), pp. 971-987.

[16] P. Liu, J.-M. Guo, K. Chamnongthai and H. Prasetyo, Fusion of color histogram and LBP-based features for texture image retrieval and classification, *Information Sciences,* 2017, Vol. 390, pp. 95-111.

[17] W. Zhou, H. Li, J. Sun and Q. Tian, Collaborative index embedding for image retrieval, *IEEE Transactions on pattern analysis and machine intelligence,* 2017, Vol. 40(5), pp. 1154-1166.

[18] L. Fei-Fei, R. Fergus and P. Perona, One-shot learning of object categories, *IEEE Transactions on pattern analysis and machine intelligence*, 2006, Vol. 28(4), pp. 594-611.

[19] S. Zagoruyko and N. Komodakis, Learning to compare image patches via convolutional neural networks, *Proceedings of the IEEE conference on computer vision and pattern recognition (CVPR)*, 2015, DOI: 10.1109/CVPR.2015.7299064.

[20] C.V. Trappey, A.J. Trappey and S.C.-C. Lin, Intelligent trademark similarity analysis of image, spelling, and phonetic features using machine learning methodologies, *Advanced Engineering Informatics*, 2020, Vol. 45, 101120.

[21] S. Appalaraju and V. Chaoji, Image similarity using deep CNN and curriculum learning, *arXiv preprint arXiv:1709.08761*, 2017.

[22] F. Schroff, D. Kalenichenko and J. Philbin, Facenet: A unified embedding for face recognition and clustering, *Proceedings of the IEEE conference on computer vision and pattern recognition (CVPR)*, 2015, DOI: 10.1109/CVPR.2015.7298682.

[23] C.-Y. Wu, R. Manmatha, A.J. Smola and P. Krahenbuhl, Sampling matters in deep embedding learning, *Proceedings of the IEEE International Conference on Computer Vision (CVPR)*, 2017, DOI: 10.1109/ICCV.2017.309.

[24] T. Lan, X. Feng, L. Li and Z. Xia, Similar trademark image retrieval based on convolutional neural network and constraint theory, *2018 Eighth International Conference on Image Processing Theory, Tools and Applications (IPTA)*, 2018, DOI: 10.1109/IPTA.2018.8608162.

[25] W. Min, S. Mei, Z. Li and S. Jiang, A Two-Stage Triplet Network Training Framework for Image Retrieval, *IEEE Transactions on Multimedia*, 2020, Vol. 22, Issue 12, Dec. 2020, pp. 3128 - 3138.

[26] A. Veit, S. Belongie and T. Karaletsos, Conditional similarity networks, *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2017, DOI: 10.1109/CVPR.2017.193.

[27] J. Wang, W. Min, S. Hou, S. Ma, Y. Zheng, H. Wang and S. Jiang, Logo-2K+: A Large-Scale Logo Dataset for Scalable Logo Classification, *AAAI*, 2020, https://doi.org/10.1609/aaai.v34i04.6085.

[28] H. Oh Song, Y. Xiang, S. Jegelka and S., Savarese, Deep metric learning via lifted structured feature embedding, *Proceedings of the IEEE conference on computer vision and pattern recognition*, 2016, pp. 4004-4012.

[29] M. Abadi, P. Barham, J. Chen, Z. Chen, A. Davis, J. Dean, . . . M. Isard, Tensorflow: A system for large-scale machine learning, *12th {USENIX} symposium on operating systems design and implementation ({OSDI} 16)*, 2016, pp. 265-283.

[30] D.P. Kingma and J. Ba, Adam: A method for stochastic optimization, *arXiv preprint arXiv:1412.6980*, 2014.

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Concept of a Multi-Criteria and Multi-Disciplinary Design Activity Supporting Tool in the Design and Development Process of CPS

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Abstract. The approach presented in the paper is about the concept of a multi-criteria and multi-disciplinary tool supporting design activities while designing and developing CPS. Designers who solve CPS design problems try to build computer models, and examine, verify and validate them. Usually, these models, often created ad hoc, are very complex and large and evolve in time, so the entire processes have many stages and variants. These processes come to an end after one or several sequences of selected knowledge-based activities, which in general have been modified and improved before. These activities usually concern two groups of issues: substantial and decision-making. The presented activity supporting tool concept can be applied in the design process of CPS. The main goal of the new tool is to improve the design process through more precise, effective and problem-dedicated management of the design activity models. It also enables and supports the ad hoc modelling of the collaborative integration of activities for multidisciplinarity and multi-criteria optimization analysis.

Keywords. design of CPS, multi-criteria optimization, multi-disciplinarity, transdisciplinarity, design support, industrial case

Introduction

The presented work was created as a result of the analysis of materials and retrospective threads related to a previously realized design of a control unit for selected systems of a tractor and, in particular, the tractor transmission box (TCU) [1, 2]. The control unit, under design with the tractor, is a typical CPS class system. The threads observed in the course of the project [1] and considered in the design analysis of the TCU concerned two main aspects: the observed degree of substantive correctness of the performed design activities and the intentionality and evolution of these activities in selected, strictly defined directions of the development of the entire project. The evolution of the design activities was primarily due to the shortcomings of the methods and approaches known to the designers at the beginning of the project.

Our previous works [1, 2] focused on knowledge modelling issues applied to the project under analysis. This knowledge formed the basis for the creation and

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implementation of the design project process subjected to the presented analysis. The models created covered both the substantial-analytical side of the project and the decision-making aspects. The decision-making process was based on the modelled knowledge, but optimization techniques (mainly multi-criteria optimization) were also taken into account. The project related to the construction of the TCU, by definition, resulted in the use of models derived from various disciplines. The realized and analyzed project became the basis for creating the concept of a dedicated approach, and related tools, for designing the CPS system presented in selected aspects in this paper.

1. Engineering knowledge modelling

The problems of capturing, storing and reusing engineering design knowledge have been the subject of very intensive research and development over the past 30 years [7, 8]. The following facts have contributed to this: the increase in the complexity of the implemented design tasks [9, 10], the attempt to reduce product development time and increase the quality of the product itself, functioning in a distributed environment [11], as well as a significant increase in the awareness of the role of knowledge in engineering processes and the necessity of its storage, maintenance and sharing [12-14]. Nowadays, additionally to the substantial knowledge [13, 14], the broader context and its long term development [15,16] are considered more often. For CPS projects the aforementioned issues are particularly important due to their scale and the high degree of multifacetedness and complexity of the problems being solved [3, 17, 18].

The presented approach attempts to integrate the concept of knowledge-based software [7, 8] with multi-criteria optimization applied to a multidisciplinary problem [3, 19]. Particular emphasis has been placed on the issue of flexible, knowledge-based, interactive management of a multi-stage evolutionary problem-solving procedure and its main functionalities [20, 21].

With CPS optimization tasks, at the initial stage of the task modelling process, or sub-tasks [4, 5] of multi-criteria optimization, it is difficult to unambiguously determine and predict the final areas/sub-areas, ranges and sizes of individual tasks that are to become analyzed models (which are the basis for final decisions). Analysis, experimentation on a large scale, and the selection of methods are necessary as tool modules have to be integrated. This is a rather labour-intensive stage.

In general, multidisciplinary CPS models are relatively large and complex [4, 5, 17, 18]. They are assemblies of partial models [23-26]. The interrelationships of partial models reflect the fact that products and their design problems are extended structures which are homogeneous and multifaceted. They are also based on knowledge from different disciplines.

The subject matter knowledge and individual preferences of designers determine which models, and at what level of model accuracy, will be used in a given case. This knowledge should be acquired, stored, and reused [1, 2, 12].

2. Modelling multidisciplinary design tasks

Machine design engineers create mental, mathematical, and computer models [9, 10]. They study them, analyze them, and use them for simulation. The next steps are the use, verification, possible modification and natural validation of the models [13, 14]. These activities are based on specific engineering knowledge resources.

It has to be noted that all these steps are accompanied by the intensive mental work of the designers aiming to build a design process composed of specific design activities based on related tools [1, 2]. As a result, each of the design activities [2] considered as necessary is implemented at a specific, preconceived level of model accuracy - initially in a more general form and in subsequent iterations in a more tailored, sometimes more detailed form.

Activities evolve as knowledge advances and develops [1, 2, 13, 14] during the design process. They are adapted to changing circumstances. Their functioning changes and their associated tools evolve [13, 14]. The problems of this class modelled today has to concentrate on storing and analyzing broad contexts of the applied knowledge [15, 16].

Usually, for each designer and his/her specific area of professional competence, a whole class of models can be built. They consist of design activities and their tools, which, remaining with each other in specific relations, give the possibility of articulating sets of plan-models for realizable design processes [8, 13, 14]. At the same time, relationships can take a "soft" form, i.a. inequalities between attribute values, mappings of a point into a set, etc. They can also take a very formal form of variables called coordination variables [12, 19] that bind together well-defined subproblems (an approach known from multidisciplinary optimization).

2.1. Classical design and elements of CPS design

Nowadays, the design processes of systems in which CPS occurs are generally largely composed of elements typical for classical design processes. They contain in many cases only a few fragments typical for CPS [1, 2]. Designers are usually cautious, approach the design of CPS elements with restraint and reserve, and observe and analyze all steps carefully. Usually, when designers start work with projects that also include CPS they do so in little steps. They are rather far from carefully building precise, complex models and approaches.

When it is possible, designers often design CPS systems mentally, as they usually do in classical design. CPS design, at least in the first iteration, is done in multiple stages. It is a standard process to which various new elements are added. Attempts to create these new elements are accompanied by integration efforts. It is important to obtain initial guiding answers to various questions. Basic ideas emerge and attempts are made to apply them. In general, this means the complexity of the basic models. The taken actions are to test a variety of basic new ideas, which usually boil down to evaluating their sensibility and assessing the rationality of raising the complexity of the models themselves. At this stage, usually no expensive and detailed models are built. Everything is based on relatively simple models or also relatively simple modifications of them.

An effective method of solving the problem in this case may be to use the relatively simple concept of modelling a multi-attribute decision-making task [8]. Then the problem is reduced to generating a set of design solution variants, where each of them has certain attributes (generally captured numerically). Some of these attributes can become criteria that may be used to extract a set of Pareto optimal solutions and further to select the single most preferred solution. In such a complex process - as even the simplest design of structures with CPS elements - it happens that more single tasks of multi-attribute decision-making occur which can also be solved in the way described above [8]. Often, formal relationships between such tasks, which are sometimes called sub-tasks, are not taken into account. However, there are cases where these links between sub-tasks cannot be ignored. The variables that bind the sub-tasks are called coordination variables. Their choice determines the trade-off in solving any of the sub-tasks. It is also possible to construct a global task, whose criteria depend both on individual sub-tasks and their mutual relations expressed in the choice of coordination variables. Further possibilities of this approach are modelling preferences for favouring any of the sub-tasks or the global task, or working out a compromise between these tasks. A hierarchical order approach can also be used for this purpose [8].

The above proposal, which solves a complex multi-discipline, multi-criteria optimization task by using approaches typical of multi-attribute decision making, has the advantage of being relatively simple, making easier an understanding of a not very extensive conceptual layer: variants-attributes, criteria, optimality in the Pareto sense, hierarchical order, related tasks. The functional side of this somehow limited class of approaches is not very complex either.

At the conceptual stage design problems with CPS elements are mostly not described by advanced formal models. Instead, they are very often models from different disciplines - we speak of their inter- and transdisciplinarity, and they rarely have any prior development behind them. But in this case a relatively simple optimization approach based on multi-attribute (as opposed to multi-objective) relatively good yields results in further refining the previously studied models in a clear way.

The above proposal can be directly related to the concept of project activity modelling, where the sub-tasks are tasks associated with a specific project activity and its specific development version [1, 2]. General tasks – mean working out the trade-offs between sub-tasks and global tasks, and also modelling the relationships between specific instances of project activities, and as a result optimization in a broader sense. Important in all this is the ability to quickly create and analyze this class of models.

The authors based their concept on relatively simple computer programs that have functions generating sets of variants, and functions allowing the selection of solutions in the Pareto sense, and solutions based on the hierarchic order. Furthermore, they allow a relatively simple integration of sub-tasks, and then processes of preferred optimal tasks selection can be performed.

3. Test use of the proposed approach in an example CPS design case

Returning to the concepts of CPS systems, we can state that the concepts presented in the previous chapter are relatively easy to implement for the designer. They gradually develop and may become a widely available tool for testing hypotheses created and modified by the designer.

Let us turn to a concrete example of modelling selected subproblems in the task of building an electronic control system for the operation of the main transmission system of a tractor as well as other supporting systems:

1. We consider the project activity: designing the part of the electronic controller which is responsible for the hydraulic valves control - which provides the definition of the characteristics of the system under study. The activity is based on the authors' personal knowledge and the mathematical models which they gained and created in previous similar projects. While implementing the

knowledge, a whole range of resultant quantities are generated, including the hydraulic valve current characteristic. The characteristics of such relationships are shown in Fig. 1. The right side of the figure shows selected design quantities identified as key elements. These quantities are used both in the physical layer (hardware) and in the built numerical models to assess the correctness of the operation of a given version of the design. The performance of an electronic system is also affected by the number and type of sensors and actuators needed in other design activities. For example, too high a temperature of the electronic system or too many connected devices with an available power source can cause the inadequate operation of electronic system components (e.g., too low voltage or current). Consequently, an improper operation of sensors and actuators can be observed which influences the whole CPS system. So, it is possible and necessary to construct a multi-attribute decision-making task for such a problem, to which various specific methods for its solution can be applied [12, 19]. Ultimately, one can choose a single optimal solution in the Pareto sense.

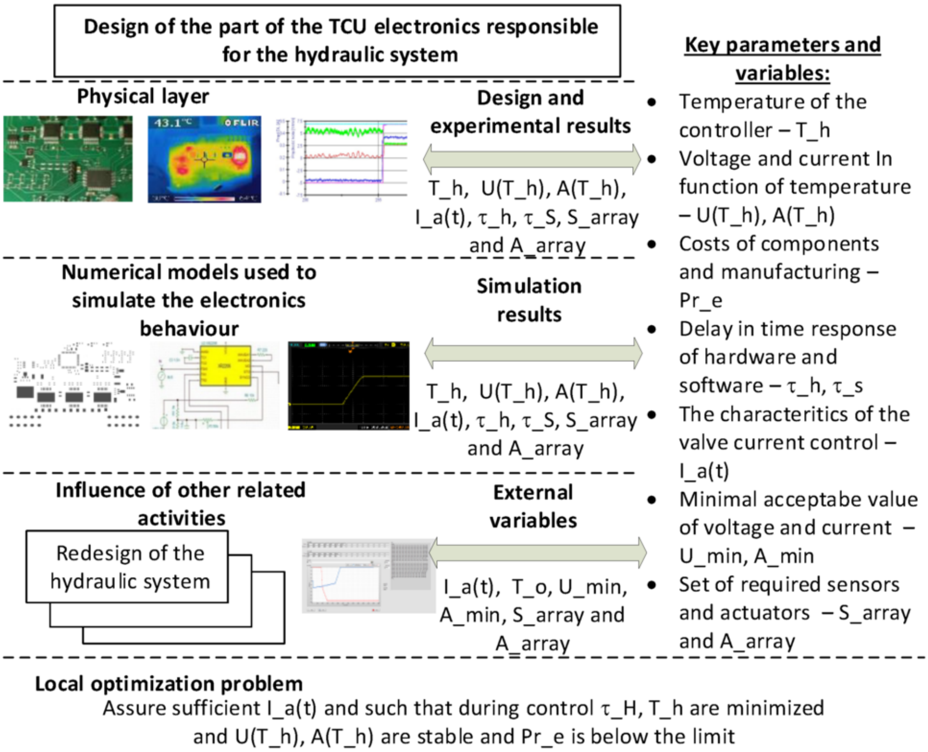

Figure 1. The design of the electronic controller responsible for hydraulic valves control.

We also present a second example of a design activity (which generally involves a different discipline): the redesign of a hydraulic system. The example is based on other models, leads to a better definition of the characteristics of the hydraulic system, and redefines the requirements for the current characteristics of the hydraulic valve controlling the operation of the clutches of each gear. However, at some stages, one of the quantities generated in 1) should be related to the set of quantities present in 2).

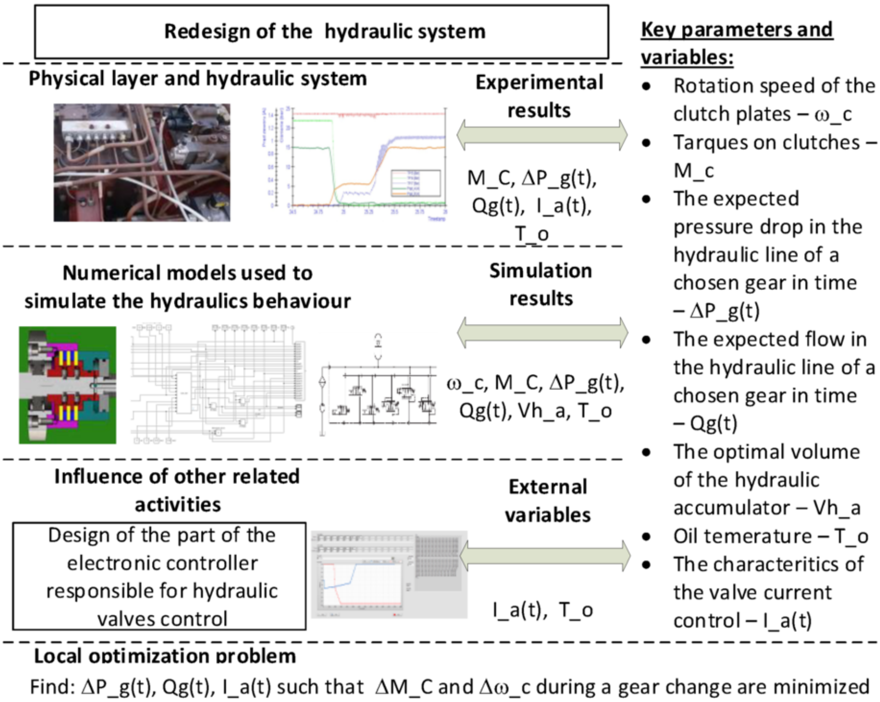

Figure 2. Redesign of hydraulic system.

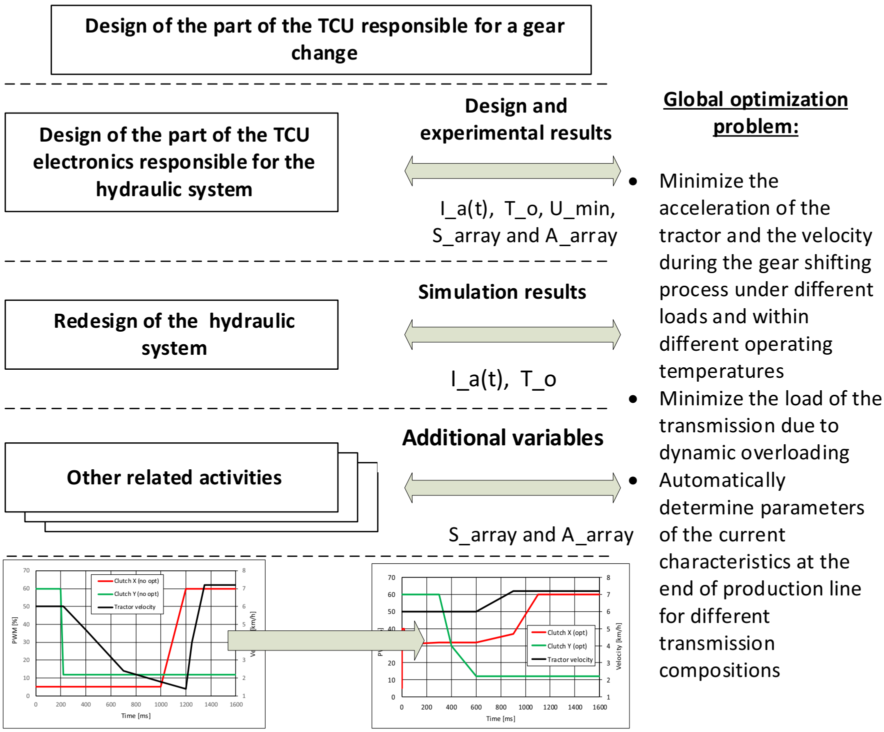

Figure 3. Activity links in the controller design process.

The functioning of this activity, and the conditions for the functioning of such a link, are shown in Fig. 2. On the right side of the figure the key quantities for the activity and the correct operation of the hydraulic system are shown. These quantities have a key effect on the gear shifting process. For example, one of the quantities I_a, which is also shown in Fig. 1, is the change over time of the current supplying the valve responsible for the operation of the multi-plate clutch hydraulic cylinder. The time-dependent actuation of the hydraulic cylinder affects local quantities such as pressure drop (ΔP_g), clutch plate speeds (ω_c), clutch torque transmission values (M_c), but also clutch plate friction lining wear and servicing costs. In this case, a multi-attribute decision-making task can also be modelled, to which various specific methods can be applied to solve it [3, 12, 19]. And, as before, the solutions obtained are optimal in the Pareto sense.

2. It is possible to link both activities, build a new complex task, and do an appropriate analysis, including multi-attribute. Integration tools are needed for this. The tools may be general purpose, but it is desirable that they provide automatic, fast and simple ad hoc integration. The structure of this class is shown in Fig. 3. Based on this structure, we are able to model the related tasks 1 and 2 as sub-problems of the global multi-criteria optimization task. The multi-attribute approach can also be used in this case. The procedure characterized above can be continued with successive sub-models of successive activities [1, 2, 20-26]. New consecutive links that make real sense can be created. The result is a map of the various integrated sub-models together with locally derived analysis and optimization results. The obtained picture shows the estimated potential of the perceived and applied model structures and allows us to find connections and influences between individual local analyses.

The whole procedure presented above leads to the extraction from a very large set of potentially integrated models those which are needed, which are promising and have innovative potential, and probably a decisive influence on the outcome of the design process.

4. The concept of a staged building of the software environment to support the CPS design process

Some example formal models of such integrated sub-problem structures tend to have application areas with a well-established history of their development. These include, for example, the aerospace industry [3, 19]. However, it is much more difficult to build this class of structures for tasks not previously solved by this class of methods.

A particularly vast search space is likely to occur for CPS systems [4-6, 26, 27]. An effective solution in this case may be a stepwise, evolutionary analysis of different types of relationships between, for example, two selected different design activities and their tools. The relationships may be relatively simple, e.g. linking a single variable in one activity to a set of variables in another activity. In addition, such a relationship can be unidirectional: first, one activity is implemented, and the results of its implementation are transferred mathematically, formally to another dependent and implemented activity. It is also possible to indicate which variables had a decisive role in the successful implementation of a given version of the activity.

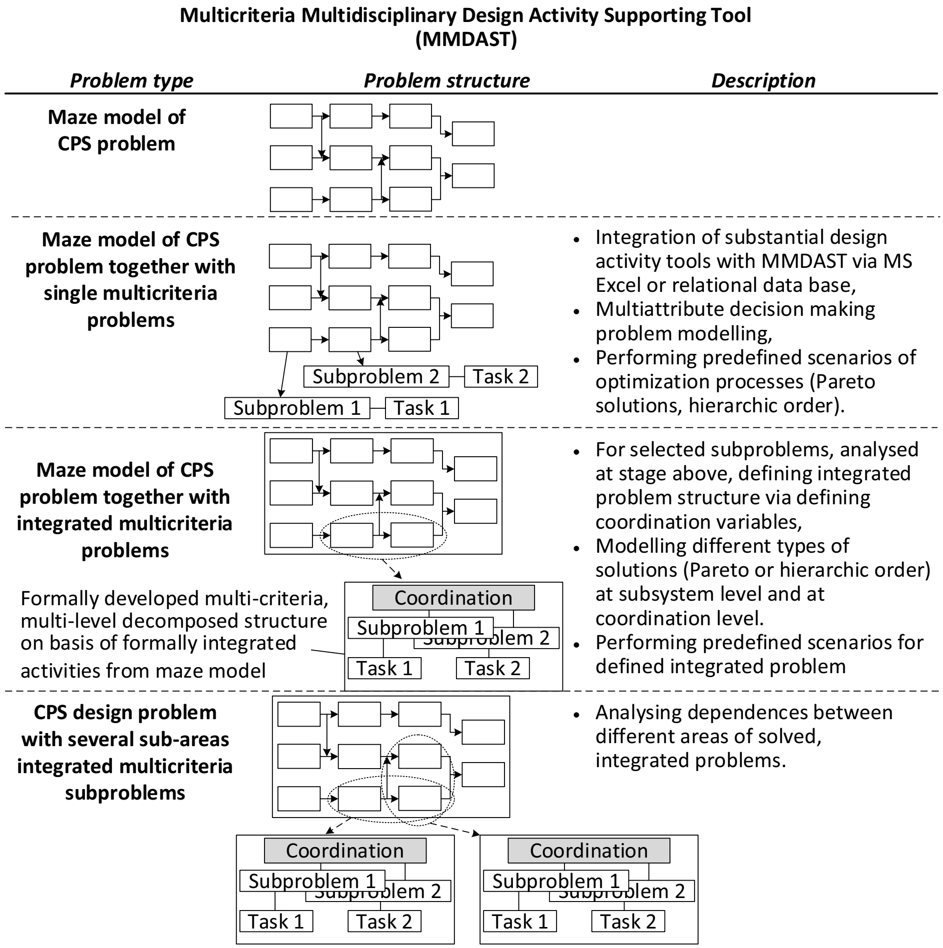

Figure 4. Architecture of the Multicriteria Multidisciplinary Design Activity Supporting Tool (MMDAST).

It is, of course, possible to analyze different types and directions of such relationships. It is also possible to impose various formal requirements on the results obtained this way, e.g. the attainability of certain preset thresholds of certain variables and functions, or the search for the largest value of some of them, or the search for the realization of a trade-off between them. All this constitutes a certain initial modelling potential of the discussed approach.

The authors propose an evolutionary strategy (c.f. Fig. 4): first to set basic hypotheses for modelling integrated tasks consisting of 2-3 problems, and then analyze them and make subsequent attempts at modelling and analysis. The approach involves a gradual refinement of the design process and the activity in it through the designer's recognition and learning of the problem. After that, mainly based on mental processing and reflection, he determines the next steps in modelling and analysis/optimization. This concept refers to processes usually performed by designers. However, it assumes making the development of design activities, the knowledge acquisition and the modelling tasks integrated from sub-tasks more efficient. The main assignment of the designer is to interactively control the development and model expansion, depending on the needs necessary to solve a given problem at a given time.

The authors also plan to develop a set of standard patterns - scenarios of operating with the proposed system.

In general, the main goal of the proposed approach is to make fast and economically rational analysis of multi-criteria decision tasks which are qualitative, multi-disciplinary, and can be modelled locally ad hoc.

Of course, large systems [3] for this class of tasks are available. However, using them is labour intensive. Expertise is required in both decision problem modelling and system decomposition, in framework integration, optimization task modelling, and optimization execution processes. This means the first valuable results appear after a lot of work in the preliminary stage.

The authors have already developed various limited implementations based on the presented concepts (chapter 9 in [8]). They have also developed concepts with probabilistically modelled elements. The authors plan to build a series of independent applications supporting different classes of decision problems with predefined task structures. Over time, it may prove effective to integrate them and transfer the complex task thus built to a system designed to solve large multidisciplinary tasks of this class.

5. Conclusion

The approach proposed in this paper attempts to make typical designers' work more efficient when they solve problems that are not fully known in a meaningful way. Usually, the engineers undertake model modifications, directed model modifications, based on knowledge, experiments and simulations. These are directions of the environment development based on the knowledge gained and the evolutionary exploration and learning of its requirements.

Each of these activities also contains a lot of manual, repetitive actions that should be gradually automated to increase the effectiveness of the entire environment. These activities include the automation of integration processes as well as the improved predefinition of decision tasks and optimization tasks. The authors' aim at both directions.

References

[1] J. Pokojski, L. Knap, M. Trojgo: Concept of an Assisting Tool in the Design and Development Process of a Product with the CPS – Case Study, *Advances in Transdisciplinary Engineering*, 2019, Vol. 10, pp. 95-104, red. DOI: 10.3233/ATDE190112

[2] J. Pokojski, L. Knap, M. Trojgo: Concept of Design Activity Supporting Tool in the Design and Development, Advances in Transdisciplinary Engineering, 2020, Vol. 12, pp. 161-170,

[3] J. Sobieszczanski-Sobieski, A. Morris and M. J.L. van Tooren, *Multidisciplinary Design Optimization Supported by Knowledge Based Engineering*, First Edition. John Wiley & Sons, Hoboken, 2015.

[4] P. Carreira ,V. Amaral, H. Vangheluwe (Editors), *Foundations of Multi-Paradigm Modelling for Cyber-Physical Systems*, Springer Open, 2020.

[5] M. Törngren and U. Sellgren, Complexity Challenges in Development of Cyber-Physical Systems, in: M. Lohstroh, P. Derler and M Sirjani (eds.) *Principles of Modeling*, Springer International Publishing AG, LNCS 10760, 2018, pp. 478–503.

[6] P. Hehenberger, B. Vogel-Heuser, D. Bradley, B. Eynard, T. Tomiyama, S. Achiche. Design, modelling, simulation and integration of cyber physical systems: Methods and applications. *Computers in Industry*. 2016, Vol 82, pp 273-289.

[7] S.K. Chandrasegaran, K. Ramani, R.D. Sriram, I. Horváth, A. Bernar, R. F. Harik, W. Ga, The evolution, challenges, and future of knowledge representation in product design systems, *Computer-Aided Design*, 2013 , Vol. 45 , pp. 204–228.

[8] J. Pokojski, *IPA (Intelligent Personal Assistant) – Concepts and Applications in Engineering*, Springer-Verlag, London, 2004.

[9] G. Pahl, W. Beitz, and al., *Engineering Design: A Systematic Approach*, Springer-Verlag, Berlin, 2007.

[10] D.G. Ullman, *The Mechanical Design Process*, Third Edition, McGraw-Hill, New York, 2002.

[11] J. Stjepandic, N. Wognum, W.J.C. Verhagen, *Concurrent Engineering in the 21st Century: Foundations, Developments and Challenges*, Springer International, Cham, 2015.

[12] J. Pokojski, Integration of Knowledge Based Approach and Multi-Criteria Optimization in Multi-Disciplinary Machine Design, *Advances in Transdisciplinary Engineering*, 2017, Vol. 5, pp. 683-692.

[13] J. Pokojski, K. Oleksiński, J. Pruszyński, Knowledge based processes in the context of conceptual design, *Journal of Industrial Information Integration*, 2019, Vol. 15, pp. 219-238.

[14] J. Pokojski, K. Oleksiński, J. Pruszyński, Conceptual and Detailed Design Knowledge Management in Customized Production - Industrial Perspective, *Journal of Computational Design and Engineering*, October 2019, Vol. 6, Issue 4, pp. 479-506.

[15] X. Li , Z. Jiang , B. Song, L. Liu , Long-term knowledge evolution modeling for empirical engineering knowledge, *Advanced Engineering Informatics*, 2017, Vol. 34, pp. 17–35.

[16] O. D. Lee, B. Choi, H. Lee, How do knowledge management resources and capabilities pay off in short term and long term? *Information & Management*, 2020, Vol. 57, 103166.

[17] I. Horváth, Z. Rusák,Y. Li, Order Beyond Chaos: Introducing the Notion of Generation to Characterize the Continuously Evolving Implementations of Cyber-Physical Systems, *Proceedings of the ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE 2017* August 6-9, 2017, Cleveland, Ohio, USA, DETC2017-67082, pp 1-14.

[18] L. Knap, *Design and Construction of the task-oriented Cyber-Physical System*, The Institute for Sustainable Technologies – National Research Institute, 2017 (in Polish).

[19] C. Bil, Multidisciplinary Design Optimization: Designed by Computer, in J. Stjepandic et al. (eds) *Concurrent Engineering in the 21st Century*, Springer Switzerland, 2015, pp. 421-454.

[20] S. Biffl, A. Luder, D. Gerhard (Editors): *Multi-Disciplinary Engineering for Cyber-Physical Production Systems. Data Models and Software Solutions for Handling Complex Engineering Projects*, Springer International Publishing, 2017.

[21] Kendrik Yan Hong Lim1,2 · Pai Zheng1,2,3 · Chun-Hsien Chen1,2 A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives. *Journal of Intelligent Manufacturing*, 2020, Vol. 31, pp. 1313–1337, https://doi.org/10.1007/s10845-019-01512-w.

[22] B. Liu et al., A survey ofmodel-driven techniques and tools for cyber-physical systems. *Front Inform Technol Electron Eng*, 2020, 21(11), pp. 1567-1590.

[23] M. Amir, T. Givargis, Pareto optimal design space exploration of cyber-physical systems. *Internet of Things*, 2020, Vol 12, 100308C.

[24] Zheng et al., Multidisciplinary Integration during Conceptual Design Process: A Survey on Design Methods of Cyber-Physical Systems, *INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016*, Dubrovnik - Croatia, May 16 - 19, 2016, pp. 1-10.

[25] J. S. Gray et al., OpenMDAO: an open-source framework for multidisciplinary design, analysis, and optimization. *Structural and Multidisciplinary Optimization*, 2019, Vol. 59, pp. 1075–1104, https://doi.org/10.1007/s00158-019-02211-z.

[26] V. Brandstetter, J. C. Wehrstedt, A Framework for Multidisciplinary Simulation of Cyber-Physical Production Systems. IFAC PapersOnLine, 2018, 51-11, pp. 809–814.

[27] A. Sadlauer, P. Hehenberger, Using design languages in model-based mechatronic system design processes, *International Journal of Agile Systems and Management*, 2017, Vol. 10(1), pp. 73-91.

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Technology Mining for Intelligent Chatbot Development

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Abstract. Natural language processing (NLP) is an indispensable part of advancing the AI era, especially in the realm of the human-computer interface/interaction (HCI) for all state-of-the-art software applications. NLP enables interfaces between machines and humans allowing machines/computers/systems to understand human languages and engaging in dialogues. An intelligent chatbot development must incorporate NLP technologies to allow the understanding of users' utterance and responding in understandable sentences in versatile scenarios. This research investigates the emerging technological trend of intelligent chatbot development. The systematic trend analysis is described in the research. First, patents related to intelligent chatbot domain are retrieved using a well-defined search query. The queries are derived from the knowledge ontology, which is extracted using text-mining algorithms - key term frequency analysis, clustering for sub-domain identification, and Latent Dirichlet Allocation (LDA) for topic modelling. Afterwards, the management and technology maps of a patent portfolio, such as patenting trends and technology function matrix, are extracted and drawn. The technology trend analysis also investigated the distributions of the relevant patent claims for specific industries.

Keywords: Natural language processing (NLP), chatbot; patent analysis, Latent Dirichlet Allocation (LDA), ontology, text mining, transdisciplinary

Introduction

In the context of the global fight against epidemics, when the communication between people is restricted, artificial intelligence (AI) has got more expectations and important tasks. It has demonstrated its skills in the fields of information collection, data aggregation and real-time updates, epidemiological investigations, vaccine drug development, and new infrastructure construction. At the same time, with the continuous emergence of new technologies and new formats, the power of AI to condense global wisdom and help global economic recovery has become more prominent. AI is extremely practical and a very representative multidisciplinary subject. At present, AI has been applied to various fields such as machinery, electronics, economy and even philosophy. The global industry is digitizing. As the first window of customer service, chatbots can handle simple customer questions in real time. However, the development of AI has made chatbots more intelligent, so chatbots can replace junior employees. Intelligent chatbots mean that they can understand/process natural language. It is a transdisciplinary engineering technology that integrates multiple disciplines to enable chatbots to simulate human behavior. Therefore, NLP is the key to intelligent chatbots. By collecting a large number of conversations with customers and obtaining key information, the company

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can enhance customer relationship management and make customer preference predictions. There are countless examples of applying NLP in various fields, such as the application in the medical industry. Using NLP technology to analyze the elderly who narrate specific events, which can diagnose the level of cognitive impairment in patients with Alzheimer's disease [1]. In some applications of administrative affairs automation, NLP is also a helpful tool. Google incorporates NLP technology and optical character recognition to identify key parameters of documents, thereby saving time-consuming manpower reading work [2]. As mentioned previously, NLP is the most widely used in customer service. Customer's emotions and intentions can be extracted by analyzing a large number of customer feedback of NLP, and used to improve products or as a strategy for developing new products [3].

Chatbot is a virtual system composed of functional programs. It is known as a conversation agent that simulates human thinking and responds. To determine whether a chatbot is intelligent, the Turing test can be used, which is an experiment to judge whether a machine has the ability to think [4]. In the beginning, chatbots could only respond according to the rules defined by the developer. With the advent of deep learning, the process design of making chatbots respond is no longer just based on rules, but to learn human communication logic by reading a lot of conversations. Since then, chatbots have begun to incorporate voice recognition functions to make them more intelligent. Nowadays, people can operate machines or make automatic changes through chatbots, and this technology is widely used in car assistant and robots.

This research uses the Derwent Innovation patent index (DWPI) to retrieve patents related to intelligent chatbot technology and provides an ontology map and patent portfolio analysis of the subject to understand the development trend of intelligent chatbots and the current market layout. In addition, this research provides strategies for formulating technological development in related fields. First, an overall ontology map is required, which is followed by a well patent analysis strategy. Also, several text mining techniques are adopted in the ontology construction process, such as k-means clustering [5], LDA [6] and term frequency-inverse document frequency (TF-IDF) [7].

1. Literature review

In this section, the recent patent review workflow is discussed in the first paragraph, which aims to develop a reliable patent review process for this research. In order to be able to analyze massive related patents, some powerful patent analysis methods are discussed in the second paragraph. Last, an ontology construction is discussed, which can organize patent review findings into a systematic knowledge framework.

Patent contains an ample amount of textual content and attribute data. How to effectively integrate these data into useful information is the focus of a patent review. However, the development of information technology has made patent review easy and reliable [8]. For instance, text mining is a technique widely adopted in patent review, which provides patent reviewers with specific information, such as key terms and topic distribution. Nowadays, many powerful information technologies are used to assist in a patent review. However, if a proper patent review process is not established, it may lead to the possibility of deviation from the research subject. Abbas, Zhang [9] proposed an overview of the patent review workflow, which contains three main sections, pre-processing, processing and post-processing. The key to preprocessing is to search for appropriate patents and convert unstructured data into usable information. Afterwards, extracting specific quantitative or qualitative data is the purpose of the processing section, such as topic modeling and outputting some statistical information. Finally, patent analytics methods are related to the past-processing section, which is classified into two patterns. Text mining-based methods are for quantitative data, and visualization approaches are for qualitative data [10]. Kim and Bae [11] proposed an approach that can predict emerging medical technologies through patent analytics. Their patent review workflow can be divided into four processes: retrieving domain patents, technology clustering, defining the output of the technology clustering, and patent clustering evaluation. In the third process, the results may vary from analyst to analyst. To avoid this problem, Cooperative Patent Classification (CPC) is used to define the output of the technology clusters. Both patent and non-patent literature are available resources for exploring emerging technologies. Thilakaratne, Falkner [12] proposed a literature-based research review workflow, which formulates a literature retrieval process in detail to avoid missing any representative literature. The main research purpose and keywords are the criteria for judging whether the article is suitable for being placed into the database. After the resources are collected, all literature needs to be further filtered through three processes. The first is to analyze the title and abstract to check the relevance, the second is to analyze the introduction and conclusions of the article, and finally, to fill in the quality checklist through a complete reading. Afterwards, some graphs were constructed through visualization techniques to present the findings. In summary, the knowledge document review workflow can be divided into three stages: resource acquisition, knowledge document analysis in a database, and output presentation.

Since patent contains information that has characteristics of volume and variety, therefore, how to filter information becomes a big issue of patent analysis, which is a method that attempts to gather information from a structured patent document. The realm of patent analysis has two major methods, which are text mining [13] and visualization [14]. When it comes to the text mining approach for text mining, the main ways of representing a patent are semantic information identification and semantic similarity comparison [15]. By way of illustration, first, Hu, Li [16] made use of the characteristic of the frequency of appearance to extract key terms from patents and compare them with TF-IDF method. Second, Li, Hu [17] utilized a deep learning model called DeepPatent to classify patents, the ensemble model merges CNN model and the word embedding model. Third, Lee and Hsiang [18] wanted to gain a better result, they fine-tuned a BERT model and compared it with DeepPatent consequently. The final result had higher precision by 9 percent. As the above three ways mentioned, they all use the common text mining wat by selecting keywords and converting them into machine-readable vectors. Compared with text mining, visualization approaches for patent analysis have progressed early. Take three major development of visualization approaches for example, ontology map focuses on domain-related knowledge discerption, K-means focuses on topic modeling [19], and technology function matrix focuses on tracking status [20].

An ontology graph is a tool of knowledge engineering, which center is the research theme and links related fields from the center outward, provides a clear domain knowledge classification. In this research, ontology is used to construct a logical criterion for classifying a technology and show are core techniques of the domain. Ontology construction must rely on sufficient data and some text mining for extracting key terms and topic modeling. Weng, Tsai [21] purposed a lexicon-based ontology construction approach that utilizes term frequency and weighted factor to define the relationship between key terms and research theme. Trappey, Trappey [22] presented an ontology construction approach which is knowledge-based and utilized an unsupervised machine learning technique to extract the information in the smart retailing industry for chasing emerging technologies and trend. For constructing a complete ontology map, some algorithms are applied to continuously refine the ontology, such as LDA and clustering. Tsatsou, Davis [23] presented an automatically constructing ontology method, which utilized TF-IDF to determine key terms that may be branches or nodes of the ontology. Subhashini and Akilandeswari [24] mentioned that constructing an ontology is required to follow the six key steps: determining the scope of the ontology, capturing related data, encoding those useful data to machine-usable, integrating the results, evaluating the results, and documenting the ontology. In summary, constructing an ontology can mainly be divided into three parts: data source, determining the relationship between terms and effectiveness evaluation.

2. Ontology construction using patent

A patent-based ontology, which presents the knowledge connection that contains sub-domains or key terms for a specific topic, provides a way for non-experts to can quickly understand the topic. In this research, the ontology construction process contains four-stage. Stage 1 is patent retrieval, which aims to find the patents related to an intelligent chatbot. This research selects DWPI as the source for searching patents. At stage 1, search some keywords related to the topic and the most relevant 50 patents of the search result be manually checked whether related to the topic. If not, adjust the keywords and re-query until the results are related to the topic. Table 1 lists the final query condition and the amount of the relevant patent.

Table 1 Query condition for ontology construction

Derwent innovation query keywords	Result
"natural language processing "&"natural language understanding" & "NLP" & "NLU" & "chatbot" & "VIRTUAL ASSISTANT"&"INTELLIGENT ASSISTANT" & "automated conversational interface"	508 patent families

Stage 2 is patent clustering and main sub-topic selection, which aims to find the main domains related to the topic. At stage 2, the patents' abstract and claim are used for k-means clustering. Using k-means clustering requires inputting the number of clusters. In order to have the best result, this research utilizes the Silhouette score for determining the number of clusters. On the other hand, TF-IDF is used to identify keywords or key terms and the results of TF-IDF are utilized to check the result of k-means clustering whether related to the topic. If not, back to stage 1 and re-query.

Stage 3 is topic modelling. In order to understand more detail in each sub-topic, the process of stage 3 is further classifying the result of stage 2 into several subdomains. The previous stage has identified several sub-topics related to the topic. At stage 3, LDA is used to do topic modelling for each sub-topic. For each sub-topic, first is setting respective search conditions which similar to stage 1, and then doing LDA topic modelling. After that, define each topic-word and if can't clearly define the topic-word then ignore the topic. The distribution of the ontology has been almost completed at this stage. The last stage is keywords and key phrases finding. Representative keywords and key phrases will be selected from stage 2 and stage 3 to strengthen the description of topic modelling results.

Figure 1 shows the ontology of this research. Based on the query condition listed in Table 1, 508 most relevant patents are found and used to construct the ontology. After doing patent clustering which is stage 2, 13 clusters are classified and summarized into three sub-topics, which are natural language techniques, model and system. Level 3 information connected with the sub-topics are the results of stage 3. For instance, in Nature language techniques sub-topic, 4 main sub-domains are found, voice control, linguistics, dialogue and knowledge. This research figures out the keywords or key phrases for each category classified by LDA. After that, generate a topic-words for each category based on the keywords found. Last, level 4 information which are the leaves of the ontology are set based on the frequency of appearance and the importance.

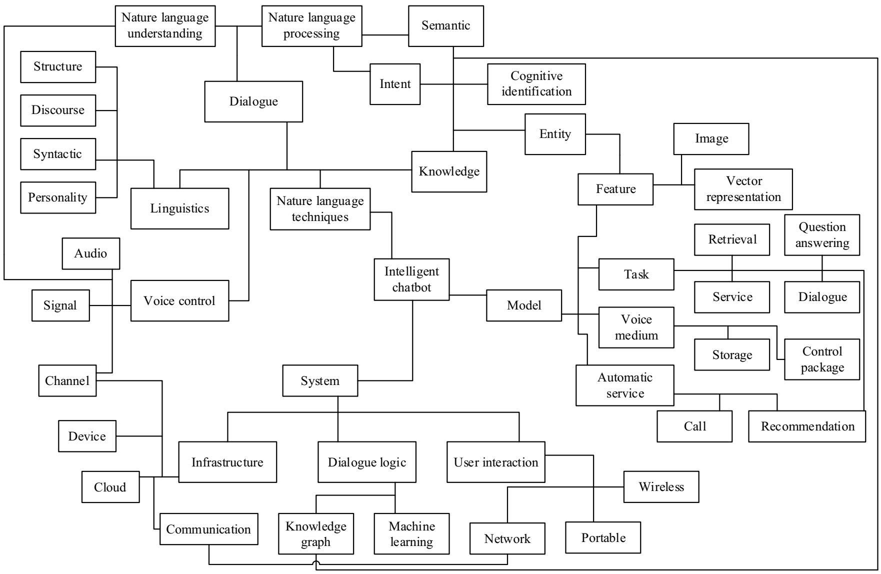

Figure 1. Intelligent chatbot ontology.

3. Patent portfolio analysis

A patent portfolio is a patent combination that related to a specific subject, used to analyze the market outlook and investigate the value of a potential market. In terms of chasing emerging technologies, a patent portfolio is an efficient and valuable tool for knowledge mining. In this section, the patent portfolio of intelligent chatbot is discussed, which presents technology hotspots through a layout of emerging technologies. First, use DWPI smart search to retrieve patents related to an intelligent chatbot. **Table 2** lists the query condition and 5,638 patents are found.

Figure 2 shows the trend of intelligent chatbot publishing patents, which presents the publishing patents are concentrated to 2020 and illustrates the topic is recently developed technology. Since avoiding selecting outdated patents, this research narrows down the publishing date to 2020 (5,390 patents) for follow-up analysis.

Table 2. Query condition for patent portfolio analytics.

Query keywords	Publication year
"intelligent" & "Natural language processing" & "Natural language" & "Natural language understanding" & "NLP" & "NLU" & "chatbot"	2010 to 2020

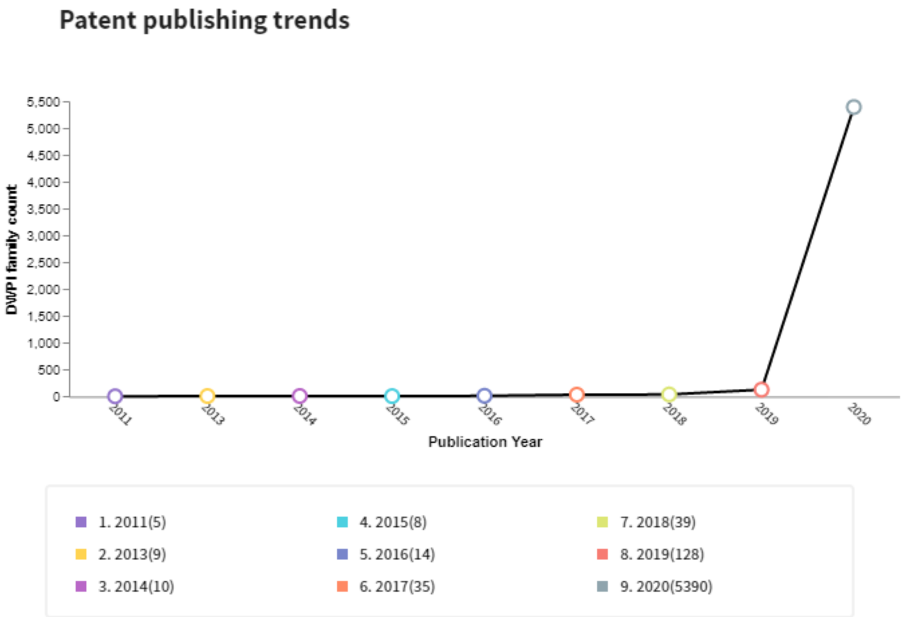

Figure 2. Patent publishing trends.

A technology function matrix (TFM) is a 2-dimensional matrix, which presents the distribution of patents by placing patents in the cells corresponding to defined technology and function. Technologies and functions of TFM can be defined according to the clustering result found in k-means before. After defining technologies and functions, each patent is reviewed iteratively to determine the belonging technology and function. According the patent distribution of TFM, analysts can quickly understand which technology is applied to achieve which functions in a specific field. Furthermore, It represents the current patent layout of technology in a specific industry, by which companies can avoid hot areas of technology or deploy areas where technology is not yet mature.

Technology definition. International Patent Classification (IPC) is a standard taxonomy developed and administered by the World Intellectual Property Organization (WIPO) for classifying patents and patent applications, which covers all areas of technology and is currently used by the industrial property offices around the world. Table 3 lists Top 10 IPCs of 5,390 patents found in DWPI. In terms of IPCs, technology related to an intelligent chatbot can be classified into five categories, which are the medium of communication, Natural language processing, intention recognition, language model, Interface.

Table 3. Top 10 IPCs.

Top IPC	Keywords
G06N Computing	3/08 Learning methods 3/04 Architecture 20/00 Machine learning
G06F Electric digital data processing	40/30 Unsupervised data analysis 16/33 Querying 16/332 Query formulation 16/35 Clustering; Classification
G10L Speech Recognition	15/22 Procedures used during a speech recognition process 15/18 using natural language modelling
G06K Recognition of data	9/62 Methods or arrangements for recognition using electronic means

Combining IPCs results and k-means results to arrive at technologies of TFM which lists in **Table 4**, 7 technologies are defined, speech recognition, natural language processing, feature engineering, machine learning, transformer, cloud computing and immersive technologies. Speech recognition is the technology of enabling a chatbot to process human sounds which advances the user experience of using chatbot. Feature engineering is the technology of utilizing domain knowledge to extract features which helps the process of building the knowledge base of the chatbot. Transformer is a sequence to sequence language model which is a popular language model for developing intelligent chatbot. The quality of an intelligent chatbot is based on the knowledge base and response mechanism, but a good enough knowledge base and response mechanism are a burden for the device. Through the cloud computing technology can reduce the memory and computing power of the device. Incorporating immersive technologies into chatbots can advance the user experience.

Table 4. Technologies of TFM.

#	Technology
T1	Speech recognition
T2	Natural language processing
T3	Feature engineering
T4	Machine learning
T5	Transformer
T6	Cloud computing
T7	Immersive technologies

Function definition. 6 functions listed in Table 5 are defined based on the results of ontology construction stage 4, which are natural language understanding, system efficiency, conversation, prediction, user experience and personal assistant.

Table 5. Functions of TFM.

#	Function
F1	Natural language understanding
F2	System efficiency
F3	Conversation
F4	Prediction
F5	user experience
F6	Personal assistant

Patent mapping. As mentioned previously, 5,390 patents published in 2020 are as the source for the TFM construction. First, some representative descriptions for defined technologies functions are collected from Wikipedia and other websites. Then, Organize the abstract, description and claims of all patents. Last, each patent is cross-compared and assigned to suitable cells which means the patent related to the technology and the function simultaneously. The result of TFM is listed in **Table 6**, which composed of 7 technologies and 6 functions. The area marked in red is the first third, and the blue area is the back third. From the results of TFM, it can be seen that the current patents related to an intelligent chatbot are focused on speech recognition and natural language processing. The core of an intelligent chatbot lies in the ability to understand natural language, so natural language processing, as the main technology, is also a hot spot. However, an intelligent chatbot usually provides multiple communication media, such as SIRI. Speech recognition technology plays a major role. It is a technology hotspot in the current market that transforms audio into machine readable information so that humans and machines can interact. In terms of the blue area. The current patents are relatively irrelevant in cloud computing and immersive technology, and they can be used as future development goals. Cloud computing allows a large amount of calculation to be performed, which enables some simple portable devices to have powerful functions. The immersive technology provides virtual and real image overlay, immersive environment, etc. to greatly enhance the user experience. In terms of function, user experience and personal assistant are notable potential markets. A well user experience can lay the company's image and consolidate its position in the market. Personal assistants are the future trend, such as smart assistants for cars or smart assistants for homes, to change people's lifestyles.

Table 6. The TFM result

	F1 Natural language understanding	F2 System efficiency	F3 Conversation	F4 Prediction	F5 User experience	F6 Personal assistant
T1 Speech recognition	2,233	3,036	3,967	3,566	1,934	2,051
T2 Natural language processing	1,798	1,911	1,419	1,844	627	460
T3 Feature engineering	1,519	2,033	1,059	1,527	617	407
T4 Machine learning	886	1,111	976	1,603	208	305
T5 Transformer	1,048	1,136	1,303	1,862	452	448

T6 Cloud computing	341	678	909	595	452	458
T7 Immersive technologies	992	1,220	2,517	1,504	1,442	1,270

4. Conclusion

This research proposes a macro patent analysis on the newest technologies of an intelligent chatbot. A systematic ontology construction workflow is defined, which utilizes some text mining technologies, such as k-means clustering, TF-ITF, and LDA. After that, the four-level hierarchical structure of the ontology is constructed. The ontology map can be used as the basis for strategic and sustainable R&D planning, from which researchers are able to quickly understand the related key technologies and can determine technology gaps.

This research uses TFM analysis to divide chatbots into 7 technologies and 6 functions. According to the analysis result of TFM, the main patent layout of chatbot is mostly in NLP, mainly including machine learning and information extraction. In addition, there is also the second most patent layout in speech recognition, mainly including natural language modelling and speech recognition. In the application of E-Business, there are surprisingly many patent layouts at the management level, including marketing, resources management, and office automation.

In short, Knowledge is the basis; machine learning is the main method; speech-related technologies have been widely developed. Observed emerging trend focuses on speech-driven application, including automatic control for system integration and human 'object' interaction for better user experience.

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References

1. S. Reeves, , et al., Narrative video scene description task discriminates between levels of cognitive impairment in Alzheimer's disease. *Neuropsychology*, 2020. 34(4), p. 437-446.
2. J. Dai and Z. Ma, Automatic Identification of Bond Information Based on OCR and NLP. *Journal of Computers*, 2019, Vol. 14(6), pp. 397-403.
3. V.K. Jain and S. Kumar, Predictive analysis of emotions for improving customer services, in *Natural Language Processing: Concepts, Methodologies, Tools, and Applications*, IGI Global, Hershey, 2020.
4. A.P. Saygin, I. Cicekli, and V. Akman, Turing test: 50 years later. *Minds and machines*, 2000. Vol. 10(4), pp. 463-518.
5. S. Lloyd, Least squares quantization in PCM. *IEEE transactions on information theory*, 1982, Vol. 28(2), pp. 129-137.

6. D.M. Blei, A.Y. Ng, and M.I. Jordan, Latent dirichlet allocation. *The Journal of Machine Learning Research*, 2003, Vol. 3, pp. 993-1022.
7. S. Robertson, Understanding inverse document frequency: on theoretical arguments for IDF. *Journal of Documentation*, 2004, Vol. 60, No. 5, pp. 503-520.
8. B. Yoon and Y. Park, A text-mining-based patent network: Analytical tool for high-technology trend. *The Journal of High Technology Management Research*, 2004, Vol. 15(1), pp. 37-50.
9. A. Abbas, L. Zhang and S. Khan, A literature review on the state-of-the-art in patent analysis, *World Patent Information*, 2014, Vol. 37, pp. 3-13.
10. Y.G. Kim, J.H. Suh, and S.C. Park, Visualization of patent analysis for emerging technology*, Expert systems with applications*, 2008, Vol. 34(3), pp. 1804-1812.
11. G. Kim, and J. Bae, A novel approach to forecast promising technology through patent analysis, *Technological Forecasting and Social Change*, 2017, Vol. 117, pp. 228-237.
12. M. Thilakaratne, K. Falkner and T. Atapattu, A systematic review on literature-based discovery workflow. *PeerJ Computer Science*, 2019, Vol. 5, p. e235.
13. Y.-H. Tseng, C.-J. Lin and Y.-I. Lin, Text mining techniques for patent analysis. *Information processing & management*, 2007, Vol. 43(5), pp. 1216-1247.
14. Y.Y. Yang et al., Enhancing patent landscape analysis with visualization output. *World Patent Information*, 2010, Vol. 32(3), pp. 203-220.
15. D. Korobkin, et al. Methods of statistical and semantic patent analysis. in A. Kravets et al. (eds.) *Conference on Creativity in Intelligent Technologies and Data Science*, Springer, Cham, 2017. pp. 48-61.
16. J. Hu et al., Patent keyword extraction algorithm based on distributed representation for patent classification. *Entropy*, 2018, Vol. 20(2), 104.
17. S. Li et al., DeepPatent: patent classification with convolutional neural networks and word embedding. *Scientometrics*, 2018, Vol. 117(2), pp. 721-744.
18. J.-S. Lee and J. Hsiang, Patent classification by fine-tuning BERT language model, *World Patent Information*, 2020, Vol. 61, p. 101965.
19. T. Shanie, J. Suprijadi, and Zulhanif. *Text grouping in patent analysis using adaptive K-means clustering algorithm*. in *AIP Conference Proceedings*. 2017. AIP Publishing LLC, DOI: 10.1063/1.4979457.
20. A.J. Trappey, et al., Ontology-based technology function matrix for patent analysis of additive manufacturing in the dental industry. *International Journal of Manufacturing Research*, 2017, Vol. 12(1), pp. 64-82.
21. S.-S. Weng et al., Ontology construction for information classification. *Expert Systems with Applications*, 2006, Vol. 31(1), pp. 1-12.
22. A. Trappey, C. Trappey, and A.-C. Chang, Intelligent Extraction of a Knowledge Ontology From Global Patents: The Case of Smart Retailing Technology Mining. *International Journal on Semantic Web and Information Systems*, 2020, Vol. 16, pp. 61-80.
23. D. Tsatsou, et al., *Ontology construction*, in *USPTO*. 2013, US8620964B2, Google Technology Holdings LLC: US.
24. R. Subhashini and J. Akilandeswari, A survey on ontology construction methodologies. *International Journal of Enterprise Computing and Business Systems*, 2011, Vol. 1(1), pp. 60-72.

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Towards an Uncertainty Management Framework for Model-Based Definition and Enterprise

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Abstract. Globally the manufacturing industry is undergoing a shift in the way product specifications are defined, used, and re-used from conventional drawing-based systems to a comprehensive 3D digital product model. This transformation is at the heart of the digitization processes. The true benefits lie in the adoption of this technology throughout the product lifecycle. However, this digital transformation is partial and many of the stages in the product lifecycle are still heavily reliant on traditional drawings. This is due to the involvement of several uncertainties in the process of adoption of model-based definition. In this paper, a framework is proposed for the systematic assessment of the prevailing uncertainties in the adoption of model-based definition and enterprise. The framework proposed in this paper is aimed at identifying, categorizing, prioritizing, and mitigating the uncertainties in this process.

Keywords. Digital manufacturing, Uncertainties, Model-based definition, Model-based enterprise.

Introduction

The conventional form of product definition had been the 2D drawings for a long period. The advancements in technology made it possible to present 3D models in place of conventional drawings. This 3D model was initially used for visualization of the product only while the authentic source for engineering activities remained the conventional drawing. Gradually the evolution in this process allowed embedding functional tolerance and annotations (FT&A) to the 3D model and it started replacing 2D representation. This evolution continued with the introduction of semantic product manufacturing information (PMI) to the 3D model. This evolutionary advancement process aims to make this model a complete source of product information with semantic properties that can be used for all the lifecycle stages of the product. This leads to the digitization of the product definition, the realization of which is called a model-based definition.

Model-based definition (MBD) is a 3D model digital product model which is used as a single and complete source of product information instead of conventional drawings [1]. Model-based enterprise (MBE) adopts MBD for all the lifecycle of the product [2–

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4]. The high-value manufacturing industries like aerospace and automobile are ahead in this adoption. However, the journey towards MBE involves many challenges and uncertainties [5]. The previous researches had highlighted several uncertainties involved in this process. However, systematic work is needed to model these uncertainties from the perspective of risk and uncertainty management. This work addresses this gap by presenting the prevalent uncertainties in the adoption of MBD and proposing a methodology towards the development of a framework for the management of these uncertainties. The methodology involves using NUSAP pedigree assessment and Analytical Hierarchy Process (AHP).

1. Uncertainty Management Framework

In this study, the word “uncertainty management” has been used instead of “risk management” based on a concrete rationale. Firstly, the word “uncertainty” removes ambiguity related to the word “risk” which is a synonym of “threat” and “hazard”. Secondly, uncertainty management unlike risk management provides a broader horizon for the identification of uncertainties in project management practices. Thirdly, uncertainty management focuses on managing the source of the threat instead of only the threat itself [6].

The process of risk and uncertainty management has been described by various resources presenting almost identical phases. These are plan, identity, analyze (qualitative and quantitative), respond (treat), and manage (monitor, control, record, and report) [7,8]. This framework involves three of these phases that are explained below.

1.1. Identification

The first phase in uncertainty management is the identification of the types of uncertainties and their categorization. The documentation of the list of uncertainties at an early stage is a baseline for uncertainty management. This can be carried out by many tools like literature review, brainstorming, checklists, surveys, interviews, root cause analysis, assumption, and constraint analysis, SWOT analysis, document analysis, prompt lists, and use of structured facilitation in meetings and workshops [7]. The application of a suitable tool depends upon the dynamics of the project which can vary from case to case. The result of this process is a list of uncertainties that contains a description of each uncertainty in the project. In this work literature review, brainstorming and interviews are used for the identification of the uncertainties.

1.2. Assessment

In the second phase of uncertainty management, assessment of the uncertainties is made for achieving the goal of prioritizing. To ensure the authenticity of this assessment, both qualitative and quantitative methods are applied. The qualitative assessment builds on the level of respondent approach in the understanding of each of the uncertainty. For this purpose, Pedigree Assessment is adopted. The quantitative assessment on the other hand is used to measure the weight of the uncertainty. For quantitative assessment, Analytical Hierarchy Process (AHP) is adopted in this project. The combination of these two assessments provides the relative significance of each uncertainty in the form of a rating. The outcome of this phase will be a classification of the identified uncertainties in low, medium, and high significance groups so that each of the uncertainty could be dealt with concerning its importance in the project.

1.3. Response

The third phase in this uncertainty management framework is the response to deal with the uncertainties. This phase is helpful for the decision-makers to handle both opportunities and threats by reducing threats and enhancing the opportunities [7]. This will result in a knowledge base for the mitigation of the uncertainties in the implementation of MBD within the organization. Figure 1 provides an overview of all these three phases which are being followed in pursuance of the development of the framework.

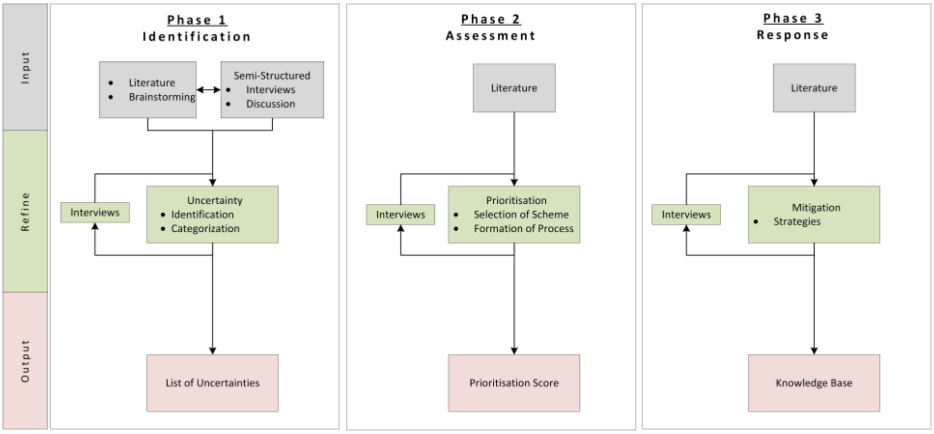

Figure 1: Phases for development of the framework

It is important to mention that this paper focuses on the first two phases of the framework. The response phase will be addressed later in the project. In the following section 2, the identified uncertainties are presented (Phase 1). While Sections 3 and 4 respectively present the qualitative and quantitative assessment methods (Phase 2).

2. Uncertainties in MBD

In their previous work, the authors [4] have figured out the key issues and challenges associated with the adoption of model-based definition. After further literature study and critical brainstorming, an initial list of uncertainties is prepared and sorted out into five categories. This project is being carried out in collaboration with two renowned aerospace organizations. Semi-structured interviews were conducted with cross-domain experts within these organizations to refine the list of uncertainties. It is further extended to brainstorming sessions with the co-researchers in the digital manufacturing research group at Cranfield University. This refinement process resulted in the addition of a few uncertainties and removal of a some other which do not fulfill the definition of uncertainty. Additionally, the terminologies and definitions of prevailing uncertainties are modified to enhance generalization, practicality, and understanding. While determining these uncertainties following dimensions of the area are explored.

- Elements of MBD
- Software support
- Hardware support
- Cost of implementation
- Supplier readiness
- Data trust- Both user and certification perspectives
- Other digital data challenges

The list of the key uncertainties that have been determined during this research is presented in Table 1 with a short description of each.

Table 1: List of Uncertainties

No.	Uncertainty Category	Uncertainty Type
1	Technological Readiness	• Software capabilities to meet the requirements of all lifecycle stages • Semantic PMI incorporation capability • Semantic PMI consumption capability • Interoperability between systems, data, languages, products, and processes • Hardware that supports MBD data • Low-cost hardware and software solutions for suppliers • Standards of MBD unlike standards of conventional drawings • Interpretation of standards and PMI application techniques
2	Managerial/Implementation	• Legacy data shifting to MBD • Vendor Lock-in • Supplier readiness for MBD - Technology and manpower capabilities • Supplier MBD capability assessment criteria • Absence of framework for evaluating benefits of MBD adoption at different stages of the product lifecycle • Clear MBE strategy (Phased/At-once) • Framework/criteria for evaluation and selection of MBD software • Ability to handle product complexity • Change management strategies to suit modified workflows and procedures • Training - Within organization and at supplier end
3	Trustworthiness	• Privacy, Confidentiality and Security of data • Model Quality: Caused by an error from software user, poor model development technique, CAD system, or translation • Reliability - Fulfilment of all the requirements which were available in the conventional form of product definition. • Resilience - Formats that support technological advancements which are fast and frequent

No.	Uncertainty Category	Uncertainty Type
4	Certification	• Availability - Uncertainty in the availability of data over a long period (Long Term Archival and Retrieval) • Accessibility- Over a long period the software provider no longer exists or if exist whether the current version supports older data • Interpretability - Lack of the capability of data format to be interpretable by all versions of the software • Integrity - Internal inconsistency or corruption of electronic data • Quality - Model data prone to quality defects cannot be certified as master data • Security
5	Affordability	• Supplier affordability • Lack of cost-benefit analysis framework to plan adoption of next level in MBE maturity • Organization's own ability to spend on new technology

3. The NUSAP System - Pedigree

The available knowledge base for new technology adoption is usually a combination of fragmentary information, assumptions, domain-specific knowledge, and incomplete awareness of the technology and its application. This could result in incorrect assessments that do not represent the factual state. While modeling uncertainties, problem framing is a critical aspect and different views or opinions are needed to be oppugned and refined through value-laden assumptions. For this purpose, a notational system of assessment (NUSAP) has been proposed by Funtowicz and Ravetz [9]. It is composed of five qualifiers that encompass many angles associated with the understanding of uncertainties. It records both the quantitative and qualitative dimensions of the problem and facilitates communicating them in an unambiguous, standard way. Letter P denotes 'Pedigree' in this system.

Benefitting from this system, the pedigree assessment approach is adopted in this paper. Pedigree is an evaluation mechanism for the production of information. The benefit of its use is that it reduces arbitrariness and subjectivity of the judgment and thus improves the quality of information. Moreover, it can transform qualitative data into quantitative data.

It is composed of a set of criteria. The assessment involves a qualitative judgment of the expert against each criterion. A pedigree matrix is used for coding this qualitative judgment into a discrete numeral scale with the linguistic description of each level on the scale. The criteria and the description of each level can be tailored in the pedigree matrices to suit the type of information in the project [10].

The process of applying the pedigree approach involves four steps. [10]. Firstly, the researcher needs to know the subject matter under consideration for interviewing the expert. And the expert is needed to have access to the related material. Second, a structure of uncertainty for the project is needed to be set. Thirdly, the expert thinking process encompasses the knowledge of uncertainty under consideration. The final step is an encoding which describes quantitatively the expert belief over the uncertainty variable [11].

In this work, three criteria have been adopted for the pedigree assessment. Each criterion and its description for various levels are tailored to suit this research.

1. 'Basis of Estimate' refers to the availability of the relevant data and the experience of the expert in the area.
2. 'Rigor in assessment' refers to the method used to collect and analyze the data being used for the assessment.
3. 'Level of Validation' refers to the degree of effort to check the data against independent resources.

A scale comprising of values 1, 3, 5, and 7 is used for this assessment. The greater the value the greater would be the level of uncertainty. The description of each level in the three criteria is shown in Table 2.

Table 2: Pedigree Matrix

Score	**Basis of Judgement**	**Rigour in Assessment**	**Level of Validation**
1	Best possible data, Large sample of data, Use of historical data	Best available practice in a well-established discipline	Best available, independent validation within the domain, full coverage of processes
3	Some experience in the area, Small sample of historical data, Internally verified data	Sufficiently experienced and benchmarked internal process with consensus on results	Internally validated with sufficient coverage of processes and verified data, Limited independent validation
5	An educated guess, Indirect approximation, Rule of thumb estimate	Limited experience of process with a lack of consensus on results	Limited internal validation, No independent validation
7	No experience in the area, Speculation	No discernable rigour	No validation

For each of the uncertainty, the expert has to assess the source of his knowledge and score accordingly. The average assessed score of the three criteria will be used in the prioritization of the uncertainty in combination with the AHP assessment.

4. Analytical Hierarchy Process

For weighting the relative importance of uncertainties in terms of their significance, Analytical Hierarchy Process (AHP) is adopted. AHP is a popular and long-used multi-criteria decision-making methodology [12]. It uses the approach of pairwise comparison between the decision criteria and thus makes it easy for the user to judge the criteria concerning their relative importance. The decision support methods are supposed to provide a trade-off between modeling and usability of the model. AHP fulfills this criterion well. Due to unambiguous methodology and ease of use, it has obtained wide acceptance among practitioners in addition to academia [13].

In AHP there is a goal, some decision criteria, and a set of alternatives for which decision is to be done [14]. The decision-maker uses pairwise comparison to give his opinion on his preference of the criteria using relative ratio scales [15]. For this comparison, Saaty has suggested a 9-point scale. These comparisons result in a comparison matrix. From this pairwise comparison matrix, the weight vector (w) is calculated based on Saaty's eigenvector procedure. This weight vector (w) provides the percentage relative significance of each of the criteria [16].

On the other end, the decision alternatives are judged by the experts who rank the alternatives against all the criteria set by the decision-makers. The same procedure of pairwise comparison and formation of a comparison matrix is repeated here to get the score matrix (S). Finally, the aggregation of both the processes i.e., for decision criteria and the decision alternatives, is done and the final result of this process is a ranking of the decision alternatives which takes into account both the decision-maker requirements and the expert judgment. This process is shown in Figure 2.

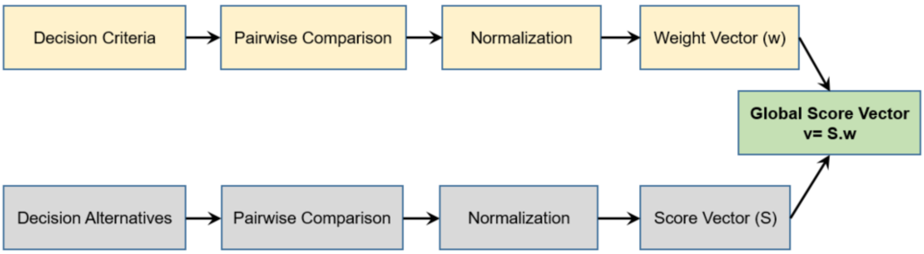

Figure 2. Analytical Hierarchy Process.

This framework involves AHP pairwise comparison of all the uncertainties to obtain weight vector (w). The relative significance thus obtained will be used in combination with the average pedigree score from the previous section to obtain the overall relative significance of the uncertainty factors.

5. Conclusions

Model-based definition is the core of digital transformation for product data and an important enabler of smart factory and industry 4.0. Model-based enterprise provides a competitive advantage to manufacturing organizations by improving their processes. The manufacturing industry in general and high-value manufacturing in particular is adopting it at a rapid pace. But this adoption is partial. The uncertainties in the process of this adoption are the obstacles in the realization of a complete model-based enterprise.

The pedigree assessment provides a purifying method for any judgment. By scoring the quality of the judgment, it facilitates to increase the credibility of the uncertainty management process. AHP is a tested and long-used technique for weighing the relative importance of various criteria. The use of this method eases the process of uncertainty management in the framework. It facilitates the comparison process by providing a pairwise approach and at the same time converting the qualitative judgment into quantitative data.

This paper has presented a novel approach for uncertainty identification and assessment for MBD. This will provide a platform for the industry to assess the uncertainties involved and subsequently formalize effective MBE policy. This is an ongoing research project. The data collection is being carried out from academia and industry. Based on this framework a software tool is also being designed. This tool will facilitate industry and practitioners in setting an effective MBE organizational strategy.

Working on mitigation of each uncertainty presented in this work is a unique area of research, however, the next phase of this work will focus on exploring and presenting mitigation strategies for the most significant uncertainties. This will be followed by presenting a tool for the management of these uncertainties.

References

[1] V. Quintana, L. Rivest, R. Pellerin, F. Venne and F. Kheddouci, Will model-based definition replace engineering drawings throughout the product lifecycle? A global perspective from aerospace industry, *Computers in Industry*, 2010, Vol. 61, pp. 497-508.

[2] T. Hedberg, J. Lubell, L. Fischer, L. Maggiano and A.B. Feeney, Testing the digital thread in support of model-based manufacturing and inspection, *Journal of Computing and Information Science in Engineering*, 2016, Vol. 16, pp. 1-10.

[3] S.P. Frechette, Model based enterprise for manufacturing, In: *44th CIRP International Conference on Manufacturing Systems*, Madison, 2011, pp. 1-6.

[4] K. Goher, E. Shehab and A. Al-Ashaab, Model-based definition and enterprise: State-of-the-art and future trends, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 2020, pp. 1-12.

[5] K. Goher, E. Shehab and A. Al-Ashaab, Challenges of Model-Based Definition for High-Value Manufacturing, In: *17th International Conference on Manufacturing Research,* Belfast, 2019, pp. 22-27.

[6] S. Ward and C. Chapman, Transforming project risk management into project uncertainty management, *International Journal of Project Management*, 2003, Vol. 21, pp. 97-105.

[7] K.H. Rose, *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)*, Project Management Institute, Newtown Square, PA, USA, 2017.

[8] *Risk management — Guidelines*, ISO 31000, 2018.

[9] S.O. Funtowicz and J.R. Ravetz, *Uncertainty and Quality in Science for Policy*, Kluwer Academic Publishers, The Netherlands, 1990.

[10] J.P. Van Der Sluijs, M. Craye, S. Funtowicz, P. Kloprogge, J. Ravetz and J. Risbey, Combining quantitative and qualitative measures of uncertainty in model-based environmental assessment: The NUSAP system, *Risk Analysis*, 2005, Vol. 25, pp. 481-492.

[11] J.A. Erkoyuncu, R. Roy, E. Shehab and E. Kutsch, An innovative uncertainty management framework to support contracting for product-service availability, *Journal of Service Management*, 2014, Vol. 25, pp. 603-638.

[12] A. Ishizaka, *Analytic Hierarchy Process and its Extensions*, Springer, Cham, 2019.

[13] A. Ishizaka and A. Labib, Review of the main developments in the analytic hierarchy process, *Expert Systems with Applications*, 2011, Vol. 38, pp. 14336-14345.

[14] T.L. Saaty, Decision making with the analytic hierarchy process, *International Journal of Services Sciences*, 2008, Vol. 1, pp. 83-97.

[15] A. Ishizaka and A. Labib, Analytic hierarchy process and expert choice: Benefits and limitations, *OR Insight*, 2019, Vol. 22, pp. 201-220.

[16] K. Goher, M. Jahanzaib, M.K. Ali, Consumer Preferences for Selection of Solar Home systems in Urban Areas, Pakistan, *Mehran University Research Journal of Engineering and Technology*, 2014, Vol. 33, pp. 441-448.

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Using AutomationML to Generate Digital Twins of Tooling Machines for the Purpose of Developing Energy Efficient Production Systems

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Abstract. The development of energy efficient production systems such as machine tools is a complex process. All specialised departments must work interdisciplinary during the design process in order to achieve an optimal result. In addition to the mechanical aspects, e.g., lightweight construction, the optimization of the Programmable Logic Controller (PLC) programs of tooling machines plays an increasingly important role. By optimizing the programs in terms of energy efficiency, the energy consumption of a machine can be significantly reduced. However, energy consumption depends on many parameters, so the optimization process is complex and a matter of all engineering disciplines working together. By using Digital Twins of tooling machines, simulations can be used to perform many parameter studies for optimizing energy consumption. However, the generation of Digital Twins of production systems is very expensive if they are to represent all relevant features of a production system. Through an IT system of networked software programs and using AutomationML as a special data interface these Digital Twins of machine tools can be generated automatically. The article describes the structure and function of this IT system and how it will be efficient within all involved engineering disciplines.

Keywords. AutomationML, Graph-based Design Languages, Digital Twin, Cross-domain Engineering, RAMI 4.0, transdisciplinary development

Introduction

According to numbers published by Eurostat, the industry is one of the biggest energy consumers in Europe, using 25.8% of all the Energy, that was consumed over all sectors in 2018 [1]. The European Union wants to decrease the greenhouse gas emissions to at least 55% compared to 1990 by 2030 as a part of the European Green Deal [2]. To achieve this and to reduce the footprint and the impact on the environment in the future, it will be mandatory, that energy consumption is a key factor within the development process of industrial used machines.

Besides the restrictions that will be made by the governments, another issue is the increasing cost of Energy, especially in Europe, that will make it harder for European

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companies to compete in the international economy. Companies in Europe will be forced to innovate their production processes in terms of Energy Efficiency.

Optimizing a production system towards Energy Efficiency is a complex task, as there is a big number of factors that impact the result. Therefore, a very close collaboration of all engineering disciplines, that are involved within the development process, e.g., mechanical engineering, electrical engineering, and information technologies, is required.

Simulations as digital twins of technical systems can help to optimize production systems. Many studies can be carried out on digital twins with little effort to determine a balanced relationship between productivity and energy consumption. These studies can also be carried out in parallel with a running production because production of the real system does not have to be interrupted.

However, the model generation of accurate digital twins is complex and there is no unified software platform that represents both the physical characteristics of a plant and its control. So, now data will be passed from one department to another and often needs to be converted, what is time consuming and will result in some type of data loss at any point [3]. The approach presented in this article involves an IT-technical combination of the AutomationML interface format with an automated process of model generation of digital twins using Graph-based Design languages to optimally implement the requirements in the development of energy-efficient production systems. The goal is, to create am IT-System, that integrates all involved engineering disciplines, so an iterative optimization cycle, as shown in Figure 1 can be approached, to optimize a production plant within the very early design phase. To achieve an optimised overall system, it is imperative to create a common data basis for all engineering disciplines to be able to use all the advantages of transdisciplinary cooperation throughout the entire life cycle.

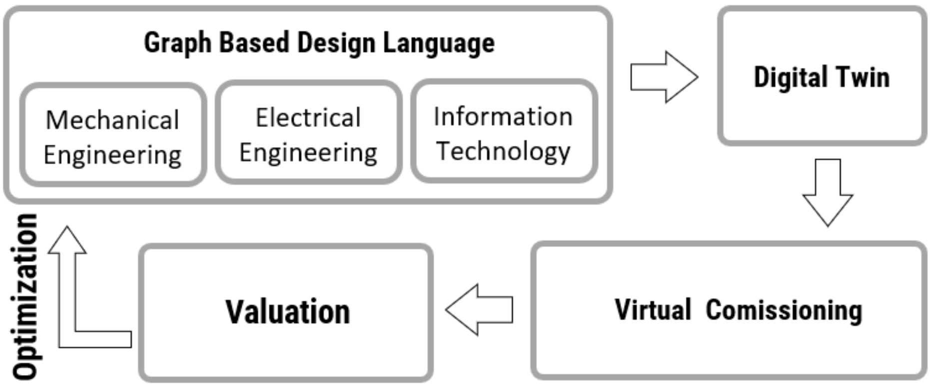

Figure 1. Iterative Cycle of Digital Production Optimization.

1. Relevant Work

This chapter will give a brief overview over the fundamental technologies and concepts that were used for this research as well as some hints to some other approaches towards achieving energy efficiency with the help of digital twins.

1.1. Production-System Design using Graph-based Design languages

Graph-based Design languages are used within all kinds of engineering disciplines. They are a useful method to systemize knowledge and therefore achieve interdisciplinary results by systemizing all features of the engineering process. They have three main aspects [4]:

- Vocabulary
  Vocabulary is part of abstract knowledge. It describes the available components within the design language and their correlation to each other.
- Rules
  The rules form the second part of abstract knowledge, and they are basically the blueprint for the design process. The rules can be influenced by a variety of parameters, which may lead to completely different models.
- Compilers
  A compiler is used to create instances of the design described in the vocabulary and rules. The model created by the compiler can then be used as a central model for various other applications.

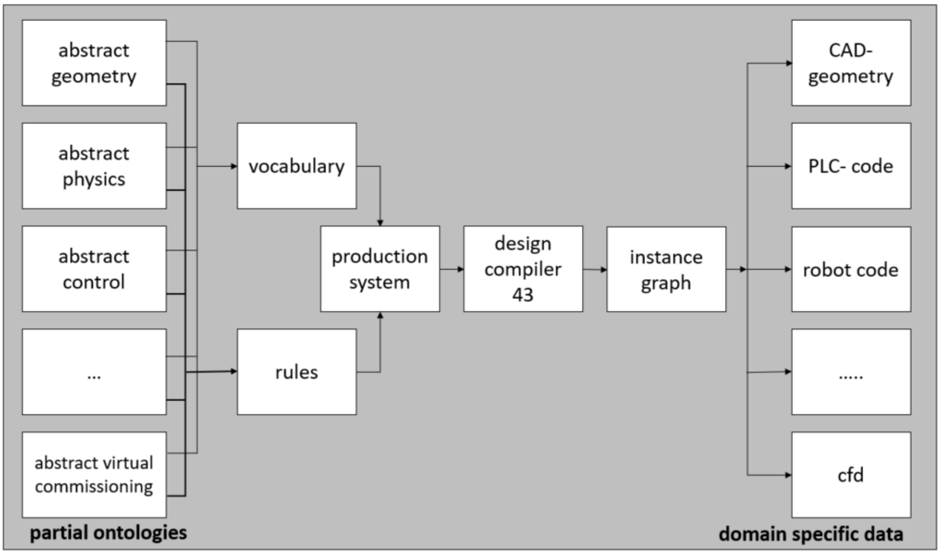

Figure 2. Schematic of the Graph-based Design languages, based on [5].

Figure 2 shows an overview of the structure and functions of Graph-based Design languages. Using these Graph-based Design languages, all functions and properties of a product and the according production system can be generated. For example, a production system that consists of different tooling machines and handling robots can be completely generated, including geometric data, production process flow and the programmable logic controller (PLC) codes, that will be running on the controls of the tooling machines and handling robots. The complete model can then be used along with the programmed controllers for Virtual Commissioning. For this purpose, it is mandatory that all knowledge from all involved engineering disciplines will be systemized using Graph-based Design Languages.

1.2. AutomationML

AutomationML is a data interface in the form of a data container as a file, that allows the departments of different engineering disciplines to easily exchange data. It is an XML-based format and can store all data, that is relevant for a production system. It can store 3D CAD geometries as well as PLC codes or robot programs. The exchange is standardized in IEC62713. Because the architecture has already been excessively described in numerous articles e.g., Beisheim et al. [4] [6] [7], only a brief overview is given here.

Figure 3 displays an overview of the structure of the data format of the AutomationML container. The Architecture itself is based on the CAEX-Format, which can be easily extended by linking to other files. Geometric and Kinematic data is stored as COLLADA standard, PLC Programs can be stored as PLCOpen XML. The format can also be extended to store additional data formats [8].

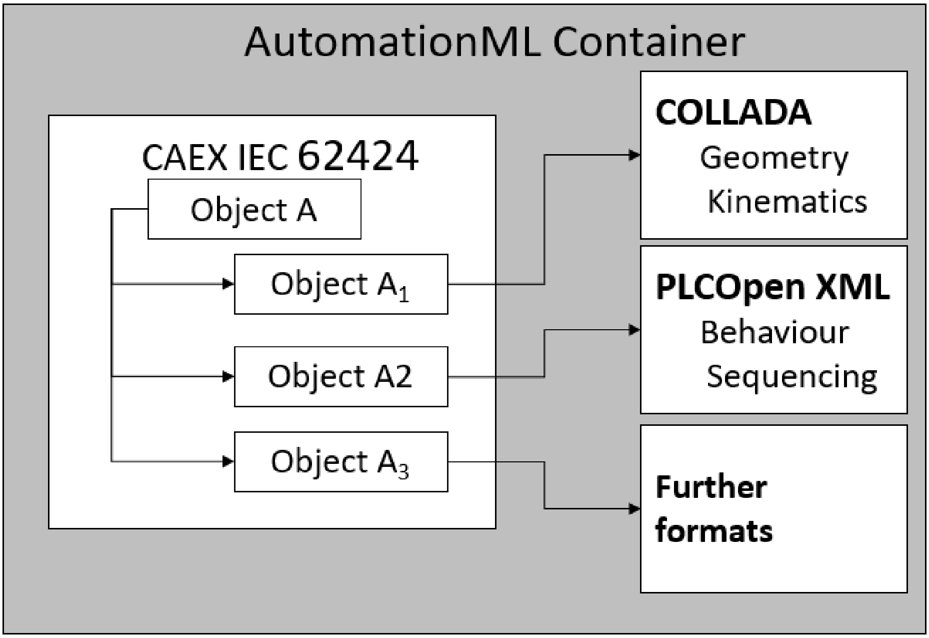

Figure 3. Schematic of the AutomationML container (based on [8]).

1.3. Attempts to using Digital Twins for Energy Efficiency Optimization

Using Digital Twins and Virtual Commissioning was a major topic in some recent research, but it is not a very common topic in the industry, as Lechler et al [9] are pointing out. Especially since it is very hard to start developing physical models of production systems, because there are no physical models of the components that are used within the production system available so far. Some attempts that try to increase energy efficiency focus on the process timelines and switching the production systems to standby modes during breaks and downtimes [10]. But to achieve more accurate results, it is mandatory, that the physical behaviour of the production plant is considered as well.

Damrath et al. [11] describe their approach to energy simulation using Physics Engines, that inherit from the gaming industry. Physics Engines can handle rigid bodies, soft bodies, and fluids. The problem with physics engines is, that most of them calculate the movements and forces based on contact forces. This method is working very well for rigid bodies, but makes the simulation computationally very intense, if fluids or soft bodies need to be considered within the calculation [11].

So, although Physics Engines make Virtual Commissioning more accurate, they still do have limitations, which is why the authors chose a different approach to involve accurate physics in Virtual Commissioning, which will be described in the following sections.

2. Virtual Comissioning

In order to be able to determine the energy consumption of a machine using a digital twin, it is imperative to create a very accurate image of the machine using the functions of a Virtual Commissioning model. The model must also have interfaces to the PLC code so that the actual production processes can be examined and optimised.

2.1 Using Unity3D for Visualisation of a Digital Twin with AutomationML

Unity3D is a software engine for creating 3D content and applications. It was originally created as a Game Engine but because of the open software, that Unity provides, it is now used for all kinds of 3D content creation, including Virtual Commissioning purposes. Unity is based on C# so it can work with many APIs and SDKs for all kinds of use cases. Therefore, Unity3D is an excellent choice for visualisation of Virtual Commissioning Model. A custom developed import extension for AutomationML (AML) files allows the user to load with other software generated files into the simulation environment in Unity3D at runtime. The Collada geometry data contained in the AML file is placed as geometry objects in the scene and each object is assigned its position and functional properties by attributes in the file.

Logic Facets as functions newly developed in Unity3D within the scope of a research project enable the animation of the production process without interfacing with a PLC software. This is very helpful for a first check of the production process or for simple presentation cases. But for an accurate Virtual Commissioning Environment it needs interfaces to commercial software e.g., Beckhoff TwinCAT, so the PLC code can be tested with the Digital Twin of a machine or a robot handling system. For this purpose, interfaces for commercial PLC software were programmed in Unity3D. The interface for Beckhoff TwinCAT is based on the Beckhoff TwinCAT ADS framework, which can be used as an interface with all kinds of C# applications.

As shown in Figure 4, the ADS interfaces connect the input and output communication between the TwinCAT PLC Simulation and the Unity3D Simulation Environment. This has created a Digital Twin of a machine or robot that responds to PLC code. Via the ADS interface, the TwinCAT software, for example, receives input signals from events from the Logic Facets in the Unity3D environment, such as the interruption of a light barrier by an object. TwinCAT then triggers programmed actions at the output of the PLC Simulation e.g., that the rotation of a motor shaft should stop. The signal is transferred to Unity3D as input via the ADS connection. The Logic Facet of the motor object then stops the rotation of the motor shaft. In this way, the PLC code can be tested and optimised within the Virtual Commissioning Environment to achieve an optimal production process with good energy efficiency.

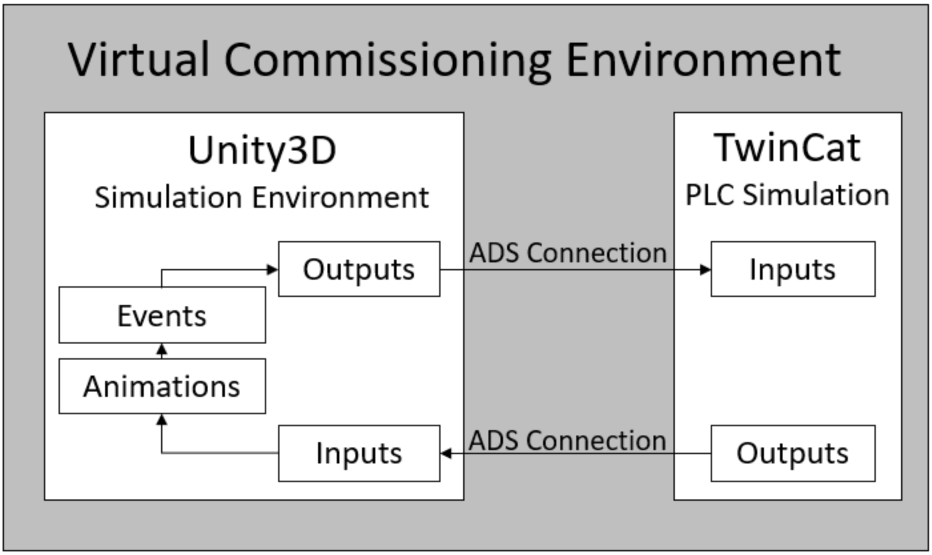

Figure 4. Schematic of the Unity3D - TwinCAT communication.

2.2 Using ISG Virtuos for physically accurate Virtual Commissioning

The software Virtuos is a real time simulation software for physically accurate models provided by the Company ISG. Virtuos provides a very large library of mathematical models that can display an accurate behaviour of all kinds of used actors of a production system e.g., hydraulic/pneumatic cylinders, servomotors, gearboxes etc. Using these physically models, it is possible to calculate the energy that is needed for every component, without dealing with the challenges and limitations that come with other Physics Engines.

To be able to use this mathematical model within the Virtual Commissioning Environment, a custom C++ UDP-Interface in Unity3D was developed. The interface is based on the publisher-subscriber principle for communication data. For this communication function, where something can be calculated in Virtuos, a special attribute is added in the AutomationML container. As displayed in Figure 5, the calculations of each process e.g., hydraulic cylinder forward, will be triggered by a write request from the Unity3D Environment. The calculation of the progress is calculated than in Virtuos and the Unity3D Environment will subscribe to the topic, which enables the Simulation Environment to update the actual position of the movement via the UDP interface. The updates will be displayed each frame, what means, that it will update all movements with a framerate of 30 fps, so a very fluent visualisation can be achieved. This way, the simulation of the production process can be very detailed and physically accurate.

Virtuos does not support the use of AutomationML files by default so far. However, the program can import a simulation model as an ecf file, but this presents some challenges for automatic modelling. The solution developed in the research project is to create a suitable ecf file outside the program, which then must be imported into Virtuos.

This file is therefore created by the Graph-based Design language in parallel with the AutomationML file.

2.3 More Interfaces for more accurate Simulations

With the interfaces described a solution for a detailed visualisation, accurate physical calculations as well as for the connection to a PLC control software has been achieved. However, to make the Virtual Commissioning environment even more complete, an interface for a commercial robot control software is still needed. The software KUKA.OfficeLite from the company KUKA offers a good solution for virtual robot programming. Therefore, another UDP interface to Unity 3D was developed, which enables communication between the Unity3D Simulation Environment and the Kuka Control Software.

The open architecture of Unity3D allows the creation of a complete virtual commissioning environment with further interfaces to all types of commercial software that will be able to meet many requirements for digital twins of machine tools while working with the AutomationML container. Further interfaces to other types of software for commercial applications can also be added to Unity3D.

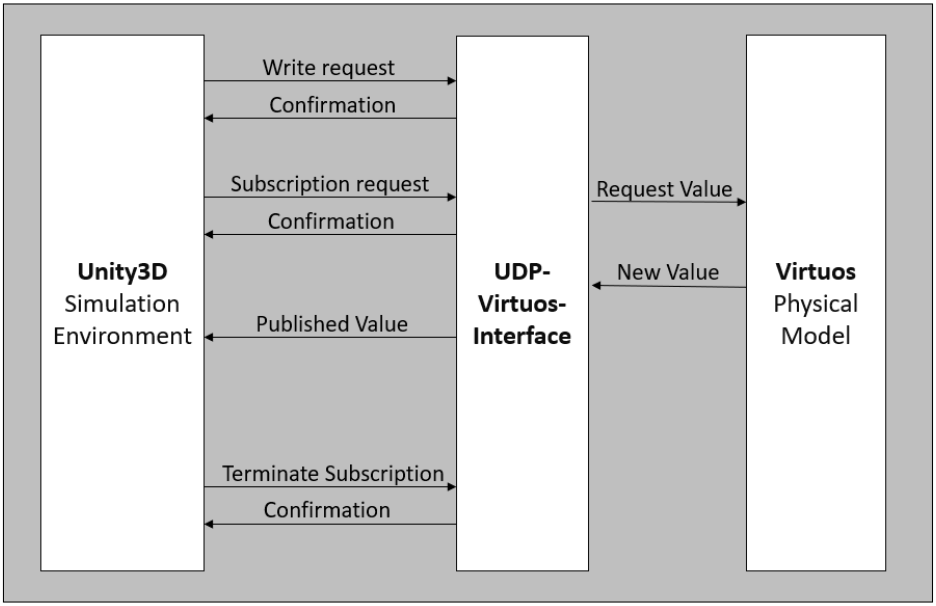

Figure 5. Schematic of the Unity3D - Virtuos communication.

3. Optimizing the Production Process and Energy Efficiency

The graph-based design language generates all the data needed for a complete virtual integrated product and production process development. All engineering disciplines can work with the same database, which prevents data loss and additional effort for data conversion between different IT tools.

Figure 6 shows the entire IT system with the schematic workflow for optimising a production process and its energy efficiency. The use of a complete IT system makes it possible to carry out many iterations through numerous different variations of the product itself as well as the production system with which it is to be manufactured, even before any form of actual production must take place. During the simulation, pre-defined data is stored. The evaluations of this data are the base for further optimization of the production process and energy efficiency. For this purpose, the parameters are then manually changed in the graph-based design language.

With the help of this IT system, which was developed as part of a research project, products with their production processes can already be developed in the development phase through the application of digital twins and virtual commissioning, which have an optimal relationship between economic, functional and ecological aspects.

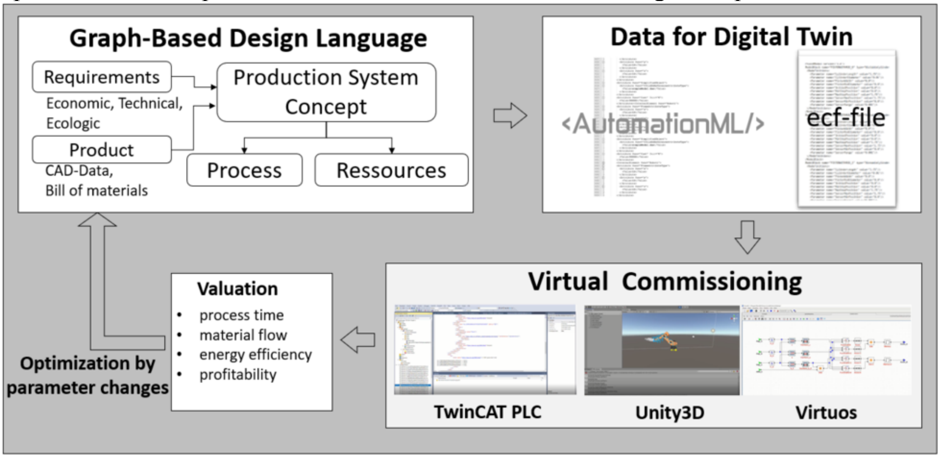

Figure 6. IT system for the optimisation of Product, Production Process and Energy Efficiency.

4. Application of the IT-System for Virtual Commissioning

In this section, a small example of the application with a single robot arm will be described, because a complete study of a production system would exeed the volume of this paper. As an example, an industry standard 6 axis robot is used to unload parts from one machine and loading it onto the next machine in the production process.

Given the fact, that there are infinate possibillities on how this small part of the production can be structured, it seems impossible for humans to optimize an entire, complex production plant.

The first task would be to choose the correct robot arm for this purpose, which will primarily be a matter of the required workload, but also of the required workspace, that the robot will need to cover. Choosing the correct robot arm is a simple task that a human can complete without effort. The next step to plan the process of the robot would be to determine the spot where the robot will be placed in the production process. Normally the planning engineer will just choose a place where the robot will be able to reach both points for loading and unloading the workpieces. On Site, there will be a programmer who will program the robot arm to load an unload the parts. Often, the robot programmer will just use the point-to-point programming feature of the robot programming software. The trajectory speed will be roughly adjusted to the rest of the process.

The described way to place a robot within a production plant is a simple, straight forward process. However, it does leave room for optimization.

If a production plant is entirely described as a digital twin that was generated by a graph based design language, it is easy to swap out single components. Therefore it is very simple to carry out a big number of parameter studies, where basically every component of the production plant can be swapped or modified, no matter if it is an actual component, PLC code or robot code. This enables an iterative approach, to optimize a production plant in a way, that is needed.

So, the 6 axis robot arm needs to be optimized to use a minimal amount of energy, without causing a bottleneck in production capacity. The robot arm is physically described in an .ecf file, that is loaded into the Virtuos Software. It consists of frequency converters, synchomotors, gear drives and the axes of the robot. The code of the robot is saved in the AML file and imported into the robot control software (e.g. KukaOffice Light). The geometries are then loaded into the visualization environment in Unity3D that also handles all events and acts as the center of the virtual comissioning IT system. The trajectories are given by the robot program, that connects to Unity3D. There the trajectories will be shown according to the calculations in Virtuos. Given the required speed and acceleration of the robot arm, determined by the robot code, as well as the robot axes and the weight at the Tool Center Point, the needed energy can be calculated by Virtuos. An iterative process, where the position and the robot, as well as the trajectories, speeds and accellerations can be adjusted, enable the development team to find the optimal parameters by testing a large number of different combinations.
The robot speed can therefore be adjusted precisely to the rest of the production process. So unneccesarily high accelerations and speeds can be avoided.

To confirm the results of the digital optimization, an existing robot arm in the laboratory of the university was equipped with sensors to collect data of accelerations in the tool center point and also measure current on all frequency converters simultaneously. The measurements show, that the robot did use less energy when it used the optimized movement commands, because they used slower speeds, so the robot never has any pause times, but just fulfills the requirements to move the parts, so the rest of the plant also does not suffer from a bottleneck that is created by slow trajectory speeds.

5. Conclusion and Further Research

The mapping of machines as Digital Twins and used in Virtual Commissioning Environment have a great potential to optimise products and production processes. Such an IT system consisting of a Graph-based Design language, AutomationML interface and visualisation in Unity3D with interfaces to PLC, Physics Engine and robot controllers enables closer cooperation between the various engineering disciplines.

The automatic generation of Digital Twins by Graph-based Design languages, as described in detail in Kiesel et al. [6] and Beisheim et al. [7], enables the rapid development of different variants of simulation models of the products and processes for parameter studies e.g., regarding energy efficiency. This automatic generation also reduces the effort of using Digital Twins for optimization in the development phase of a new product and its production processes. The usage of Graph-based design language as an instrument to systemize (capturing, storing and providing) knowledge off all product engineering disciplines makes it easier for the departments to collaborate interdisciplinary.

The use of the Virtuos software integrated into the IT system enables the calculation of the physical relationships of the simulation objects. However, it also increases the effort to create the models. A future improved availability of simulation models of components such as motors, pneumatic cylinders, etc., which are made available online by the component manufacturers, will significantly reduce the effort for model creation. In further research projects, the IT system is being validated using data from machines and processes from the industry. And through further functional developments of the overall system, the degree of automation is constantly being increased.

Acknowledgement

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References

[1] European Commission/Eurostat, 2019, *Final energy consumption by sector, EU-27*, 2018 (% of total, based on tonnes of oil equivalent), Accessed: 15.02.2020. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Final_energy_consumption_by_sector,_EU-27,_2018_(%25_of_total,_based_on_tonnes_of_oil_equivalent).png

[2] European Commission, 2020, *2030 climate & energy framework*, Accessed: 15.02.2020. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2030

[3] N. Beisheim, T. Ott, S. Amann, *Einsatz von AutomationML zur automatischen Generierung von Digitalen Zwillingen von Werkzeugmaschinen zur Entwicklung energieeffizienter Produktionssysteme*. 26. Interdisziplinäre Wissenschaftliche Konferenz, Mittweida, April 14th-15th, 2021.

[4] N. Beisheim, M. Kiesel, S. Rudolph, Digital manufacturing and virtual commissioning of Intelligent Factories and Industry 4.0 systems using graph-based design languages, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 93-102

[5] S. Rudolph, On the problem of multi-disciplinary system design - and a solution approach using graph-based design languages, *1st ACCM Workshop on Mechantronic Design*, Linz, November 30, 2012.

[6] M. Kiesel, P. Klimant, N. Beisheim, S. Rudolph, M. Putz, Using Graph-based Design Languages to Enhance the Creation of Virtual Commissioning Models, *Procedia CIRP*, Vol. 60, 2017, pp. 279-283.

[7] N. Beisheim, M. Kiesel, M. Linde, T. Ott, Using AutomationML and graph-based design languages for automatic generation of digital twins of cyber-physical systems, *Advances in Transdisciplinary Engineering*, 2020, Vol. 12, pp. 135-142.

[8] AutomationML e. V., 2016, *Standardized data exchange in the engineering process of production systems*. Accessed: 15.01.2020. [Online]. Available: https://www.automationml.org/o.red/uploads/dateien/1544706233-automationml.pdf

[9] T. Lechler, E. Fischer, M. Metzner, A. Mayr, J. Franke, Virtual Commissioning – Scientific review and exploratory use cases in advanced production systems. *52nd CIRP Conference on Manufacturing Systems*, Ljubljana, Slovenia, June 12-14, 2019.

[10] S. Mechs, S. Lamparter, J.P. Müller, J. Peschke, Networked Priced Timed Automata for Energy-efficient Factory Automation, *Proceedings of the American Control Conference*, June 2012.

[11] F. Damrath, A. Strahilov, T. Bär, M. Vielhaber, Establishing Energy Efficiency as Criterion for Virtual Commissioning of Automated Assembly Systems, *Procedia CIRP*, Vol. 23, 2014, pp. 137-142.

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A Preliminary Discussion of Digital Transformation and Semantic Interoperability to Support the Information Exchange in the Business Process

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Abstract. The development of interoperability is more and more an essential task for all kinds of organizations. It needs to be measured, verified, and continuously improved. With the advent of the Internet of Things, Industry 4.0, Digital Transformation, as well as all technologies it brings, such as big data, cloud computing, and mobile applications, this subject become quite ordinary and necessary, not only in a manufacturing scenario but also in a business process. As crucial benefits, it can bring possible gains for developers and users, also reduce the efforts to communicate multiple and different platforms. Like all new implementations, there are significant challenges that have to be overcome to allow satisfactory results. In this paper, after a systematic literature review to better understand the technologies and this new situation, we conduct a study involving a case in a business process, presenting some actions that can be executed and technologies that can be implemented to reach a well interoperable environment. For instance, to analyze the interoperability maturity level and to adopt ontologies as an alternative to integrate heterogeneous systems. Finally, in the last part of the paper, we give conclusions and perspectives for futures works.

Keywords. Enterprise interoperability, digital transformation, digitalization, ontologies, transdisciplinary.

Introduction

In the globalization scenario, enterprises are challenging several tests, like the emergence of new technologies, personalized customer demand, globalization. To handle that, most companies are gradually changing their vision and the market structure, becoming more collaborative with whom it gets involved. It permits all stakeholders to create more value for their business.

As observed in source [1], it is crucial since the current customers are more connected to the internet, especially the digital natives, for whom technology is part of daily life. It has caused a transformation in the way to select, buy, and consume products

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and services. This kind of change has been called Digital Transformation (DX), otherwise called Digitalization. Nowadays, the manufacturing DX is the most common, but others exist, like the Digital Business Transformation, which is also becoming essential for the entire market. Data analytics, cloud computing, augmented reality, pattern recognition, artificial intelligence, and machine learning are some technologies that enable those changes.

All those processes have to break down barriers that, somehow, are slowing or making it impossible. To source [1], organizations need to deal with those companies are in-depth traditional sectors while finding an alternative to adapt themselves as soon as possible, since customers are imposing their rules faster and faster. The inadequate or overly heterogeneous systems, companies' structure or culture, lack of DX strategies, ROI (Return on Investment) visibility, and shortage of skills and a qualified labour force are some points of [2].

As a successful result, companies can connect people, businesses, and things. Highly influenced by disruptive IT, it enables them to create new products and services or make them more efficient, with a competitive advantage, generating good results not only for the economy, but also for society, industry, and business [3]. For instance, Vivo has adopted the agile-squad model and open innovation as the basis of its DX implementation; Hospital Samaritano and Hospital Sírio-Libanês had invested in it to improve their patient experience and operational performance [1].

To source [4], the business DX is a set of 7 elements: business model, organizational structure, digital skills of employees, digitization of business processes, IT infrastructure, digitization of products/services, and digital channels for interaction with clients.

The digital transformation is different for each company since there are infinity strategy possibilities. Knowing that and that exist several ways to implement the DX, the communication between companies, even inside themselves, can become a huge barrier. In this context, interoperability is a must to make everything work correctly, making systems share and use the information without losing it or having a weak interpretation [5].

1. Problem Statement

Digital transformation has been placed users at the heart of the corporate strategy. Indeed, they are more and more demanding concerning products and services' quality and custom. Nevertheless, it does not concern only the company's customers but also collaborators and employees. Mobility, connected objects, and collaborative platforms are investments done by enterprises to provide value-added services to them [1].

Since that, DX is providing business and market dynamism, principally in technology-intensive industries. Products, business models, company culture, labour market are continuously changing, and all companies need to adapt themselves as soon as possible to prevent being consumed by the new reality. Some of them are reorganizing themselves to work with two modes. In the first one, companies keep a traditional business operating. In the second one, the disruptive, they seek opportunities to introduce products and services that take advantage of the new market. However, most companies do not commercialize technologies that may cannibalize their own business unless a big part of the market needs it. With that, disruptive companies explore the gap left by the market leaders, developing new products and services that fill customers' additional requirements [1][2].

One of the most crucial steps of DX is the transformation strategy. A successful scenario must have a good plan and a well-defined reengineering and optimization of the business process. Without that, companies may become more focused only on technology instead of on the customer.

Even though all benefits digital transformation can bring, there are also adverse outcomes and potential issues, principally in the security and privacy domain. Eliminate them is necessary, or they may cause serious problems. Decision-making algorithms, for instance, carry significant risks since big decisions can be made without human concern. Since that, this kind of technology should be carefully developed and tested [6].

DX is opening the path for technology innovation, new business models, and cross-industry collaboration. The increased number of software, intelligent machines, systems, and applications created complications involving interoperability. It exists more than only among the same level or enterprise. Interoperability can share data and information between interacting enterprises and their related systems. An interoperability problem can cause several difficulties and can drastically influence the performance and the outcomes of enterprise business [5]. Accordingly [7], the United States Department of Commerce Technology Administration estimated that inadequate interoperability between systems in the United States Capital Facilities Industry was U$15.8 billion for them.

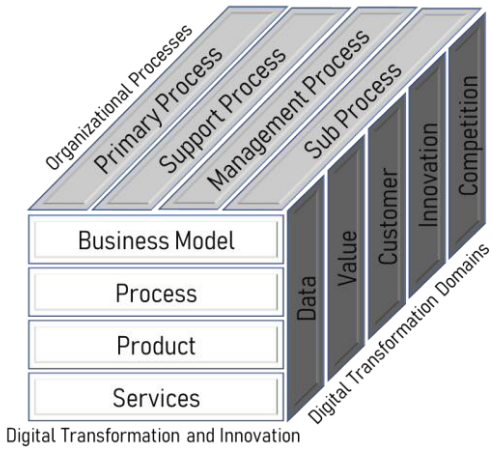

Figure 1. Business Digital Transformation Dimensions.

For analysing the barriers of DX implementation, it is possible to consider three dimensions, as illustrated in Figure 1: the dimension of the domain, the organizational process dimension, and the digital transformation and innovation type dimension. The first dimensions concern the set of domains involved in the company business or sector where DX will be applied. Here, each domain has its digital transformation and innovation type since its needs are different from the others require different approaches. The second dimension is related to all activities necessary to transform all its resources into products and services. The last represents all layers that the DX can achieve, from the product to the entire business process.

The interoperation between all dimensions is also identified. It is crucial to maintain the system working correctly, besides allowing quick and easy implementation of future technologies and systems. Moreover, it permits a transparent sharing of information and the continuous improvement of the entire environment.

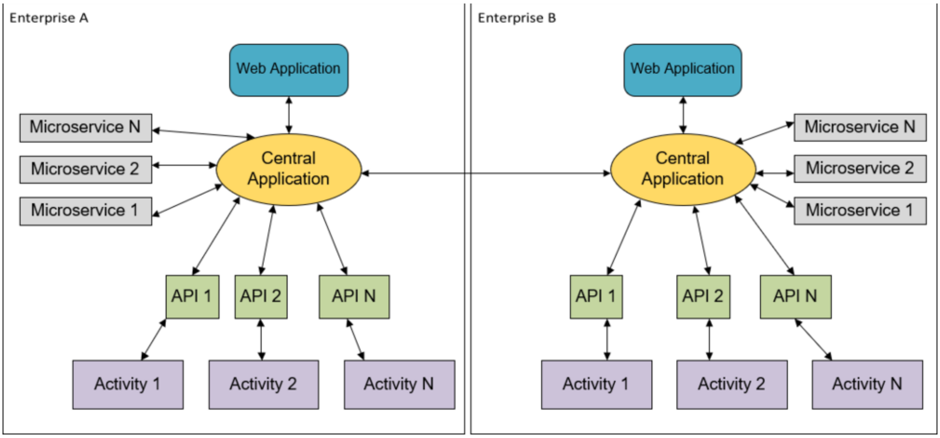

Figure 2. Communication between enterprises and inside them.

Figure 2 shows a model capable of solving the problem of integrating information and digitizing its processes. It is represented the integration of two companies but can be applied to the integration of N companies.

To carry out the necessary activities, the model makes use of several APIs and Microservices. Those techniques are widely used in the development of MRP and ERP systems, and their modularization capacity makes the development of new tools more efficient and robust [8].

In the “Web Application” block exists a web application, where all the services that the various employees of the company can use.

Right below, there is the “Central Application” block. This layer is responsible for managing the requests from inside and outside the company. It allows filtering information and requests for the APIs that do the work. This layer is the most important for this model, as it is in this layer where the integration of several companies occurs. This role is just to route calls to the distinct APIs, and it is crucial that, in this layer, no functionality of the process to be digitized is implemented.

The “Central Application” has the role of integrating several Microservices and APIs, which are responsible for carrying out all the activities necessary for process digitization in question. It is recommendable that, during development, standards such as semantic WEB and ISA 95 be used, especially in this layer.

2. Technological Background

This section analyses existing works that support the understanding of what Digital Transformation is and what is vital during implementation. Besides, it is treated about interoperability (which is viewed as a reliable way to communicate with all other systems around it).

2.1. Digital Transformation

As related in source [9], digital transformation is understood as to how technologies influence aspects of human life. It is possible to unify this idea with the role of digital transformation in influence how software is developed to facilitate integration and support activities [8].

Nowadays, it is common to use multiple platforms, such as tablets and cell phones, to do plenty of activities. As a result, companies started to use new development methods for their applications instead of developing the same applications for each existing platform on the market [8].

The digital transformation brings significant changes, such as integration of various sectors of the company and distinct companies, new market opportunities, and gains in competitiveness [2]. More than this, the digital transformation of society brings what is called Hyper-Connected World, where human and artificial actors are linked with each other, allowing a new way to execute business processes [3].

With customer satisfaction and operational excellence as motivation, digital transformation proves to be a decent solution to optimize existing processes or assist in the optimized processes creation since it has an attractive implementation cost. It occurs since most digitization problems can be solved with software development to integrate existing systems and tools [2]. However, most companies do not have a good plan for implementation or an idea of how to start their DX journey. In this scenario, a well-defined strategy is crucial [10].

In the development of digital transformation software, it is recommended to use development techniques based on Microservices and APIs (Application Programming Interface). Microservices can reduce development time as they can be developed independently for each activity they must perform and can communicate with varied technologies. On the other hand, APIs can establish standards for how distinguished applications communicate [8].

APIs can also be used to provide functionality and information for various platforms, providing robustness and flexibility. Some examples of APIs on the market are the Google and Facebook APIs [11].

2.2. Interoperability

In the globalization scenario, enterprises are challenging several barriers, like the emergence of new technologies, personalized customer demand, globalization itself, for example. To handle that, most companies are gradually changing their vision and becoming more collaborative with whom it gets involved. It permits all stakeholders to create more value for their business. In this context, interoperability is a must to make everything work correctly. Systems can share and use the information without losing it or having a weak interpretation [5].

Interoperability is also necessary between systems in the same enterprise. Each year, the need for more information and data is becoming more significant. In most cases, it is crucial to share data among departments, factories, countries so on. Communication should be complicated since there are heterogeneous domains, different languages, and environments where the same symbol may have distinct meanings or overlap it [12]. But to it be clear, some technologies should be applied, such as OWL (Web Ontology Language), to allow everyone to understand the information in the same way, as showed by source [13].

There are a variety of frameworks that have been suggested to allow interoperation between different systems. Usually, they transform the information into more structured data. Source [5] presented some examples in their research: the ATHENA Interoperability Framework (AIF), responsible for capture the research elements and solutions to interoperability issues, the European Interoperability Framework (EIF), which describes the different interoperability levels and focus on the interoperability between public entities from various government around Europe, and the INTEROP Network of Excellence (INTEROP NoE).

3. Preliminary method to support interoperable information exchange in the business process

The case study is a process in a Brazilian multinational company, more precisely in the logistic system. In that process is done the transport schedule of production commodities. It is necessary to execute two planning: (i) the material collection in suppliers; and (ii) the delivery in a consolidation centre; the transportation from it to eight company's plants around the country and neighbour countries. In that is used data from SAP and suppliers' documents. The current process must be made once a week. The logistic team does some procedures manually, which costs approximately ten hours. Besides that, plenty of mistakes occur accidentally, causing additional costs to the company and rework hours. The enterprise is studying to digitalize the entire process to reduce extra costs and repetitive works.

After reviewing the related works, a solution is proposed for the business process's digital transformation. Its four stages are shown in Figure 3.

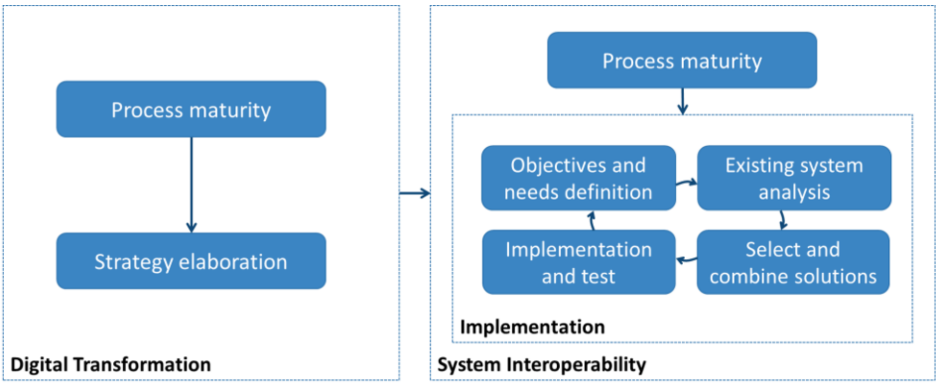

Figure 3. Stages of Business Process's Digital Transformation.

As the first step, it is necessary to measure the digital transformation maturity, in other words, verifying the process transformation stage. It allows us to know how the enterprise approaches its transformation and maps how it can or should be after that. Besides, it is possible to realize what kind of strategy would be more accurate for the case. Two different models can be used, proposed by sources [14] [15].

In the first one, the authors created a list with twenty-eight statements, where each interviewee needs to respond how much does he/she agrees with it, on a scale of zero to three (completely disagree, somewhat disagree, somewhat agree, and completely agree). The questionary is divided into four dimensions: (i) Culture: A company's approach to digitally driven innovation, and how it empowers employees with digital technology; (ii) Technology: A company's use and adoption of emerging technology; (iii) Organization: How aligned a company is to support digital strategy, governance, and execution; and

(iv) Insights: How well a company uses customer and business data to measure success and inform strategy. The potential score range is 0 – 84, and there are four possible maturity stages, presented in Figure 4.

Maturity segment	Characteristic behavior	Strategy	Score range
Differentiators	Leveraging data to drive customer obsession.	Blend the digital and physical words.	72-84
Collaborators	Breaking down traditional silos.	Use digital to create competitive advantage.	53-71
Adopters	Investing in skills and infrastructure.	Prioritize customer over relationships over production.	34-52
Skeptics	Just beginning the digital Journey.	Prompt a willing attitude.	0-33

Figure 4. Distribution into Four Maturity Segments.

In the second model, the author identified six stages of digital maturity, represented in Figure 5, each one representing the company's key moments and milestones through the digital transformation, offering visibility and guidance to the leaders and participants.

For that model, interviewed should identify which level is more proximal to their enterprise reality. It is permitted to select one adjacent stage if there are elements located in both, for example, in a stage transition.

The second stage, where is defined as the transformation strategy, is also described in Figure 4 and Figure 5. For the implementation stage, to measure the interoperability maturity, some models fit with the requirements, such as the Interoperability Measurement Approach (IMA), applied by source [16], and the one presented by source [17] called the Maturity Model for Enterprise Interoperability (MMEI). In this article, the MMEI approach will be explored. It deals with all key interoperability aspects and covers the main concepts of existing interoperability maturity models. MMEI is a long and iterative process, with interoperability potentially view and with a posteriori approach, which means that the interoperation already exists, and the analysis is over the existing interoperability situation. This model allows us to understand the system probability to support efficient interoperations and its weakness.

There are four levels, or stages, of interoperability:

- Level 0 - Unprepared: There is no capability for interoperation
- Level 1 - Defined: Capable of modelling and describing to prepare interoperability
- Level 2 - Aligned: Capable of making changes to align with common formats and standards
- Level 3 - Organized: Capable of metamodeling to interoperate with multiple heterogeneous partners
- Level 4 - Adapted: Capable of dynamically accommodating with any partner

Those levels could be summarized as isolated, connected, integrated, unified, and federated, respectively.

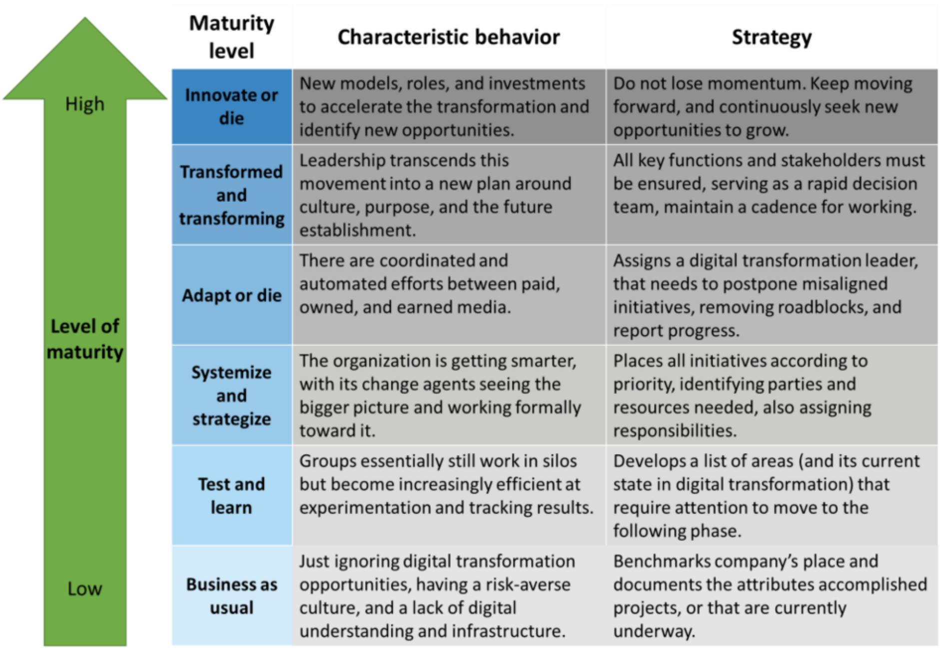

Figure 5. Distribution into Six Stages of Digital Maturity.

Table 1 is presented the focuses and concerns at each maturity level and for each interoperability barrier category.

Table 1. Focuses and concerns of MMEI for each interoperability barrier.

Maturity Levels / Barriers	Conceptual	Technological	Organizational
Level 4 - Adapted	Accommodated	Reconfigurable	Agile
Level 3 - Organized	Mapped	Open architecture	Trained
Level 2 - Aligned	Adhered	Arranged	Flexible
Level 1 - Defined	Modelled	Connectable	Specified
Level 0 - Unprepared	Incomplete	Inaccessible	Inexplicit

The final score of each maturity level is the metric "*Mk*", calculated from the scores Sij assigned by the evaluators for each interoperability concern "*i*" and interoperability barrier "*j*". It needs to be evaluated using a linear percentage scale, from 0 to 100%. For a maturity level "*k*", the following scale can be used: (i) $0 < S_{ij} \leq 15$: not achieved; (ii) $16 < S_{ij} \leq 50$: partially achieved; (iii) $51 < S_{ij} \leq 80$: achieved; (iv) $81 < S_{ij} \leq 100$: fully achieved.

M_k then is calculated by Equation (1).

$$M_k = \frac{1}{n_i.n} \sum_{i,j=1}^{n,n_i} S_{ij} \quad (1)$$

where, “n_i” the number of interoperability barriers to evaluate; n the number of interoperability concerns, “S_{ij}” the scale associated with the interoperability concern j at the interoperability level “i”

This stage is crucial since interoperability is considered one of the most challenging steps to implement collaborative activities and increase collaborative network performance [16].

For the last part, the implementation itself, the authors based on the approach [18], which presented a generical methodology of interoperation implementation, focusing on reducing the time needed to develop interoperability and avoid execution of non-adapted solutions.

The structured approach, where there are four main steps and activities, needs to be followed sequentially, performing several iterations between them.

Step 1. Definition of objectives and needs. To define the performance of interoperability that is aimed, by the levels of maturity.

Step 2. Analysis of existing system. To identify actors, applications, and systems that are involved, as well as problems involving interoperability.

Step 3. Select and combine solutions. To search and select interoperability solutions that take the company’s objectives and constraints.

Step 4. Implementation and test. To implement, test, and evaluate the solution encountered to remove the barriers.

The authors also used an enterprise interoperability framework to identify a solution and possible adaptations, the ATHENA Interoperability Framework (AIF). Moreover, the tool supports architectures and platforms, which provide implementation frameworks, and ontology to identify interoperability semantics in the enterprise [19].

After the implementation, a new measurement needs to be executed to verify if the barriers were effectively removed. If not, another iteration is required to adapt the solution or to choose another one. The loop continues until all obstacles are completely removed.

4. Conclusion and Future Work

This research presents a preliminary step towards an interoperable system application for enterprises or processes situated in the firsts stages of digital transformation. There is a methodology encompassing the first analysis and strategy selection and the final implementation and system validation. It is crucial since most parts of Brazilian enterprises are in the firsts phases of DX and are starting to digitalize their process and business, implementing interoperability to their heterogeneous systems.

Indeed, this paper provides a methodology that would guide researchers and enterprises through the process of interoperable system implementation, which is significant since most companies are trying to implement it for the first time. This analysis is a necessary activity before starting the digital transformation, principally to select a better implementation strategy.

For future work is planned to apply the methodology proposed for the case previously explained. If necessary, the stages can be reworked to make the method more reliable and with more chances of success. Moreover, it will describe the pros and cons of each step and how they perform in the applied case. Finally, it will present the result of the application in the digital transformation of business. With success, a well-defined methodology can be produced and replied to other processes and even companies.

References

[1] E. Henriette, M. Feki and I. Boughzala, Digital transformation challenges. *Textile Network*, 2016, (5-6), pp. 40–1.
[2] C. Ebert, C.H.C. Duarte Digital Transformation. *IEEE Software*, 2018;35, pp. 16–21.
[3] D. Beverungen, J.C.A.M. Buijs, J. Becker, C. di Ciccio, W.M.P. van der Aalst, C. Bartelheimer, et al. Seven Paradoxes of Business Process Management in a Hyper-Connected World. *Business and Information Systems Engineering*, 2021;63:145–56.
[4] G.C. Kane, D. Palmer, A. Philips Nguyen, D. Kiron, N. Buckley, Strategy, Not Technology, Drives Digital Transformation. *MIT Sloan Management Review & Deloitte*, 2015;57181:27.
[5] G. da Silva Serapião Leal, W. Guédria, Panetto H. Interoperability assessment: A systematic literature review. *Computers in Industry*, 2019;106:111–32.
[6] G. Vial, Understanding digital transformation: A review and a research agenda. *The Journal of Strategic Information Systems*, 2019, Vol. 28, pp. 118–44.
[7] M.P. Gallaher, A.C. O'Connor, J.L. Dettbarn Jr., L.T. Gilday, *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*, NIST, CGR 04-867, 2004.
[8] M. Gebhart, P. Giessler, S. Abeck, Challenges of the Digital Transformation in Software Engineering. *The Eleventh International Conference on Software Engineering Advances Challenges*, 2016, pp. 136–41.
[9] E. Stolterman, A.K. Fors, Information Technology and the Good Life, Information Systems Research: Relevant Theory and Informed Practice. *Information Systems Research IFIP International Federation for Information Processing*, 2004, pp. 687–92.
[10] M. Fischer, F. Imgrund, C. Janiesch, A. Winkelmann, Strategy archetypes for digital transformation: Defining meta objectives using business process management. *Information and Management*, 2020, Vol. 57, 103262.
[11] D. Jacobson, G. Brail, D. Woods, *APIs: A Strategy Guide*. O'Reilly Media, Boston, 2012.
[12] T. Bittner, M. Donnelly, S. Winter, *Ontology and Semantic Interoperability. Large-scale 3D Data Integration*, CRC Press, Hoboken, 2005, p. 139–61.
[13] C. Steinmetz, G. Schroeder, A. dos Santos Roque, C.E. Pereira, C. Wagner, P. Saalmann, et al. Ontology-driven IoT code generation for FIWARE. *2017 IEEE 15th International Conference on Industrial Informatics (INDIN)*, IEEE; 2017, p. 38–43.
[14] S. VanBoskirk MG and M. Gill, *The Digital Maturity Model 4.0*, Forrester, 2016.
[15] B. Solis, *The Six Stages of Digital Transformation Maturity*. Altimeter Group, 2015.
[16] A. Koulou, M. Zemzami, N. el Hami, A. Elmir, N. Hmina, Optimization in collaborative information systems for an enhanced interoperability network. *International Journal for Simulation and Multidisciplinary Design Optimization*, 2020, Vol. 11, 2.
[17] W. Guédria, D. Chen, Y. Naudet, A Maturity Model for Enterprise Interoperability. *Lecture Notes in Computer, Science*, Vol. 5872, 2009, p. 216–25.
[18] R. Wallis et al., Intelligent utilization of digital manufacturing data in modern product emergence processes, *Advances in Transdisciplinary Engineering*, Vol. 1, 2014, pp. 261-270.
[19] A.-J. Berre, B. Elvesæter, N. Figay, C. Guglielmina, S.G. Johnsen, D. Karlsen, et al. The ATHENA Interoperability Framework. *Enterprise Interoperability II*, Springer, London; 2007, p. 569–80.

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Intelligent Product Quality Failure Prediction System in Smart Factories Based on Machine Learning Techniques

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Abstract. Industry 4.0 has brought innovative principles to the entire world, especially for the manufacturing industry. The adaptation to a technological era showed limitations in the current processes, of which we can highlight the divergence between software and machinery technologies, cloud data processing, difficulty for the information to circulate within a manufacturing environment, so that it flows clearly and objectively, without ambiguity. These limitations end up generating errors between operations in the manufacturing process resulting in costs, customer dissatisfaction, low product quality, and reduced competitiveness. Thus, problems related to the semantic web, semantic interoperability, horizontal and vertical integration are responsible for such limitations in manufacturing processes. To resolve such restrictions and improve the final quality of the product, it is possible to apply Machine Learning techniques. Through the use of ensemble models of machine learning algorithm techniques, techniques with specific characteristics can be grouped, complementing each other, thus providing better prediction results during the manufacture of products, reducing costs, increasing the reliability and quality of the final product. In this way, it is expected to improve the final quality of the product and minimize the impacts that detract from the performance indicators, such as scrap, cost, rework, labor. This research will contribute scientifically to the creation of a system, which can be applied in different manufacturing production processes.

Keywords. Manufacturing Systems, Semantic Interoperability, Product Quality, Horizontal and Vertical Integration, Machine Learning, Artificial Intelligence.

Introduction

In recent years, the strong competitiveness of the market has brought about the need to change by new ways of making products, faster, less costly, and with better quality. Thus, one of the impacting and indicative factors are the quality and performance indicators, of which they are directly linked to the organization's business strategy [1].

According to the demand coming from Industry 4.0, it is noted that many points were diverging, such as the need for all information that circulates within a manufacturing environment to flow clearly and objectively, so that there is no possibility for distortion, ambiguity, loss of information during communication, errors between operations in the manufacturing process resulting in costs, customer dissatisfaction, low product quality and low competitiveness [2][3].

The transdisciplinary between dealing with product quality issues, manufacturing performance indicators, using machine learning techniques from industry 4.0 are

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intercepted, complementing each other and collaborating to achieve the same result: continuous improvement of the process/product and customer satisfaction.

Heterogeneity occurs in environments composed of different sectors (suppliers, purchases, logistics, projects) that interact with each other, which can be via system or physical, with a common goal: optimize manufacturing processes by integrating it vertically and horizontally, increasing quality and make new products viable, thus remaining competitive to the market. It is in this line of strategy that companies are strengthening their horizons, making their factories intelligent, autonomous, flexible, iterative, independent, with fast data processing and easy access, and with reliability, to make decision making much faster and decentralized [1].

To achieve this goal, companies have invested heavily in networks of increasingly robust systems, such as the Semantic Web, so that the exchange of information happens more efficiently and productively, this process is called Interoperability. Interoperability can be classified according to [4][5][6], as the ability of a system or set to communicate transparently / clearly with others, thus working with open standards, ontologies, or Machine Learning techniques.

Thus, through the use of machine learning techniques, it will act for better interoperability between machines and integration of processes, products. Through the use of ensemble models (set) of machine learning algorithm techniques, techniques with specific characteristics can be grouped, complementing each other, thus providing better prediction results, reducing costs, increasing reliability and product quality and services. This type of ensemble model has been used more and more, due to the positive results presented by the application, bringing improvements.

1. Problem Statement

The use of Industry 4.0 for industrial processes allows for higher product quality. After all, the greater the control over a given operation, the better the efficiency of the production chain and, consequently, of the merchandise that reaches the customer [2].

It can be seen that the flow of information between the manufacturing is complex, agile, and with no room for errors. The ability of independent companies and heterogeneous information systems to semantically interoperate is related to the challenges of making their semantics explicit and formal so that messages are not only ex-changed but interpreted, without ambiguity [8]. Within an organization, the main concern is to meet the customer's expectations and requirements with a product/service, respecting specifications, quality and costs.

In this way, this work aims to demonstrate the transdisciplinarity of the themes involved in several articles related to the theme, to demonstrate their contribution and how complementary they are. The objective was to select articles aimed at the manufacturing industry and product quality, and which had examples of applications in problems involving themes related to semantic interoperability, horizontal and vertical integration, application of Machine Learning techniques.

2. Literature Review and Classification

A literature review was conducting in the *Periódicos Capes* Database, which it has more than 532 scientific databases, such as SCOPUS, IEEE Xplore, Taylor and Francis, Emeralds, and so on. This literature review search papers with keywords relate to: Quality (focusing on the product), Manufacturing and Horizontal Integration and/or Vertical (focusing on information, communication within the manufacture). The results of this findings were classified following the structure presented below and the Table 1 presents the results of this classification.

- T1 - Product Quality: Articles focused on Product Quality.
- T2 - Product and Process Quality: Articles that deal with process problems as it impacts product quality, acting on this synergy, however, the main focus is product quality.
- R1 - Industrial Manufacturing: Articles focused on manufacturing processes.
- R2 - Manufacturing (scope): Articles that are also adding other areas such as logistics, hospital, and are not exclusive in manufacturing processes.
- N1 - Horizontal and/or Vertical Integration: Articles that address the exchange of information and knowledge between manufacturing processes, more specifically between machines (operations).
- N2 - Horizontal and/or Vertical Integration (comprehensive) - Articles that deal with issues related to the exchange of information and knowledge, but in a comprehensive and managerial way (MES system, management, sustainability).

Table 1. Classification of articles by keywords

Name Article	T1	T2	R1	R2	N1	N2	Accepted Article
Organizational and managerial challenges in the path toward Industry 4.0				X		X	No
Development of an open source-based manufacturing execution system (MES): industry 4.0 enabling technology for small and medium-sized enterprises				X		X	No
Digital transformation of manufacturing through cloud services and resource virtualization				X		X	No
Centrolac		X				X	No
Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union						X	No
The impacts of different ReD organizational structures on performance of firms: Perspective of absorptive capacity						X	No
Design and management of manufacturing systems for production quality	X	X	X		X		Yes
The expected contribution of Industry 4.0 technologies for industrial performance			X			X	No
Impact of quality of service on cloud-based industrial IoT applications with OPC UA		X	X		X		Yes
Dynamics of resource sharing in production networks				X		X	No
The future of manufacturing industry: a strategic roadmap toward Industry 4.0				X		X	No
Firm Boundaries, Information Processing Capacity, and Performance in Manufacturing Firms						X	No

Name Article	T1	T2	R1	R2	N1	N2	Accepted Article
Building a new culture for quality management in the era of the Fourth Industrial Revolution	X						No
Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives						X	No
Literature review of Industry 4.0 and related technologies						X	No
Assessing the value of information of data-centric activities in the chemical processing industry 4.0			X	X		X	No
A training system for Industry 4.0 operators in complex assemblies based on virtual reality and process mining	X	X	X		X		Yes
Manufacturing Data Analysis in Internet of Things/Internet of Data (IoT/IoD) Scenario		X	X		X		Yes
An artificial neural network approach for wafer dicing saw quality prediction	X	X	X		X		Yes
Design framework for model-based self-optimizing manufacturing systems	X	X	X		X		Yes
Cloud-based smart manufacturing for personalized candy packing application		X		X		X	No
Knowledge reasoning with semantic data for real-time data processing in smart factory	X	X	X		X		Yes
Smart Innovation Engineering: Toward Intelligent Industries of the Future	X	X	X		X		Yes
Quality managers and their future technological expectations related to Industry 4.0						X	No
Toward New-Generation Intelligent Manufacturing						X	No
A critical investigation of Industry 4.0 in manufacturing: theoretical operationalization framework				X		X	No
Development of a Cyber-Physical framework for monitoring and teleoperation of a CNC lathe based on MTconnect and OPC protocols.	X	X	X		X		Yes

After reading, 9 articles were selected, thus finalizing the selection of articles. These were considered as reference articles. Through reading, it is possible to analyse the area of operation that each article is located, being able to understand if there is a specific area in which the most use of fault forecasting tools in manufacturing is used.

Through selection with articles, analysing how each author solved the problem presented. It is possible to highlight the use of ontological rules to sequence operations, previously manual, in a candy factory, preventing failures in the process, sequencing errors, improving the quality of the product.

The work of [9], brought concepts that contributed mainly to data mining for application in virtual reality techniques, however for this work, we used the concept of contained IoT.

The article by [10], portrays problems found in a manufacturing industry whose production processes are similar to the case study of this work, bringing manufacturing processes for machining and assembly. The purpose of this article is to improve connectivity and data collection. The article entries are similar to the scenario reported in this work, illustrating limitations, applications, and needs.

These illustrations provided clarity for the scenario found in this work, offering input of ideas regarding the collection and treatment of data, and consequently its application. In this article, a tool for data collection called MTConnect was applied, which after this presentation, was considered to be used in this work and also allowed, from it, the exploration of similar technologies, promoting the knowledge of new techniques and algorithms.

The same reasoning was found through the article [11], which also contributed with another example of application for data collection, as well as its architecture/structure, to achieve an application for monitoring and remote operation of CNC machines, thus contributing to the interoperability of the manufacturing line, through this application.

The work of [12], also brought contributions regarding the impact of quality-of-service parameters in the delay of communication from the production line to the cloud. This fact raised the need for evaluation for the case study of this work, since it had not been identified yet, and maybe a technological impediment to the collection, transmission, and communication of data between operations.

The article by [13], contributed to the application as to the need for decision-making processes using the knowledge and experiences of previous formal decision events, supporting the manufacturing as to decision making. This fact, which we found in the application of this work, as it was a noted element that for each measurement forecast to be performed, the method should be based on histories, comparing the current piece with the previous ones, contained in its training.

Another work with a similar contribution is that of [14], as it aims to intelligently and autonomously control the main characteristics of product and process quality. This fact was identified as a necessity in the case study of this work.

In the work of [15], brought the contribution of the concept involved in cloud processing, intelligent systems applied to improve interoperability in industrial manufacturing processes, mainly focused on fault detection and problem-solving based on data analysis. The fundamental concept brought by this work was the application of ontologies for the solution of the problem addressed.

The articles by [16][17][18], brought the key contribution to complement the construction of the Intelligent Fault Prediction and Identification System in Flexible Manufacturing, as these articles presented the application of neural networks and AI techniques (machine learning) to solve the problems presented, having as requirements: manage, analyse and process data, information and knowledge, using AI techniques, focusing on a system that supports decision making by reusing experience (history). The impact to be perceived is also in reducing waste, loss of products, efficiency of the process, thus contributing to the quality of the product.

It was also evident that most articles brought the problem of horizontal and vertical integration of information, involving problems of semantic interoperability of processes (between machines), which are related to product quality. The technology used in this problematization was the connection through ML techniques and neural networks, using Python programming, connection between machines using software and hardware (MTConnect, SIE, OPC), which brought satisfaction regarding the results obtained after its application [11].

Another conclusion by reading the articles is that even being impacted by the same cause of the problem, the application of the solution is never the same, as they are different expectations, different process limitations between companies, different database architecture, changing the approach and even the type of technique used between companies.

3. Concept of an Intelligent Product Quality Failure Prediction System

In this way, these articles became the basis for the creation and development of a methodology that will act, through an Intelligent Product Quality Failure Prediction system (IPQFP), in predicting the results of products in flexible manufacture, and can be applied in any productive segment. Still, it can be adapted according to the transdisciplinary need for adequacy.

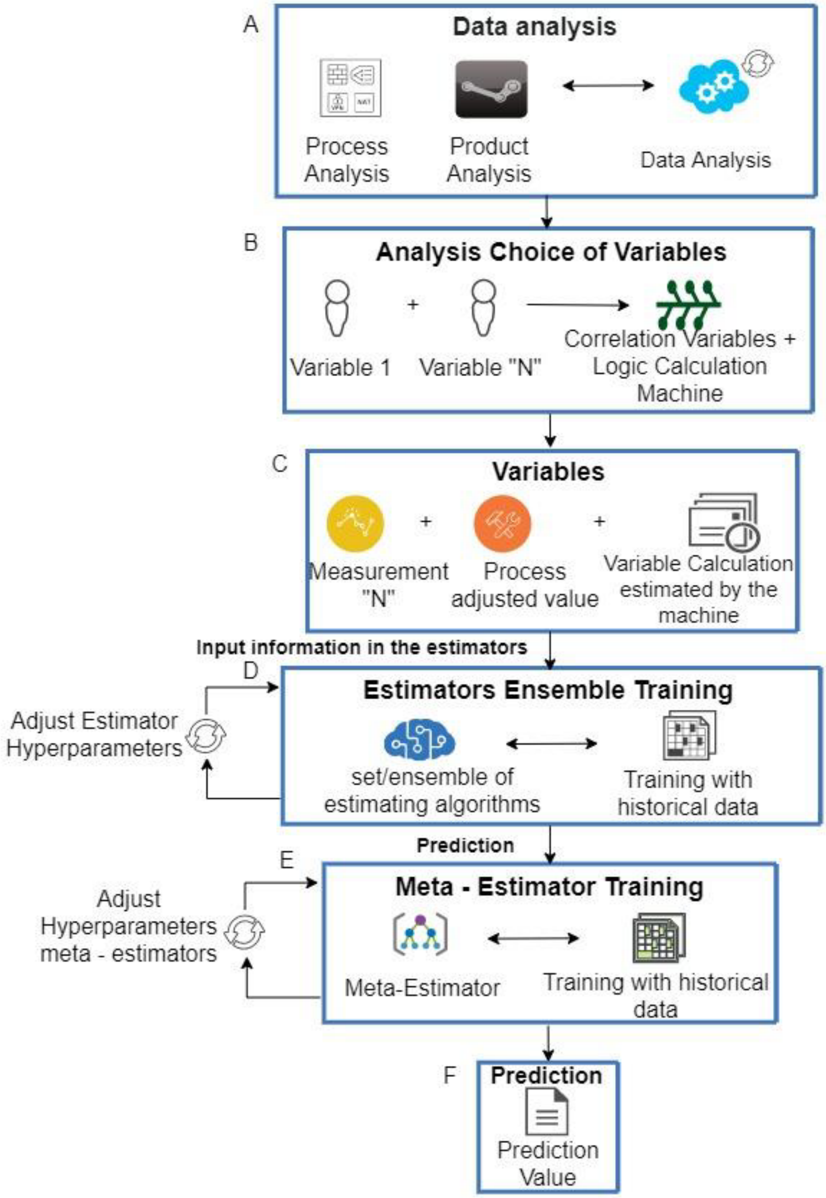

Figure 1. Structure of the IPQFP System

This system is called IPQFP (Figure 1), it consists of a logical sequence of analyses, data collections, interpretations, creation of variables, data processing, application of artificial intelligence techniques, to produce an information forecast. This process shows transdisciplinarity since it encompasses several areas of knowledge involving the engineering perimeter.

Figure 1 shows the entire structure of the system, which consists of:

- **Data analysis** (Detail "A"): It is responsible for analyzing process and product data (Figure 2). The objective is to understand in detail its operation, its deviations, impacts on the product, standard deviation, oscillations, characteristics, influences of temperature and humidity, machine behavior, operator influence, statistical analysis, running performance throughout the day, under stops programs, under long periods of production stoppages and mainly to understand if there is a difference or impact between different types of products and product generations.

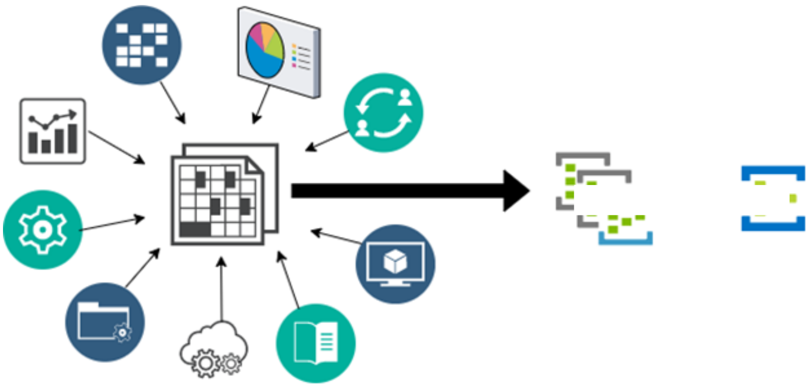

Figure 2. Data Analysis.

- **Analysis and choice of variables** (Detail "B"): It is dedicated to identifying all the potentials of variables, originated from the analysis of process, data, and product, which may be used for the training and validation of the algorithm models later. In the step of analyzing and choosing the variables, the variables already identified in the previous step are correlated with each other, through a correlation matrix and after identifying the most relevant ones, through an ABC curve analysis (Figure 3), the correlation with the logic is made of the processing unit.

Table 2. Correlation Matrix.

	Operation	Op. 10	Op. 11	Op.12	Op. 13	Op. 14	Op. 15
Operation	1						
Op. 10	0.06342	1					
Op. 11	0.12375	0.53468	1				
Op. 12	0.41001	0.35711	0.17992	1			
Op. 13	0.25781	-0.56731	0.65823	0.67537	1		
Op. 14	0.35812	-0.08753	0.54719	-0.45923	0.46723	1	
Op. 15	0.08239	-0.12282	-0.75231	0.56261	0.35913	0.8733	1

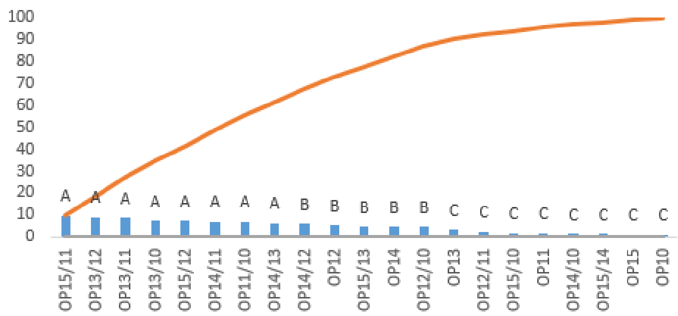

Figure 3. ABC Curve

- **Variables** (Detail "C"): It is the stage where the variables used by the machine logic are identified, forming a data entry, and processed by the line processing unit, obtaining an output variable, thus generating a data entry, called "Input information in estimators", for the next step.
- **Estimator Ensemble Training** (Detail "D"): it has a great role because it will receive inputs from the previous level, which will be processed in a set of algorithms and machine learning techniques. This processing will be the entrance to the training stage, which will add the variables identified as potential, to contribute to the training of the set of models (Figure 4).

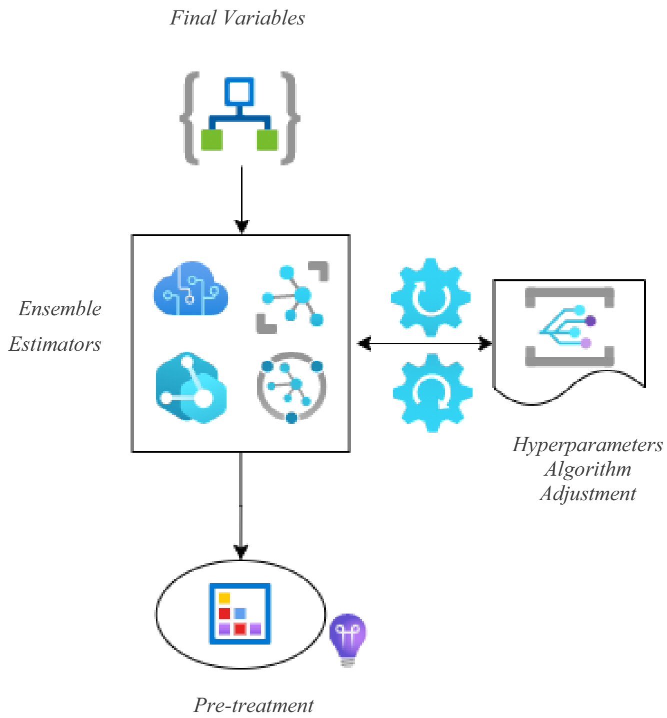

Figure 4. Estimator Ensemble Training

- **Meta-Estimator Training** (Detail "E"): is responsible for processing the result in a model to complement, and ensure a better prediction of the result, bringing greater precision and reliability. The same occurs in a similar way to the previous step.
- **Prediction** (Detail "F"): This is the result of the prediction value.

4. Result of the IPQFP application

To measure the result, 2 scenarios were compared: production using AI versus production without using AI, in this same Product 1. The same batch size was taken into account, as for the process, there were also no changes, maintenance that may impact the test result, as shown in Table 2.

Table 2. Result of the application in a real case.

Product	Quantity	% Error reduction	% reduction mean absolute error	% standard deviation reduction
Product 1	258	6,03%	48,95%	44,54%

According to the results presented, Product 1, in a batch of 258 units (parts), AI was shown to reduce 6.03% of errors, with about R$5,000.00 per year of savings in this product according to the volume produced, when compared to production not using AI. This represents that the AI proved to be more assertive than the standard process in question.

The mean absolute error, that is, it measures the difference between the exact value that you want to reach and its approximate value (expected), obtained a positive result, presenting an improvement of 48.95%.

When the standard deviation is observed, that is, the dispersion among the batch of manufactured parts, it also presented a positive result, having an improvement of 44.54%, which means that the process became more stable using the AI. This phenomenon is very important especially in types of products that have more precise characteristic tolerances, which makes the window between tolerance limits smaller.

5. Conclusion

Problems involving themes that address issues related to Industry 4.0 are still unknown for both the scientific and technical circles. Industry 4.0 is innovative, and as much as it is a technological evolution, its concepts are new, which challenges industries to adapt physically and socially to these addenda. Thus, when it is individualized by communication problems between machines, in particular, it can be seen that it is a characteristic problem of Industry 4.0, but it comes from several causes, among them the divergence between machine technologies, generating communication divergence between them and for problems originating from vertical and/or horizontal integration, in addition to human technological mastery and their social resistance.

Transdisciplinarity is present in this work addressing themes and disciplines that correlate to achieve a greater objective: IPQFP system, aiming as a final result to forecast results, measurements, increasing product quality, product and process reliability, in addition to increasing customer reliability and loyalty to the brand.

References

[1] M. Ghobakhloo, The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *Journal of Manufacturing Technology Management*, 2018, Vol. 29, No. 6, pp. 910–936.

[2] M. Zdravković, H. Panetto, The challenges of model-based systems engineer-ing for the next generation enterprise information systems. *Information Systems and e-Business Management*, 2017, Vol. 15, No. 2, pp. 225–227.

[3] B.S. Adamczyk, A.L. Szejka, O. Canciglieri Junior, Knowledge-based expert system to support the semantic interoperability in smart manufacturing. *Computers in Industry*, 2020, V. 115, 103161.

[4] A.L. Szejka, A. Aubry, H. Panetto, O. Canciglieri Junior, E.R. Loures, Towards a conceptual framework for requirements interoperability in complex systems engineering. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2014, Vol. 8842, pp. 229–240,.

[5] A.L. Szejka, O. Canciglieri Junior, E.R. Loures, H. Panetto, A. Aubry Requirements interoperability method to support integrated product development. In: *Proceedings - CIE 45: 2015 International Conference on Computers and Industrial Engineering*, Metz, 2015, pp. 1–10.

[6] F. Ma, Y. Chen, Y. Zhao, Research on the organization of user needs information in the big data environment. *Electronic Library*, 2017, Vol. 35, No. 1, pp. 36–49.

[7] S.K. Rao, R. Prasad, Impact of 5G Technologies on Industry 4.0. *Wireless Personal Communications*, 2018, Vol. 100, No. 1, pp. 145–159.

[8] A. Pirayesh Neghab, A. Etienne, M. Kleiner, L. Roucoules, Performance evaluation of collaboration in the design process: Using interoperability measurement. *Computers in Industry*, 2015, Vol. 72, pp. 14–26.

[9] J. J. Roldán, E. Crespo, A. Martín-Barrio, E. Peña-Tapia, A. Barrientos, A training system for Industry 4.0 operators in complex assem-blies based on virtual reality and process mining. *Robotics and Computer-Integrated Manufacturing*, 2019, Vol. 59, pp. 305–316,.

[10] M. Colledani, T. Tolio, A. Fischer et al. Design and management of manufacturing systems for production quality. *CIRP Annals - Manufacturing Technology*, Vol. 63, n. 2, p. 773–796, 2014.

[11] A.J. Álvares, L.E.S Oliveira, J.C.E. Ferreira, Development of a Cyber-Physical framework for monitoring and teleoperation of a CNC lathe based on MTConnect and OPC protocols. *International Journal of Computer Integrated Manufacturing*, 2018, Vol. 31, No. 11, pp. 1049–1066.

[12] P. Ferrari, A. Flammini, S. Rinaldi et al. Impact of quality of service on cloud based industrial IoT applications with OPC UA. *Electronics (Switzerland)*, 2018, Vol. 7, No. 7, pp. 1–14,.

[13] M.M. Waris, C. Sanin, Szczerbicki, E. Smart Innovation Engineering: Toward Intelligent Industries of the Future. *Cybernetics and Systems*, 2018, Vol. 49, No. 5–6, pp. 339–354.

[14] U. Thombansen, G. Buchholz, D. Frank, et al. Design framework for model-based self-optimizing manufacturing systems. *International Journal of Advanced Manufacturing Technology*, 2018, Vol. 97, No. 1–4, pp. 519–528.

[15] S. Wang, J. Wan, D. Li, C. Liu, Knowledge reasoning with semantic data for real-time data processing in smart factory. *Sensors (Switzerland)*, 2018, Vol. 18, No. 2, pp. 1–10.

[16] S.I. Shafiq, E. Szczerbicki, C. Sanin, Manufacturing Data Analysis in Internet of Things/Internet of Data (IoT/IoD) Scenario. *Cybernetics and Systems*, 2018, Vol. 49, No. 5–6, pp. 280–295.

[17] T.J. Su, Y.F. Chen, J.C. Cheng, C.L. Chiu, An artificial neural network approach for wafer dicing saw quality prediction. *Microelectronics Reliability*, 2018, Vol. 91, No. 9, pp. 257–261.

[18] S. Wang, J. Wan, M. Imran, D. Li, C. Zhang, Cloud-based smart manufac-turing for personalized candy packing application. *Journal of Supercomputing*, 2018, Vol. 74, No. 9, pp. 4339–4357.

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Exploring the Transition from Preventive Maintenance to Predictive Maintenance Within ERP Systems by Utilising Digital Twins

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Abstract. Over the years, there has been an advancement in how manufacturing companies conduct maintenance. They have begun transitioning from Preventive Maintenance (PM) to Predictive Maintenance (PdM). With the introduction of technologies such as Digital Twin (DT), Internet of Things (IoT), and Intelligent Manufacturing (IM), the world is rapidly changing, thus allowing companies to optimise existing processes, products and reduce costs. The existing literature offers limited investigations and best practices in the end-to-end optimisation for maintenance transformation. The current paper intends to explore (a) the transition from PM to PdM and (b) the utilisation of DTs and IM for maintenance optimisation. The paper articulates the scope and features of end-to-end maintenance optimisation for asset uptime and cost benefits. The findings can help industries understand the introductions and advancements of technologies for predictive maintenance and end-to-end optimisation with the benefit of investigating and illustrating how companies can move forward.

Keywords. Predictive Maintenance, Preventive Maintenance, Digital Twin, Internet of Things, Enterprise Resource Planning (ERP), Artificial Intelligence, Intelligent Manufacturing, Optimisation, Transdisciplinary

Introduction

The advancements brought about by *Industry 4.0* have enabled the integration of digital technologies in many businesses. Exploring this digital integration uncovers new improvement opportunities and challenges. However, the latest technologies are not sufficiently understood by many companies yet. Manufacturers do not create the right conditions for their optimal implementation and thus do not fully exploit the inherent potential. When transitioning from PM to PdM within the manufacturing industry, there are multiple advanced technologies that companies need to consider for their production

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assets. It is almost certain that companies embracing the digital transformation will generate insights from their processes they did not have before.

This paper investigates how advanced technologies enable the transition from PM to PdM and its integration into a companies' ERP system. It emphasises that in a value-driven maintenance approach, the benefits of PdM must outweigh transition costs coming with it to generate a positive business case. A potential business case is reinforced by an innovative end-to-end optimisation that allows the inclusion of all relevant data for holistic optimisation and decision-making enabled by the use of PdM. This paper, therefore, adds to the literature while it provides valuable and actionable guidance for manufacturers considering the implementation of PdM by combining and relating different transdisciplinary technologies and methods. Practical implications when applying DT and IM technology to a PdM approach are elaborated. Potential stumbling blocks and possible responses to them are also discussed to provide a complete picture. A developed PdM implementation roadmap and defined system requirements round up the approach and facilitate the implementation process.

1. Total Cost of Maintenance

A successful business is primarily defined by a positive Return on Investment (ROI). In the present case, manufacturers use the ROI to measure the value generated through maintenance activities (see Table 1) and assess the success of single measures. The ROI depends on the scale of operations, which assets are critical to maintaining and how much a company spends. To achieve a positive return, measurable and nonmeasurable factors must be identified. Subsequently, companies can identify the necessary technologies for the transition from PM to PdM. Once a company applies the costs of new technologies to its circumstances, it can effectively compare the potential cost saving and the impact of maturing the systems and equipment with the investment costs to assess whether the transition to PdM is economically viable for them. Figure 1 illustrates the potential programme savings for PdM.

Table 1. Predictive Maintenance Programme Savings.

Increase asset availability	5-15%		9%	V	30%	
Reduce Maintenance Cost	18-25%	25-30%	12%	10-40%	50%	25%
Reduction in breakdowns		70-75%			55%	70%
Reduction in downtime		35-45%		50%		50%
Increase in production		20-25%		V		
Reduce H&S and quality risks			14%	10-20%		
Extend lifetime of aging assets			20%	3-5%		
Increase employee morale				V		
Repair and overhaul time					60%	12%
Spare parts inventory					30%	
Return of investment		10				
Cut unplanned outage						50%
Reduction capital investment						3-5%
References	(Morgan Cox et al., 2017)	(Gutenberg-technology, 2019), (U.S Department of Energy's Federal Energy Management Program,2004)	(Kupervas Amir, 2019) (AI Multiple, 2020)	(AI Multiple, 2020)	(SPD group, 2020)	(IBM, 2017)

Manufacturers need to consider the following aspects to estimate the cost of maintenance and its associated losses:

- Direct maintenance and repair costs: labour and materials
- Indirect costs: downtime, lost sales due to quality/delays, low quality (rework/scrap), and energy usage.

Additionally, the cascading consequences which are linked to subsequent losses should also be accounted for, as outlined by [1]:

- Overtime due to improper balance of work, wrong people for the job
- Spares maintenance due to poor management, low ordering or missing spares
- Downtime of downstream machines
- Downtime on the capital and labour cost due to maintenance
- Low quality on sales and delivery, but also the losses due to rework/scrap.

Whilst the significant effect of PdM is being estimated using a range of metrics when it comes to quantifying the maintenance, this is not well documented across organisations. The NIST publication examines asset maintenance cost and provides comprehensive guidance regarding the data needed for making discrete estimates. Understanding and quantifying the different data enables optimal maintenance decision-making, including choosing between PM and PdM, selecting resources and a spare part management methodology. One method for measuring maintenance cost is using the input-output data, alongside particular equations for calculating the overall maintenance cost [1]. A prerequisite to estimating maintenance costs is gathering the correct data, which means data is accurate, complete, and appropriately provided [2]. The information in the ISO standard [2] is recommended for data collection during the whole life cycle of an asset until the asset is decommissioned. Digital manufacturing using an IoT platform as an interface can facilitate the data gathering of various differing sources.

2. Transition from Preventive Maintenance to Predictive Maintenance

Organisations are focusing on ensuring that their physical assets are productively running and functioning correctly to reduce costs. Maintenance activities generally include functional testing, examination, servicing, repairs, or overhaul of assets to restore or maintain the assets operational condition throughout its working lifecycle [12]. PM is carried out regularly while the asset is still in a working condition to prevent sudden breakdowns. PdM uses various data sources to determine when a machine or component within an asset will fail, and it also incorporates asset data from the environment in which it operates and the associated processes and resources that interact with the asset. PdM does not tell when an asset will fail but forecasts the future performance and analyses these cycles to define the probability of failure based on various parameters. This methodology, therefore, requires *Predictive Modelling*, of which there are many different approaches. *Fuzzy Logic*, *Regressions* and *Decision Trees* are commonly used forms of logic when building the predictive model. The selection depends on the machine's application [3].

PdM relies on a live data feed coupled with analytics to determine a flexible schedule because it changes based on the input data stemming from the asset. Therefore, predictive analytics must be performed on the data received from that particular asset to define this new schedule. Companies must understand at what point in the process flow and what method of analytics to use. Figure 1 illustrates the input to output flow.

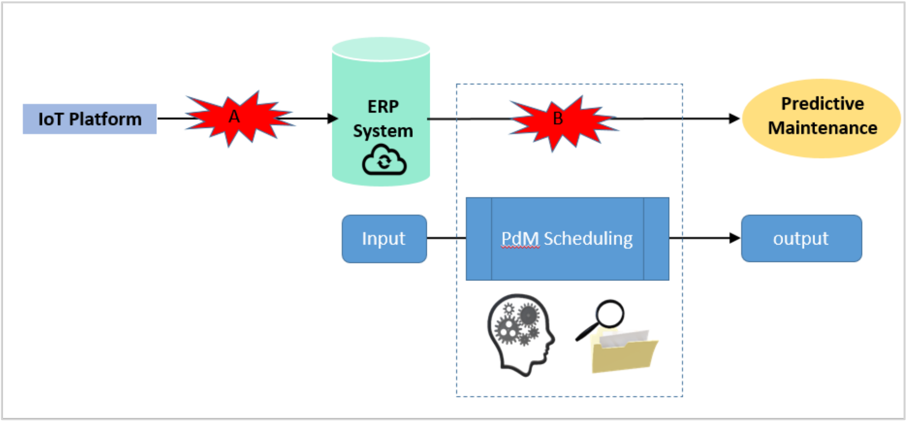

Figure 1. Predictive Maintenance Solutions.

The data input is shared via industrial IoT from the asset to the companies' ERP system. It is this integration with ERP that enables the business decisions, including PdM, to be executed. As shown, there are two logical points in the process flow highlighted as "A" and "B" where a manufacturer can perform predictive analytics. Point "A", which is closer to the source of data collection, offers the potential to utilise ML and Industrial Edge computing strategies [4], while point "B" requires the ERP system to be capable of predictive analytics. Although both methods prove capable of predictive analytics, the method selected must be suitable for any specific business context.

It is suggested that there are multiple methods to achieve this analytic process. ML, Industrial Edge Computing, Algorithmic Programming and AI prove to be some of the most appropriate ways of achieving this. These advanced technologies require a good understanding of reliability engineering and data science to provide useful maintenance information. To act upon this information within a maintenance programme, integration with ERP becomes necessary. Integrating analytics data into ERP demands additional functionality of the system, and it becomes apparent that the integration is highly individual and dependent on the products, assets and system landscape of every manufacturer. This can make the implementation more complex and costly. ERP systems tend to be generic in their design, so often, parts of the optimisation are not economically realised in an ERP system. Therefore, manufacturers must find ways to design and implement an upstream application that feeds into an existing ERP system. Ultimately, it is down to the ERP suppliers to create the functionality to integrate and process industrial IoT data.

2.1. PdM Roadmap

Performing predictive analytics is one section of the puzzle when transitioning towards PdM. Any organisation seeking to establish a PdM regime should follow a defined strategy outlining the requirements that define which activities to undertake. Before implementing any strategy and incurring the associated cost expenditure, the organisation should first assess its current maintenance capabilities and justify its business requirement to transition to PdM. Table 2 outlines an appropriate roadmap. The outlined scope of the implementation roadmap would typically require the organisation to hold a prerequisite of diagnostic condition-based monitoring capabilities. The end of the roadmap forms the foundation of prescriptive maintenance, should that be a future aspiration of the organisation.

Table 2. Predictive Maintenance Implementation Roadmap.

Strategy	Activity	Requirements	Enablers
Step 1	Identify asset(s) for PdM	Define the scope of Programme Complexity/value evaluation of asset	Total cost of Maintenance Evaluation
Step 2	Establish data sources	Acquire Software as a Service tools, software, and computational infrastructure	Edge Computing (Optional)
Step 3	Analyse failure modes (e.g. Failure Mode Effects and Analysis)	Define prognostic logic of asset(s), Define prognostic logic of asset(s)	Asset Lifecycle Management, Digital Twin
Step 4	Select and implement condition-based monitoring techniques and equipment	Sensors and data sharing	IoT; Cloud
Step 5	Produce predictive algorithms and Key Performance Indicators (e.g. Remaining Time-to-Failure)	Creation of ML predictive model (e.g. Unsupervised Learning, Supervised Learning, Reinforcement Learning) Typically requires data science consultants.	Machine Learning, Artificial Intelligence
Step 6	Generation and deployment of a predictive maintenance schedule	Work Order Tracking, Material Resource Planning, Labour allocation	ERP, Manufacturing Execution System (MES)

2.2. System Functionality Requirements for Maintenance Optimisation

Maintenance optimisation has different system requirements for transitioning from PM to PdM, especially when using a DT. First, companies must fulfil particular prerequisites to implement these technologies. Secondly, the enterprise systems must be able to use the generated outputs of the PdM algorithms and DT applications. If, for example, the PdM algorithm generates an optimised maintenance schedule (as shown in Figure 3) and the maintenance scheduling application (within the ERP or MES) is technically unable to schedule the maintenance accordingly, the effect equals zero. Therefore, a company considering the transition to PdM must understand if its existing systems are capable of the shift or if they must be updated, extended, complemented, or replaced. Bumblauskas et al. [5] have identified multiple gaps in information systems literature for asset management. They outline that research on the usage of information systems for maintenance cost control and optimisation is hard to find. Moreover, they highlight that available research papers do not define requirements or specifications for asset management and maintenance systems in publicly disclosed form. This emphasises the necessity of the present paper and further research. There are three major functional requirements in this context:

1. The system must be able to collate and store the necessary data
2. The system must be able to process the data and make use of it
3. The system must be able to generate actionable outputs from the generated insights

Decision Support Systems are a viable solution for optimisation problems within complex maintenance systems [6]. However, decision-making approaches are seldom part of an enterprise information system [7]. This makes the implementation of an optimisation approach much more complicated. Manufacturers must deploy an optimisation (sub-)system and achieve integration into the existing maintenance scheduling module. If a company is keen to automate its maintenance decisions, it must provide the same data and functionalities to the algorithm as a maintenance employee typically has available.

3. Digital Twin and Intelligent Manufacturing for Maintenance Optimisation

PdM relies on the use of products/equipment to optimise maintenance operations. The transition of maintenance is accelerating across industries through the emergence of IoT, whilst utilising DT as a critical enabler for PdM for high-value or high-risk assets, such as aircraft turbines, as airlines' asset. In a short definition, DT is a visual representation of a physical asset or object across its lifecycle, and this is supported by different enablers, including ML algorithms, IoT and AI [8]. DT performs real-time analysis and optimisation. Companies can perform this through the income of real-time data, rather than historical data, which upgrades and optimises the virtual model of the actual asset. This improves efficiency and facilitates the reduction of inconsistencies through the ability to forecast behaviour and verify changes virtually before impacting the real asset. DT can optimise assets, products and processes through its ability to link vast amounts of data to fast simulation. Realistic models allow improvements to performance, increase the quality, and allow product failure to decrease.
A spin on the technology is the presence of multiple classifications of a DT. It has been identified that there are three dominant dimensions to classify the DT. Figure 2 illustrates the dimensions as the hierarchical level, lifecycle phase, which allow 252 combinations to be formed [9]. It also presents a new understanding that DT can be different in many ways, depending on which combination is used with limited overlap.

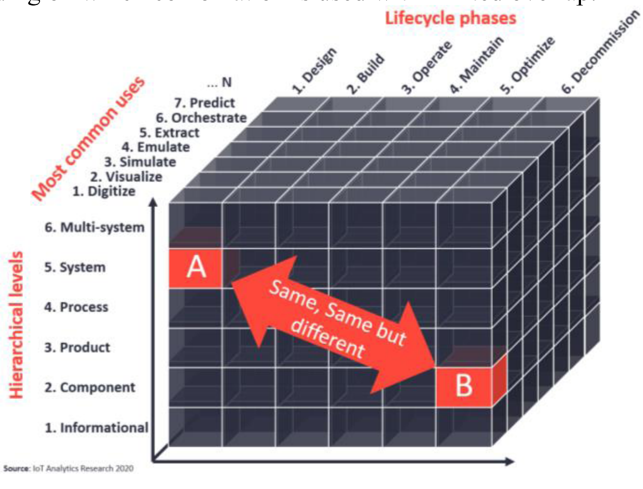

Figure 2. Digital Twin Classifications Cube [9].

Introducing IM through IoT and Edge Computing is at the forefront of production optimisation, thus enhancing PdM. The concept of IM has the purpose of optimising production and product transitions using advanced information and technologies in manufacturing. Although this is the next level transformation, companies need to consider the challenging transition due to lack of funding, maturity, and knowledge of advanced technology. IM can be introduced and implemented through utilising multi-objective optimisation algorithms alongside a customised design and other technologies. This enhances the design for maximum performance and the application of PdM. IM enables better productivity and quality with increased flexibility and minimal costs. When looking at the enablers of IM, it is essential to understand how they enhance the maintenance, manufacturing, and synergies to form a powerful front. DT optimises the physical objects based on models that have been mapped and hold a description of elements, whilst IoT facilitates the optimisation of production resources by converting them into smart manufacturing objects [10]. Additionally, Edge Computing increases analytics speed and maximises maintenance penetration, therefore enhancing the production line. Ultimately, for movements towards IM, it is vital to work towards a closed-loop to complete tasks that require intelligent equipment; the movement allows specific tasks to be focused on and applied to actual production, which provides advanced optimisation of individual components. IM is a step in the right direction and will reduce the cost of maintenance for applying manufacturers.

Whilst being promised optimisation with slicker maintenance, companies need to understand that it is virtually impossible or economically viable to incorporate every operating and breakdown mistake within a DT. However, if a company witnesses an unknown situation within a production asset, it can quickly receive support from the supplier. Here, the DT facilitates data transmission from the company to the supplier. Additional information from the DT regarding the location of an asset and parts within the asset provides more detailed work instructions making the maintenance work more efficient and less expensive.

4. End-to-End Optimisation

The end-to-end optimisation of processes does not only become available through digital advancements; it also becomes one of the crucial points for successful implementation. If companies spend extensive amounts on a PdM approach and do not integrate it into the overall process, it can hardly cover the investment costs. However, if a company can funnel all process components and the generated data into a single source of truth, it can optimise the whole system and lead to an even more significant financial improvement. By linking all relevant system parameters in a single model focusing on optimising a few selected outputs, asset managers can identify the parameters with the highest impact on the inputs. They can determine which part of an asset causes the highest downtime of a system. Most of the maintenance literature in manufacturing-related fields is concerned with developing analytical models of the actual maintenance [11]. There is a lack of literature and research investigating the here discussed end-to-end optimisation. While the extension of every asset's lifetime is indeed crucial, companies should not neglect the overall optimisation. A door opener for this is that with the introduction of the PdM, the exact timing of the maintenance of individual assets becomes variable, which Figure 3 vividly illustrates. As opposed to PM, companies applying PdM have a specific time window to schedule the maintenance work for every single asset. If available, this information can be enriched with numerous further data, for example, from a maintenance bidding and quotation system. Suppose a company can include this within a multiple-input-multiple-output (MIMO) optimisation approach related to the outputs mentioned, the maintenance for each asset can be scheduled to maximise the asset uptime while reducing costs. MIMO approaches are highly complex; however, it offers companies an entirely new scope for asset management.

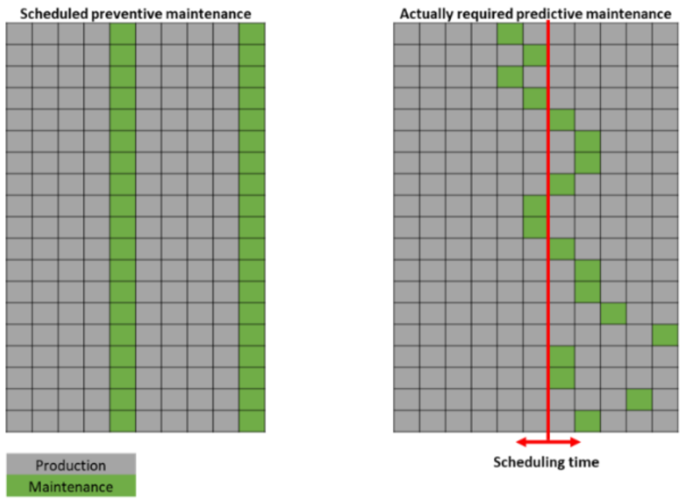

Figure 3. Change of the Maintenance time between PM and PdM.

A further optimisation potential is coming from the assessment of interdependencies of different production departments. If two departments have a separate maintenance budget, but their work is interdepending, the management should assess how a breakdown in the upstream department impacts the downstream department. By having this information interlinked, the management can make a holistic decision that reduces the costs of the whole organisation, not of a single department.

End-to-end relates to the value chain of a company and the lifecycle of a production asset. The Bill of Materials (BOM) is used across a lifecycle consisting of product development, manufacturing, and servicing. Figure 4 illustrates the ideal process of maturing the BOM within the lifecycle and derives from one step to the next. Within this report, the as-maintained BOM is the target of a successful movement on PdM and DT. Whilst transitioning to PdM, it is critical to ensure the as-maintained BOM of the asset is kept accurate and up to date. It must include information about the parts of a machine when they have been maintained. If the BOM is not accurate or up to date, then the DT is effectively no longer one as the actual and virtual models differ. This circumstance can increase the risk of failures and lead to a misprediction of maintenance demand. A challenge here occurs when an unexpected breakdown happens, which is indeed possible under PdM. In this case, every part must be checked for damages and be aligned with the DT to ensure accurate predictions.

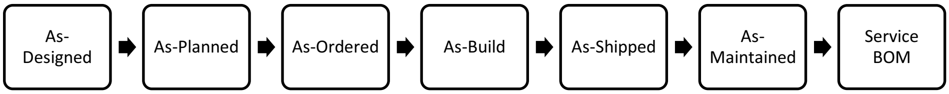

Figure 4. Bill of Materials Lifecycle.

5. Discussion and Conclusions

The digital transformation can feel overwhelming for an organisation, especially for those with low digital maturity. PdM and DT approaches are highly complex. Both represent systems that have not been modelled to this level of detail before. Consequently, there is a risk that employees and managers cannot comprehend the generated outputs. This can jeopardise the whole endeavour if employees do not act in accordance with the model. Therefore, it is crucial to commence the described end-to-end preparation and optimisation before companies implement PdM and DT to ensure that every part of the approach is understood.

An ERP system builds the backbone of every large manufacturing organisation. The high complexity and design of an ERP system are widely known to be a significant challenge in the industry. Thus, manufacturers should review every approach in changing or adapting the ERP in an overall context. A successful ERP integration is essential to realise the benefits of the proposed end-to-end optimisation.

Although PdM offers massive potential within asset management, further business operations are considered within this equation. To achieve predictive business operations, including maintenance, integrating live data into management systems is critical. Predictive Analytics within ERP systems requires complex configuration. It seems the future of successful predictive maintenance applications requires ERP systems to receive this data in an analysed state. New exciting technologies capable of ML, such as Edge Analytics and Edge Computing, enabled through IoT and DT technology, appear to be the answer, performing predictive analytics closer to the data source before ERP integration. The report illustrates IM in this context and how it can use DT and other identified enablers to transform manufacturing across industries. While it does not answer all questions at this stage, it provides practitioners with the necessary insights to commence the transition towards PdM.

This paper provides visibility into how integrating different systems and data allows a transition into PdM and ensures that essential steps are considered before commencing the transition. PdM brings massive benefits to an organisation by reducing the breakdowns of machines. When integrated adequately within the end-to-end process, manufacturers can achieve additional advancements. PdM adds more complexity to the maintenance approach of a manufacturer, but if implemented correctly, it also provides an enhanced ability to simulate the companies performance in the real world and act accordingly. The gained flexibility, agility, and increased asset uptime can constitute a competitive edge in an everchanging market environment.

5.1. Outlook and Future Research

The initial thought for the future is understanding whether factories will function entirely autonomously, meaning there would not be any employees within the production line. This environment would minimise human interaction unless it were for maintenance, repairs, base checks, or servicing. This outlook allows the researcher to focus on the linkage between humans and machines to understand how they augment and feed into each other. When machines and robots are not limited to a fixed location anymore, the DT technology will become even more essential. DT, IoT and AI work together to enable advanced and Intelligent Manufacturing. With this advancement being forecasted, understanding how DT data and external data interrelate can add additional strength. The digitalisation of prognostic asset data that is integrated successfully through the concepts detailed within this paper does not just provide the benefit of business decision making but paves the way for automation. The foundations set out by the required systems and technologies needed to achieve PdM can potentially allow autonomous feedback loops. ML can increase its accuracy with increasing time drawing on *Deep Learning* and AI concepts as the predictive model learn what a ‘good’ output looks like compared to its collected data set. Should these practices advance further in development and the benefits exceed the costs, there is a high chance manufacturers establish Deep Learning applications that are capable of autonomous business intelligence decisions.

References

[1] N.N., *The costs and benefits of advanced maintenance in manufacturing*. NIST, Gaithersburg, MD, 2018.
[2] N.N., *Petroleum, petrochemical and natural gas industries — Collection and exchange of reliability and maintenance data for equipment*, ISO, 2016.
[3] N.N., *Predictive Modeling*. MathWorks Inc, 2020, Accessed: 16.11.2020. [Online] Available: https://www.mathworks.com/discovery/predictive-modeling.html
[4] N.N., *What is Industrial Edge Computing and why is it improtant?*, Exorint, 2020, Accessed: 20.11.2020 [Online] Available: https://bit.ly/2IhgEvk
[5] D. Bumblauskas, D. Gemmill, A. Igou and J. Anzengruber, Smart Maintenance Decision Support Systems (SMDSS) based on corporate big data analytics, *Expert Systems with Applications*, 2017, pp. 303–317.
[6] J. Bokrantz, A. Skoogh, C. Berlin and J. Stahre, Maintenance in digitalised manufacturing: Delphi-based scenarios for 2030, *International Journal of Production Economics*, 2017, pp. 154–169.
[7] M.-V Shcherbakov, A.-V. Glotov and S.-V. Cheremisinov, Proactive and Predictive Maintenance of Cyber-Physical Systems, *Studies in Systems, Decision and Control*, 2020, Vol. 259, pp. 263–278.
[8] A. Stanford-Clark, E. Fran-Schultz and M. Harris, *What Are Digital Twins*, 2019, Accessed: 26.11.2020 [Online] Available at: https://developer.ibm.com/technologies/iot/articles/what-are-digital-twins
[9] P. Scully, *How the world’s 250 Digital Twins compare? Same, same but different, Iot-analytics*, 2020. Accessed: 10.12.2020 [Online] Available: Iot-analytics.com
[10] R.-Y Zhong, X. Xu, E. Klotz, and S.-T Newman, Intelligent Manufacturing in the Context of Industry 4.0: A Review, *Engineering*, 2017, Vol. 3(5), pp. 616–630.
[11] B. He, and K.-J Bai, Digital twin-based sustainable intelligent manufacturing: a review, *Advances in Manufacturing*, 2021, Vol. 9, pp. 1–21.
[12] A.Smith and G. Hinchcliffe, *RCM Gateway to World Class Maintenance*, Elsevier Butterworth-Heinemann, San Fransico, 2004.

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Digital Twin-Driven Framework for EV Batteries in Automobile Manufacturing

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Abstract. The successful operation of Electric-Vehicle Batteries (EVB) is paramount for the ever-continuing goal of approaching a low carbon emission future. The Lithium-ion battery (LIB) is currently the best wager to implement on Electric Vehicles (EV). Nonetheless, it comes with its fair trade of challenges. The complexity involved in the design, manufacturing and operating conditions for these batteries has made their control and monitoring paramount. Digital Twin (DT) is concretely defined as a virtual replica of a physical object, process or system. The DT can be implemented in conjunction with the EVB physical embodiment to analyse and enhance its performance. ERP is a system designed to control production and planning amongst others. This paper presents the state-of-the-art battery design, production with the combination of DT and Enterprise system. A five-dimensional DT framework has been proposed linking the physical data and virtual data with ERP. The proposed method was used to model the digital twin of EVB at the concept level and solve its challenges faced in the industry Also the potential application & benefits of the framework have been formalised with the help of a case study from Tesla EVBs.

Keywords. Electric-Vehicle Battery (EVB), Digital Twin (DT), Enterprise Resource Planning (ERP), Electric Vehicle (EV)

Introduction

In a bid to create a greener future driven by the net-zero commitment, manufacturing is presented with a significant role to play. Batteries costs contribute to almost half of the total cost of an electric vehicle [1]. EVB Manufacturers face the task of optimising the use of batteries, extending their life, improving safety and boosting the performance and efficiency, at a low cost. The next step in addressing the challenges identified is by using a collaborative utilisation of Digital Twin (DT) and Enterprise Resource Planning (ERP). A DT is essentially a virtual asset management system. It is created leveraging on machine learning, Artificial Intelligence, data modelling and simulation, using sensors, actuators ultimately for monitoring, and managing the total life cycle of an asset. On the other hand, an ERP is an integrated system that supports the easy flow of information from various

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department in an organisation such as production, Material planning, human resources, and finance; it helps in the breaking down silos. ERP and DT together collectively provides the possibility of managing the EVB life cycle, supply chain and planning finance based on real accurate data and not forecasts. Existing research focuses majorly on optimising the EVB components particularly in a bid to reduce high costs however complex challenges in need of a wholistic approach persists. There is a gap in utilising the data to create value and enhance profitability in the EVB industry. This paper provides a digital-twin framework that integrates ERP as a backbone for solving these challenges associated with the EVB.

1. EV-B Landscape

1.1. Components of the Lithium-ion Battery Cell

Batteries used in Electric Vehicles such as the famous automotive brand, Tesla, falls under the rechargeable Lithium battery class. The power generated from these batteries typically powers the functioning of the Electric vehicle, and they could be recharged at EV battery stations when they are low in power. The Lithium-ion battery cell consists of a positive electrode (cathode), a negative electrode (anode), a separator, and an electrolyte serving as a conductor. Carbonaceous materials such as artificial and natural graphite, mesophase and amorphous carbon and more recently silicon and tin oxides and alloys, as well as Lithium Titanium Oxide (LTO), are used as active anode materials [2].

The performance of the Electric Vehicle (EV) relies mostly on the performance of the EVB [3]. Some of the parameters identified to be vital in measuring the EVB performance include the charge capacity, energy density, cycle life, specific energy specific power as well as energy quality.

1.2. Electric Vehicle Batteries (EVB)

Due to its clean and sustainable system, EVs have started to get popular in demand. However, the essential element that forms the backbone for the functionality, reliability and profitability of the EV is the EVB, and there are a couple of challenges still faced in its manufacturing. To fulfil the high demand and expected SLA (Service Level Agreement) metrics for EVBs in the year 2030; lead times in the manufacturing of EVBs must be shortened while maintaining maximum quality and asset management. Amongst the numerous challenges faced by the EVB, this paper addresses five of them [4], as shown in figure 1:

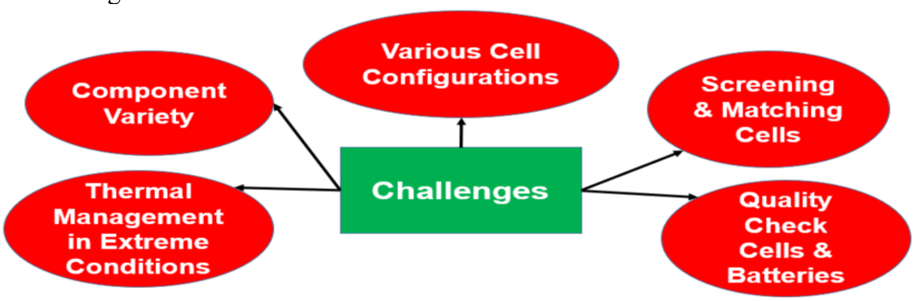

Figure 1. Challenges faced by EVB.

Batteries are widely known to dissipate heat; the lithium-ion battery used in Electric Vehicles is no exception to this characteristic. Tesla, a well-known pacesetter in EV manufacturing, in a quest to optimise thermal management, has so far developed three generations of cooling/heating systems for its Vehicles. The first generation was a system that made use of glycol coolant [5] to pass through its cell module from one direction, serially, to another. The change in the second generation was that the glycol coolant had two entrances and two exits. Finally, the third generation involved the glycol coolant passing through the cell module in parallel. What's next? The fourth industrial revolution. Thermal management should become active as opposed to being passive. The thermal management challenge as well as the others are shown in figure 1, would be discussed further in the paper.

2. Digital Twin

2.1. Concept of Digital Twin

The concept of DT goes back to 2003 when Grieves [6] proposed the concept in his executive course on Product Lifecycle Management (PLM); DT was later introduced into the National Aeronautics and Space Administration (NASA) and the US Air Force. It was not until 2010 that an official concept for DT was brought up, in this case by NASA in their report "Draft Modeling, Simulation, Information Technology & Processing Roadmap" [7]. DT is defined as "an integrated multiphysics, multiscale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin" [7]. Grieves' initial concept focused on emphasising the continuous feedback and interactions between the virtual and physical entities. Three components are the core of his proposal: the already mentioned physical and virtual entities and the connection that allows the exchange of data between the two.

2.2. Five-dimension Digital Twin

Fei Tao's [8] proposed model builds on that of Grieve and expands on its definition and approach. Grieve’s model keeps its focus solely on the physical-virtual interaction, Tao's enhanced proposal denotes a higher priority to the DT data which fuses the information acquired from both the physical and virtual entities for more capable information capture.

2.3. Digital Twin in EVB Manufacturing

DT has been defined many times, and to add one more to the dictionary, DT can be termed as "The mind of a machine", as shown in Figure 2. With an enormous and consistent flow of data, DT is enabling the manufacturing, operations and finance sector in a company to a higher limit. It not only tells how to manufacture an efficient product but also how to operate it. It covers the whole product lifecycle. DT represents the physical product in the digital world and performs tasks in the digital world, allowing us to do things faster while spending fewer resources, both monetary and workforce. For example, doing simulation instead of prototyping would be expensive and timely. DT can also predict the market analysis and help in cutting costs, grow operating margins and revenue. By making changes in the battery, it can give answers on the impact on margins, profitability, and return on investment. It can also improve a product's performance while reducing both the cost and risk of new product development [9].

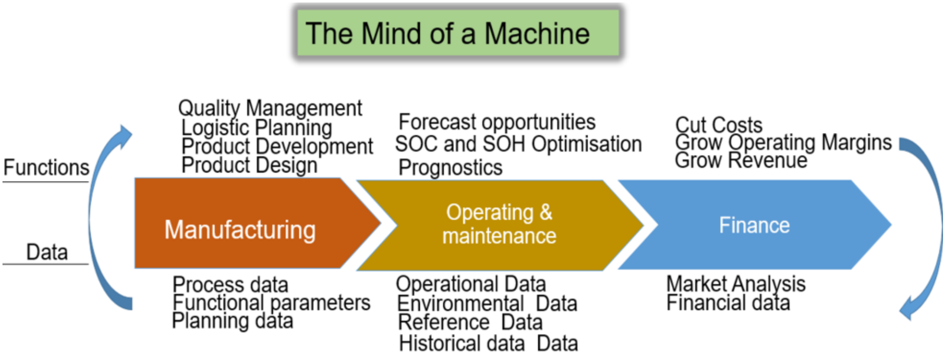

Figure 2. DT Mind of a Machine.

The DT will have its own architecture that through various simulation models would integrate engineering data, operational data and historical data. These models are going to be manually created and later modified by a model management system. Besides, the model management system can choose the best simulation model for relevant problems. [10]. It is also important to note that DT is also a feedback loop from operating to manufacturing, from operating into designing the next product generation, from the shop floor back into design, and so forth.

2.4. Digital Twin Framework

The framework for the proposal (Figure 3) is built on Fei Tao's five-dimensional DT [8][11], The Physical and Virtual data will be collected into the DT Data to be processed and analysed subsequently. The Connections between the components of the framework are enabled through the usage of dedicated ERP systems, which will lead to the services of the framework, churning out the optimisation and prognostics outcomes desired. Effective management of batteries can be approached by a basic State-of-X (SOX) estimation. The framework focuses on the basic key approaches of State-of-Charge (SOC) and State-of-Health (SOH) [12] of the batteries. These states determine the remaining useful lifetime (RUL) of a battery. This analysis incorporated with the other expected outcomes in services should enhance the work in addressing the established challenges.

The DT framework is conceptualised based on the following entities:

a. ***Physical Data:*** The data initially collected from the physical specimen is critical as it will set what can be gathered and inferred from the system through its analysis. The EVB will be monitored mainly for data on voltage, current, pressure, temperature and power consumption; environmental data is also recorded.

b. ***Virtual Data:*** Gathered physical and previously recorded experimental data is utilised to create simulation models; built on models for geometry, physics, behaviour and rules. As their names state, the first two models label geometrical and physical properties, respectively. The behaviour models analyse the conduct of the product, user, environment and their interactions. The rules set the evaluation, forecasting and optimisations models [11].

c. ***DT Data:*** Data collected from the physical and virtual entities is stored in the 'DT Data'. This data will be further analysed and integrated; afterwards will be fed into the services and be used to execute the intended services of optimisation desired for the components.

d. ***Connections:*** All the components are bi-directionally connected through and between each other and associated by the ERP Systems. Facilitating communications through the usage of the established ERP Systems, ensuring all information communications are kept through a uniform system.

e. ***Services*:** Two types of services are considered, functional service (FS) and business service (BS) [13]. FS condenses the gathered DT data into the services that will verify the model assembly and verification, analytics, connection, communication and interaction [11].

The latter is managed to provide the desired outcomes found in the centre of Figure 3: SOC & SOH Optimisation, Design, Manufacturing, Fault Diagnosis, Cell Balancing and Thermal Management.

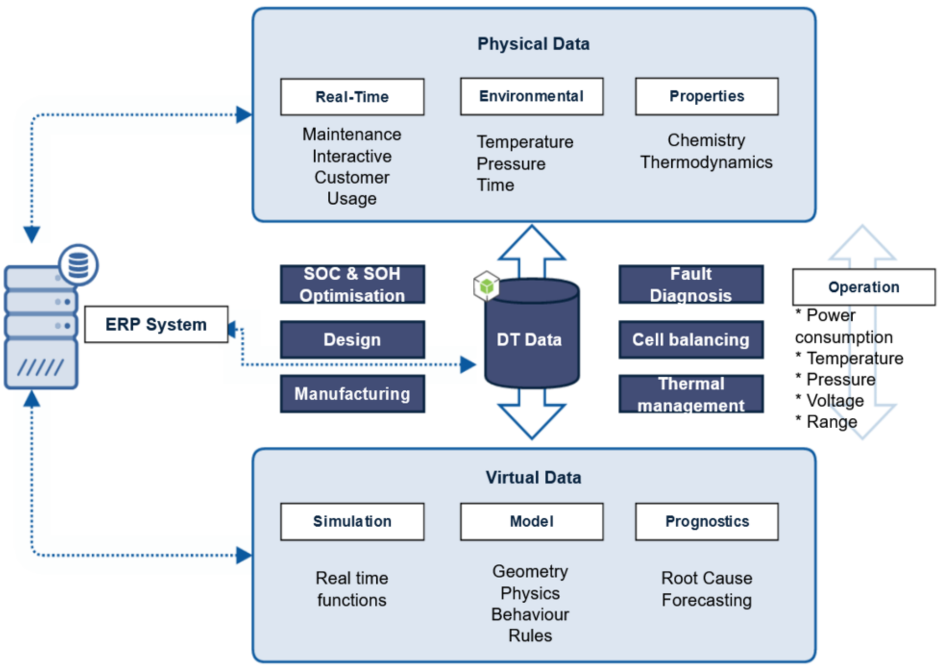

Figure 3. Digital Twin Framework.

3. Phase of ERP link to Digital Twin

3.1. ERP System

Business administration ERP [14] systems that have an extensive collection of applications integrate and control all business activities of a corporation series features as shown in Figure 4 production, financial and accounting applications, Sales and distribution, project management, materials management, supply chain management (SCM), and quality management. The centralisation of information by the unified database is the central idea of the ERP method. This involves information from sales, marketing, development, and product design, field support, production, inventory control, management and procurement of industrial facilities, quality, logistics, human resources, finance, and database systems. ERP systems are software modules that share a centralised information basis and provide information.

- Production: ERP development module contains key features specially tailored for the engineering industry's unique needs. [15] It enables production preparation, orders, and delivers to consumers. It leads a company to manage personnel, equipment, and production scheduling optimally; it encourages the administrator to organise work as needed.

- Financial: The manufacturer will incorporate the financial reporting ERP method that can streamline payroll, outsourcing, production preparation, scheduling, and partnership. Through applying the ERP framework, the accuracy of financial data will enable quick decision-making [15].

- Inventory Management: ERP systems can manage the warehouse inventory level require. It helps define product needs, offers alternatives for replenishment, records inventory status, track material utilisation, establishes goals, and more. Material management module combines warning files with sales modules. Inventory enables procedures to manage a warehouse's acceptable stock volume.

- Sales: The ERP sales module is an essential module for the company. This ERP allows for the preparation, placement, transport, and invoicing of orders. It integrates with the website of the company, which makes communication more effective.

- Integration: Open Platform Communication Unified Architecture (OPC-UA) to connect the ERP and DT communication with the same production factors.

- Product Data Management (PDM): PDM provides product data management solutions for the duration of the product life cycle. Typically, PDM systems store CAD drawings and other designs ordered and well-documented archives.

- Product Lifecycle Management (PLM): PLM is a mechanism for handling through the stages of product life, from the development to the decline. The sectors of manufacturing and marketing are both handled. As the complexity of materials and supply chains increases, the manufacturing process becomes more difficult to handle. The main benefits of PLM are the increase the speed of getting the product to market, putting a higher quality, improve the safety. The PLM can be retrieved inside specialized computer software. The functions are documents managements, design integration and process management. [16]

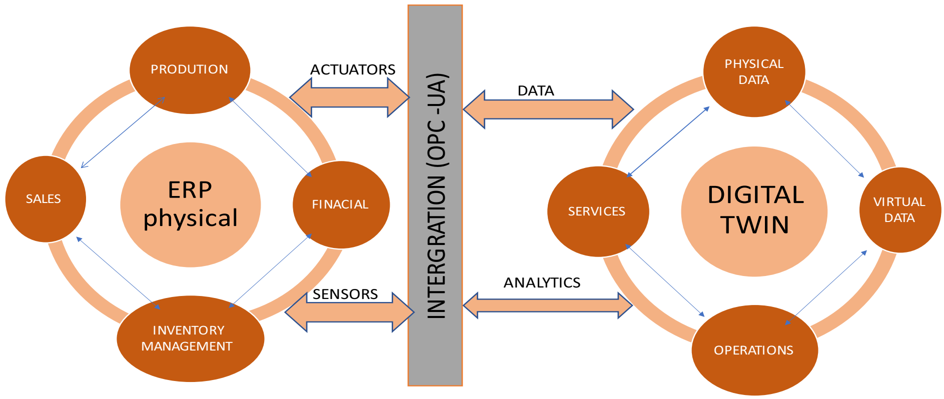

Figure 4. ERP & DT link

3.2. ERP and EV Challenges

Previously, it has been explained that the integrated management software as ERP offers an interesting solution because they facilitate the management of the company's processes, and as a result, they increase organisational performance and individual performance. The main question revolves around the possibility of integrating an ERP-type solution to the challenges offered by Electrics Vehicle Batteries.

3.3. ERP in the automotive industry

The automotive manufacturer must respond to the new shifts that are facing them today. The data would play a vital role in the industry shift. It might not be surprising that in the future, the industry's supply chain and the production lines will likely tilt to the tech sector than to the manufacturing one as before [10]. The ERP could have an impact on the supplier by collecting data into a central hub, for example, lot tracking tools that could integrate data from digital assets and IoT devices. This system could be complemented by a PDM/PLM to treat the complex asset of data and drive the production development. But these systems will not be treated in detail in our study in order to focus on EVD-DT-ERP.

3.4. Answering EV Challenges

Moreover, imagine that an ERP-type solution could help us solve the various challenges imposed by batteries. An ERP model will allow data to be centralised. These data will come from the different departments of the production line and would be easier to interpret. Designers should presume that considerable data is required for production design, voltage variance, and thermal management. Therefore, researchers may suggest a paradigm where data and perspective provided to us are at the core of the solution. This solution would be a System where a DT is implemented into an ERP-type model to answer EVB challenges. It can be assumed that DT could be implemented as software into the ERP, and this software would use the different data needed to do the experimentation and validation. The next step is the implementation of an EVB-DT-ERP solution.

4. EVB-DT-ERP System

Figure 5 shows how DT allows for blending data like customer feedback, design model, production data, engineering data, and maintenance data from enterprise applications such as ERP systems with the help of real-time data collected from the sensors placed in the physical battery. The DT can provide insights like SOC & SOH of the battery, predictive analysis, strategy optimisation which will help in optimising the production chain of battery manufacturing and speeding up the decision-making process. This leads to increased profit margins because the design and manufacturing efficiency will proliferate when variables that could impede the process are identified and eliminated. The challenges mentioned in yellow boxes in Figure 5 are explained below and how DT can find a solution for the same.

1. The chemical reactions and cell physics that happens inside Lithium-ion batteries are quite complicated, and this is where DT can track the complex thermal behaviour and electrochemical changes. There are several viable positive electrodes each having distinctive characteristics. This variability presents the need for analysis for determining the best component use for functionality required. The analysis of historical data from similar cells and batteries makes it possible to predict the performance of a battery that has not yet been constructed. The DT allows you to use this information to model different scenarios by choosing the best pack assembly. i.e., the combination of series and parallel (which determines the charge capacity and power output) and finest battery components (active and inactive) for the new product and identify areas where new batteries can be improved over previous ones.
2. Variation of voltage in a cell is very critical and this can be avoided by creating a part twin of a cell, each part of the production process can be monitored and modelled by DT to identify where quality problems could occur and to evaluate the composition of the product being produced to determine whether there were any better materials and production processes that could have been used. By acting as a single point of reference for trusted information, DT can help resolve voltage variation issues between cells.

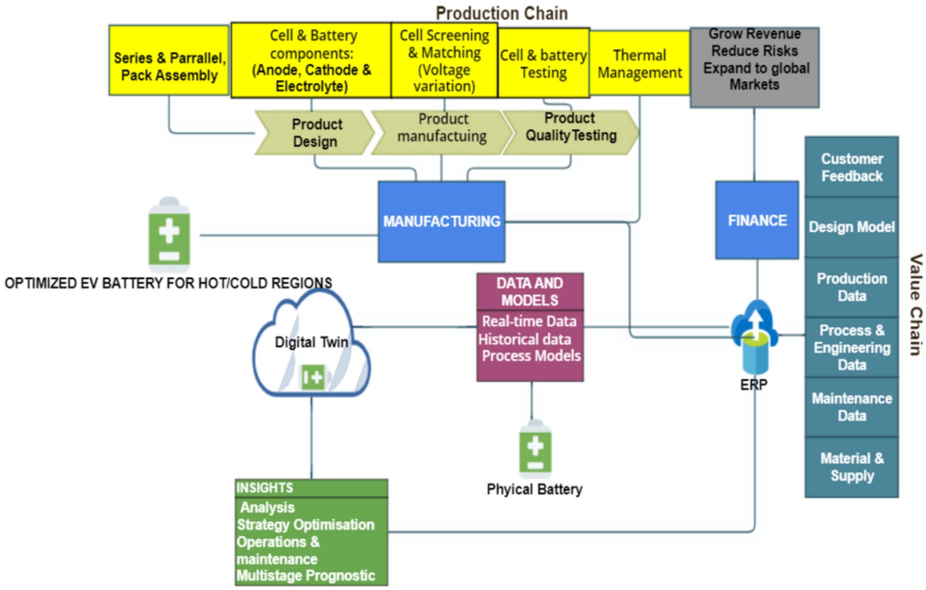

Figure 5. EVB-DT-ERP System

3. Thermal management is an exceptionally critical and significant challenge, Batteries are often optimised for either high or low temperatures and testing in relevant environment condition is not always possible. It can be computationally expensive and time-consuming, and this is where DT can perform various simulations in extreme conditions virtually and define the critical design parameters, key factors (heat generation and heat removal) and materials needed for optimal performance of the EV batteries in these conditions.

Hence by using our system companies like Tesla and EVB manufacturers who are facing challenges with the complexity of Li ion batteries can leverage upon this system to grow their business.

5. Conclusions

This paper aims to provide a reliable tool which can give investors more confidence and improve the business case, and in turn unlock more investments into EVB. This paper has addressed some of the key challenges faced by EVB. It proposes a framework of ERP integrated with digital twin for the monitoring of EVBs in hot and cold regions. Also, by Pairing real-world data with design simulation models it allows for good decisions based on realistic data on the other side. By leveraging on artificial intelligence, machine learning, and ERP, DT makes it possible to acquire insights and optimise the assets for maximum sustainability. This paper also presents a case study of Tesla, to show the current state of EVBs, their thermal management system and what benefits it could offer to improve them. Since all models and data are present in a coherent and well-aligned context, the concept of Digital Twin facilitates precisely such a process still needs further research to improve and enrich its capacity by considering more factors and practical situations.

References

[1] P. Wolfram and N. Lutsey, Electric vehicles: Literature review of technology costs and carbon emissions” *Int. Counc. Clean …*, no. July, pp. 1–23, 2016, [Online]. Available: https://pdfs.semanticscholar.org/2913/dc7927c411ba6a922f426a67f01108699fd3.pdf%0Ahttps://www.researchgate.net/profile/Nicholas_Lutsey/publication/305492926_Electric_vehicles_Literature_review_of_technology_costs_and_carbon_emissions/links/5791a34c08ae6431.

[2] N. L. Franco, D. Persio, and L. Boon-Brett, Lithium ion battery value chain and related opportunities for Europe Title: Lithium ion battery value chain and related opportunities for Europe, 2014, [Online]. Available: https://ec.europa.eu/jrc/sites/jrcsh/files/jrc105010_161214_li-ion_battery_value_chain_jrc105010.pdf.

[3] P. Roy, M. S. Akther Momin, and M.G. Kader, “Importance and Proper Way of Maintaining A Battery, *International Conference on Mechanical Engineeringand Renewable Energy 2015 (ICMERE2015)*, 2015, November 2015, pp. 26–29.

[4] J. Jeevarajan, *Separators used in Li-ion Cells Li-ion Cell Construction and Internal Protective Features*, 2016, Acessed July 3, 2021, https://thecityfixlearn.org/sites/default/files/UL%20WRI%20webinar%20Li%20ion%20safety_Part%202-%2816-30%29.pdf.

[5] G. Bower, *Tesla Model 3 Battery Cooling Much-Improved ... Track Mode?*, 2018. https://insideevs.com/news/338711/tesla-model-3-battery-cooling-much-improved-track-mode/ , accessed Dec. 10, 2020.

[6] F. Tao, M. Zhang, and A. Y. C. Nee, *Digital Twin Driven Smart Manufacturing*. Elsevier, Amsterdam, 2019.

[7] M. Shafto *et al.*, DRAFT Modeling, Simulation, information Technology & Processing Roadmap - Technology Area 11, *Natl. Aeronaut. Sp. Adm.*, p. 27, 2010, [Online]. Available: https://www.nasa.gov/pdf/501321main_TA11-MSITP-DRAFT-Nov2010-A1.pdf.

[8] F. Tao, M. Zhang, Y. Liu, and A. Y. C. Nee, Digital twin driven prognostics and health management for complex equipment, *CIRP Ann.*, 2018, Vol. 67, No. 1, pp. 169–172.

[9] D. Gamota, How Digital Twins Lead to Manufacturing Profitability, https://www.jabil.com/blog/how-digital-twins-lead-to-manufacturing-profitability.html, accessed Dec. 06, 2020.

[10] M. Kunath and H. Winkler, Integrating the Digital Twin of the manufacturing system into a decision support system for improving the order management process, *Procedia CIRP*, 2018, Vol. 72, pp. 225–231.

[11] F. Tao, A. Liu, T. Hu, and A. Y. C. Nee, *Digital Twin Driven Smart Design*. Elsevier, 2020.

[12] B. Wu, W. D. Widanage, S. Yang, and X. Liu, Battery digital twins: Perspectives on the fusion of models, data and artificial intelligence for smart battery management systems, *Energy AI*, 2020, Vol. 1, 100016.

[13] F. Tao *et al.*, Five-dimension digital twin model and its ten applications, *Jisuanji Jicheng Zhizao Xitong/Computer Integr. Manuf. Syst. CIMS*, 2019, Vol. 25, No. 1, pp. 1–18.

[14] A. Ullah, R. Bin, B. Khalil, M. Siddique, and A. Sami, Enterprise Resource Planning (ERP) Systems and User Performance (UP), *J. Manag. Sci.*, 2017, Vol. XI, No. 03, pp. 377–390.

[15] H. Abualrejal, The Effectiveness of Enterprise Resource Planning- Erp Implementation In Manufacturing Industry, *Proc. Symp. Technol. Manag. Logist. (STML–Go Green)*, 2016, Accessed: Dec. 09, 2020. [Online]. Available: https://www.researchgate.net/publication/318445385_THE_EFFECTIVENESS_OF_ENTERPRISE_RESOURCE_PLANNING-_ERP_IMPLEMENTATION_IN_MANUFACTURING_INDUSTRY.

[16] T. Segal, *Product Lifecycle Management (PLM) Definition*, 2019. https://www.investopedia.com/terms/p/product-life-cycle-management.asp, accessed May 16, 2021.

Part 4

Industry and Society

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Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Flexible Hiring Personnel Models to Promote Human Satisfaction and Business Profit for Service Industries

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Abstract. In service industries personnel performance is key to achieve business excellence. Until recently, forty to forty eight hours per week labor contracts with equal daily schedules (eight hours per day) was the only way formal employees were hired in some countries. Recently, this trend has changed and some countries started to allow work contracts with less weekly hours and flexible daily schedules. This offers some degrees of freedom to employees to work less than eight hours per day and non-necessarily having the same timetable every workday. The fabric of society is impacted since now work is at reach for many people who cannot work full time schedules for diverse reasons. The contribution of this work is a Transdisciplinary Flextime Hiring Method that considers both employee and company needs. Using organisational design concepts (business management), flexibility is analysed through integer programming modelling (engineering optimisation) to evaluate cost changes resulting from implementing flextime (societal needs). Service companies may justify and implement flextime based on cost reductions, along with its associated improvement of employee satisfaction and commitment. Numerical analysis based on industry data illustrates these concepts and consequences.

Keywords. flextime, integer programming, company culture, transdisciplinary, workforce satisfaction

Introduction

Businesses are always searching for ways to improve their operational efficiency, where flexible organizational structures are specially relevant for satisfactory goal-achievement simultaneous with lowest total cost.

As companies struggled to increase efficiency by focusing on the control of variability, competition for customers and talent in the XXI century has shifted the focus to innovation and flexibility [1]. In this context, flexibility is interpreted as the firm's ability to add or remove scarce and costly resources, with an emphasis on employees hired for their knowledge and competences to do useful work under a controlled regulatory environment.

This flexibilization of the workforce has an increasing presence in organizational design [2], based on increasing competitiveness pressures, labor market fluctuations, product innovation and adoption of new technologies [2, 3].

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However, legal regulations in most of the world force rigid labor contracts, resulting in fixed procedures that, at least, hinder flexibility. Employees, on their part, increasingly search for opportunities to confront and resolve work and non-work demands [4].

Under systemic disruptions, such as the *Black Swan* phenomena of the COVID pandemic, company's resilience is under pressure. Thus, operational practices should adopt changes to recover sustainability. For service organisations, there is an opportunity to hire more people under limited hours of working days, or less working days, to increase operational efficiency without losing service quality, while offering part-time jobs to persons in need.

Transdisciplinary engineering offers a suitable methodology to tackle this complex problem. From Ertas [5] "Transdiciplinarity is a development of new … tools & technologies shared by researchers from different family of disciplines (Social science, natural science, humanities and engineering)". Furthermore the International Society of Transdisciplinary Engineering (ISTE) [6] states that it "is a methodological approach, explicitly incorporating social sciences to gather information and to guide implementation of engineering solutions in practice" and deepens the concept with "To create engineering solutions that minimise … societal damage, engineering design and practices must involve people with the necessary knowledge and methods to determine the impact of new products and services, not only on client and user satisfaction, but also on long-term sustainability." [7].

In this work, authors present a transdisciplinary approach (engineering optimisation, business organizational design and social job opportunities for minorities) to the problem of meeting company's need for satisfactory service over long workdays versus employee's life balance needs, affecting their motivation and concentration.

By using a mathematical model designed for cost optimization and applying it to allow for the implementation of flextime, one can explore cost implications of hiring under a number of scheduling options to achieve a supportive culture, sensitive to employee's needs. Thus, improving economic efficiency and increasing job satisfaction and retention.

The contribution of this work is a Transdisciplinary Flextime Hiring Method (TFHM) that considers both employee and company needs. Using organisational design concepts (business management), flexibility is analysed through integer programming modelling (engineering optimisation) to evaluate cost changes resulting from implementing flextime (societal needs). Service companies may justify and implement flextime based on cost reductions, along with its associated improvement of employee satisfaction and commitment.

This paper is organized as follows: in Section 1 the flexible time imperative is analysed in studies in organisational behavior and psychology, from both the employee's and company's viewpoint; Section 2 presents a transdisciplinary method to implement flextime and analyse its consequences in cost; and Section 3 shows a numerical instance in a service company, based on industry data, with analysis of results and consequences.

1. Flexible time

Flexible Working Arrangements (FWA) are "mutually beneficial arrangements between employers and employees in which both parties agree on when, and how the employee will work to meet the firm's needs" [8]. Flextime is the arrangement over time, when the workday begins and ends, more working hours over less week days or part-time work.

Flexibility may also be in performed functions: job enrichment or multi-purpose contracts based on employee's capabilities and pre-existing skill enhancement, that have been found to be perceived as a favourable influence to stay in the firm [2, 9, 10].

To analyse flextime, both viewpoints are explored, as they are different: the employee's and the company's.

1.1. From the employee's view

FWA offers employees some degree of control over the context on which they work [4], they find them attractive based on their perceived signal that the company cares about them [11] and is more supportive [12, 13]. FWA have a strong effect on work interference with family life [14] and decreased work-family conflict [15] and are perceived as providers of job satisfaction [16], commitment to the organization, productivity [17] and decreased absenteeism [18].

A desired effect of non-traditional flextime is that workers are more able to find a better balance between working hours and personal time, enhanced autonomy and intensification of work commitment [19]. By having more say in their working hours, they may find a better fit of their working and personal lives [2, 20].

Employees that perceive their schedules as flexible, reported higher levels of work-personal life balance and paths to well-being [21], consistent with current theories on effects of organizational culture's effect on happiness and less stressed lives.

1.2. From the company's view

An organization's competitive advantage is often based on specific knowledge residing on its employees [22], it is crucial to attract the most talented people and manage to retain them. As more and more companies manage their human capital strategically, in times of talent shortage [23], being perceived as family-friendly helps attract and retain qualified talent [17]

Flexibility is no longer a perk but a competitive tool to meet recruitment objectives, FWA facilitate the creation of people-based competitive advantages [8, 24]. The creation of a supportive culture means the company is sensitive to employee's family needs and does not demand prioritization of work over family [21].

From a transdisciplinary approach, cost optimisation must be considered. Academic literature offers scant treatment of this crucial combination of economic optimization and strategic talent attraction and retaining.

1.3. A case in point: women in the workforce

The increased participation of women in the workforce has a profound impact on family's decisions over childbearing and home division of labor and income [25]. Women have chosen new life roles, their compatibility with work-family equilibrium have been found to be a relevant driving force behind fertility decreases in industrialized countries [26, 27].

Women who also work outside their home, face barriers to advance within corporate structures, one of such is the difficult balance of work and family responsibilities [28]. Some choose to delay work advancement while children need their concentration.

If the opportunity is offered to have a flexible work schedule, the probability that competent, career-oriented women will remain at work may increase [17], to the benefit of the woman, her family and the company.

2. Flextime transdisciplinary implementation method

Implementing a flextime arrangement in a service-oriented company, where core activities are performed through direct intervention of qualified employees, is a complex task that we aim to simplify.

While research on the impact of flexible time focus on firm or employee's performance and job satisfaction, it does not address the complex issues in managing its implementation; at the same time, operations research offers solutions for workforce scheduling but do not address the flexibility needed by workers and its regulatory restrictions. Thus our transdisciplinary approach.

Organizations under analysis require positions staffed under regulatory restrictions of daily working hours, without missing a single moment to service the customer, every day for 12, 14 or longer working days, as is the case of many service establishments such as convenience, department or grocery stores, bank tellers, cinema theaters, call centers, service stations (like fuel dispensing), parking or toll-booth attendants, or hotel reception desks, to name a few.

2.1. The Transdisciplinary Flextime Hiring Method

Mohamad and Said [29] started with the daily service capacity requirements (servers in each time slot) [30], known in operations research as the Toll-Booth Problem. In many applications, number of servers was observed to vary daily. Later, Trigos, Vazquez and Cárdenas-Barrón [31] developed a simulation-based heuristic to define daily service capacity requirements to guarantee specific quality performance indicators.

Many service companies require different daily server capacities throughout the week. Using Trigos, Vazquez and Cárdenas-Barrón [31] methodology for each weekday, a full-week daily server requirements can be obtained, namely the Weekly Service Capacity Matrix (WSCM).

Table 1 presents the TFHM steps.

Table 1. Steps of TFHM.

Step	Activity	Comments
1	Define the Week Service Capacity Matrix (WSCM).	Specify a service capacity matrix form, which defines the minimum number of servers per day and time slot (from opening to closing, hour by hour and day by day) to achieve the desired service performance indicator. One option is to use [28] for every day of the week.
2	Define working days	6 days in a row, or single-day are examples to consider.
3	Define hours of working days (possible work schedules for each day).	8, 6 or 4 working hours plus lunchtime allowance are examples to consider.
4	Set the integer programming model	The goal (the objective function) is to minimize total payroll by determining the working contracts. The constraints to be satisfied are defined per day and time period (time slot), the number of attendants present in each slot must be at least those defined in the WSCM.

Step	Activity	Comments
		The model variable is the number of contracts (people to be hired) for each combination of hours-of-working-days and working-days
5	Model execution	Several commercial software options are available, among them: the General Algebraic Modelling System® (GAMS), LINGO® or MS Excel Solver®.
6	Scenario analysis	Analyse different scenarios by modifying hours of working days and/or working days to explore as many possibilites as can be imagined.
7	Prepare the comparison table	To visualise all the options analysed and select the optimal for the company.
8	Allocate people to contracts	Each candidate selects preferred non-overlapping available contracts. Company may allot the most sought-after slots to the best candidates, based on past performance, commitment and other criteria.

The goal for the company is to meet those requirements with minimum payroll cost by way of flextime hiring.

A contract is meant as a commitment between one person and the company to perform work during a specified period (the contract schedule), in exchange for payment.

There are three concepts to have in mind: Contracts (determined by the combination of the variable indexes), Weekly-contract-equivalent (WCE) (a contract to work six days per week eight hours per day), and headcount (number of individuals working in the system); the latter cannot be directly determined, since an individual could work on several contracts as long as none of them overlap. This opens the door for multiple ways to hire individuals, for instance an individual could sign one contract for 9:00 to 13:00 and another from 15:00 to 16:00, and only on Mondays.

2.2. A numerical example

Let us analyze a particular service company (a large grocery store, for instance) that works seven days per week, twelve hours per day. Service quality analysis defines that for the next season, the number of open cashiers per working hour and day of the week must satisfy the minimum requirements shown in Table 2 (TFHM Step 1).

Table 2. WSCM for the numerical example.

Start time	Minimum number of open cashiers needed						
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
9:00	6	5	5	4	4	5	5
10:00	7	6	5	5	5	6	6
11:00	7	6	5	6	5	8	7
12:00	7	6	5	5	5	7	7
13:00	7	6	5	5	5	7	7
14:00	7	5	5	5	6	9	8
15:00	7	6	6	5	6	9	7
16:00	8	6	6	6	6	9	7
17:00	8	6	6	6	7	10	8
18:00	9	7	7	7	7	10	10
19:00	10	7	8	6	8	10	9

Company defines that it can accept that people sign-in for 6-day or single-day commitments, as shown in Table 3 (TFHM Step 2), and acceptable hours of working days are as in Table 4 (TFHM Step 3).

Management is used only to full-week contract hiring but is willing to explore new options using the WCE concept to compare final cost.

In this example, company's hourly wage rate is constant, independent of time of day or weekday. Thus, minimising total sum of working hours is equivalent to minimising payroll. Since 48 hours of work determines a WCE, minimising total WCEs is also equivalent to minimising payroll and thus cost.

TFHM Step 4: The integer programming model was run under GAMS® 33.2.0 using Cplex 12.10.0.0 with up to 378 contract variables (14 working days times 27 hours of working days), 84 restrictions (7 workdays times 12 working hours per day). Four scenarios were analysed, each one took neglible processing time on a MacBook Air computer running under MacOS Big Sur 11.2.1, having 2.2 GHz Dual-Core Intel Core i7 processor and 8GB RAM.

Four scenarios were defined for analysis: current practice and three of increased flexibility (TFHM Steps 5 and 6), described as follows.

Table 3. Working days.

Period	Description	Period	Description
Mo_Sa	Monday to Saturday	Mo	Monday
Tu_Su	Tuesday to Sunday	Tu	Tuesday
We_Mo	Wednesday to Monday	We	Wednesday
Th_Tu	Thursday to Tuesday	Th	Thursday
Fr_We	Friday to Wednesday	Fr	Friday
Sa_Th	Saturday to Thursday	Sa	Saturday
Su_Fr	Sunday to Friday	Su	Sunday

Table 4. Hours of working days

8 hours per day	6 hours per day	4 hours per day
9 to12 and 13 t o18	9 to 12 and 13 to 16	9 to 13
9 to 13 and 14 to 19	10 to 13 and 14 to 17	10 to 14
9 to 14 and15 to 18	11 to 14 and 15 to 18	11 to 15
10 to 13 and 14 to 19	12 to 15 and 16 to 19	12 to 16
10 to 14 and 15 to 19	13 to 16 and 17 to 20	13 to 17
10 to 15 and 16 to 19	14 to 17 and 18 to 21	14 to 18
11 to 14 and 15 to 20		15 to 19
11 to 15 and 16 to 20		16 to 20
11 to 16 and 17 to 20		17 to 21
12 to 15 and 16 to 21		
12 to 16 and 17 to 21		
12 to 17 and 18 to 21		

Scenario 1

Only contracts for six 8 hours of working days are allowed, i.e. everybody works full time as it is currently practiced. Table 5 presents contract assignments, the last row shows WCEs for each assigned working days, with a sum of 17 WCEs for this scenario.

Table 5. Optimal solution for scenario 1, 17 WCEs. Only full week contracts are considered.

Hours of working days	Hours per day	Working days Mo_Sa	We_Mo	Th_Tu	Fr_We	Sa_Th	Su_Fr
9 to 14 and 15 to 18	8	1			2	2	1
10 to 13 and 14 to 19	8			1			
11 to 15 and 16 to 20	8				1		
11 to 16 and 17 to 20	8			1			
12 to 15 and 16 to 21	8	1	2			2	
12 to 16 and 17 to 21	8			1	2		
Daily worked hours		16	16	24	40	32	8
Workdays		6	6	6	6	6	6
Week hours		96	96	144	240	192	48
WCEs		2	2	3	5	4	1

Scenario 2

Only one working day contracts with 4, 6 and 8 possible hours of working days are available. An employee could be hired for more than one contract, if they do not overlap.

The minimum WCEs are 16 + 1/3. The particular contracts are shown in Table 6. Notice that in this particular instance, only 8-hour days were selected.

Table 6. Optimal solution for scenario 2, 16+1/3 WCEs. Only one day contracts are considered.

Hours of working days	Hours per day	Working days Mo	Tu	We	Th	Fr	Sa	Su
9 to 12 and 13 to 18	8	6				4		
9 to 13 and 14 to 18	8		5	5				
9 to 14 and 15 to 18	8				4		5	5
10 to 14 and 15 to 19	8						1	1
10 to 15 and 16 to 19	8	1	1		1	1		
11 to 14 and 15 to 20	8		1					1
11 to 15 and 16 to 20	8	1		2		2		
11 to 16 and 17 to 20	8	1			1		2	
12 to 15 and 16 to 21	8	8	6		5		7	8
12 to 16 and 17 to 21	8			6		6	1	
Daily worked hours		136	104	104	88	104	128	120
Workdays		1	1	1	1	1	1	1
Week hours		136	104	104	88	104	128	120
WCEs		2+5/6	2+1/6	2+1/6	1+5/6	2+1/6	2+2/3	2+1/2

Scenario 3

Six working day contracts are mandatory but 4, 6, and 8 hours of working days are feasible. The minimum WCEs are 12+1/2. The particular contracts are shown in Table 7.

Table 7. Optimal solution for scenario 3, 12+½ WCEs. Six-day contracts are mandatory.

Hours of working days	Hours per day	Working days We_Mo	Th_Tu	Fr_We	Sa_Th
9 to 12 and 13 to 18	8			1	
9 to 14 and 15 to 18	8				1
9 to 12 and 13 to 16	6		1		
10 to 13 and 14 to 17	6		1		
14 to 17 and 18 to 21	6			2	
9 to 13	4	1		1	1
11 to 15	4		1		
12 to 16	4			1	
13 to 17	4	1			1
16 to 20	4	2			
17 to 21	4	1	2	1	2
Daily worked hours		20	24	32	24
Workdays		6	6	6	6
Week hours		120	144	192	144
WCEs		2+1/2	3	4	3

Scenario 4

Either six- or one-working day contracts are feasible along with 4, 6 or 8 hours of working days. The minimum WCEs are 11 + 5/8. The particular contracts are shown in Table 8. Notice that only one-day contracts were selected in the solution.

Scenario comparison

With Scenario 1 as the reference, Table 9 presents comparative results (TFHM Step 7). As flexibility increases, less WCEs are required, thus payroll decreases significantly without any loss in attendant availability.

Increasing flexibility to allow for variable-length working hours is an advantage for part-time candidates, for example women rising children or elders, and at the same time results show an important reduction in payroll. In addition, less continuous time in front of customers may aid in improving quality of service, as attendants are less tired. This particular effect is a topic for further research.

The strongest impacts are found in scenarios 3 and 4, with the adoption of more flexibility. Since the company is used to everybody having the same schedule, it is recommended to attempt Scenario 3 first, gain experience, and then embark on full flexibility (Scenario 4), while carefully observing the changes in employee's performance, satisfaction and commitment, as measures of a better personal-work life balance.

TFHM Step 8 corresponds to company decisions based on the previous comparison, not included as it is proprietary information.

3. Conclusions

Flextime is possible and economically viable for the company and beneficial to the employee. From the company's viewpoint, it can be implemented with a significant cost reductions, with the additional advantage of improved work climate and employee commitment.

Since headcount depends on the number of contracts an individual takes (as long as they do not overlap), individual-contract assignment can take a number of forms such as: a) Minimize headcount (to reduce personnel control difficulty); b) Assignment by individual performance measure, i.e. the employee with best performance in the previous planning period gets to select the contracts he/she will take first, and so on. This promotes motivation for individual performance.

Table 8. Optimal solution for scenario 4, 11+5/8 WCEs. Full flexibility.

Hours of working days	**Hours per day**	**Working days**						
		Mo	**Tu**	**We**	**Th**	**Fr**	**Sa**	**Su**
9 to 12 and 13 to 18	8		1					
9 to 14 and 15 to 18	8	1	1	1				
10 to 13 and 14 to 19	8							1
11 to 14 and 15 to 20	8						1	
12 to 15 and 16 to 21	8	1				1	2	
12 to 17 and 18 to 21	8	1	2	2				2
9 to 12 and 13 to 16	6	2	1	2		2	3	2
10 to 13 and 14 to 17	6						1	
11 to 14 and 15 to 18	6						1	
14 to 17 and 18 to 21	6	2	1	1	1	2	2	
9 to 13	4	3	2	2	4	2	2	3
10 to 14	4	1	1		1	1		
11 to 15	4				1			1
12 to 16	4					1		
13 to 17	4	1			3			2
14 to 18	4					1	1	
15 to 19	4				1			
16 to 20	4	2	1	2	1	2	1	2
17 to 21	4	4	3	3	4	3	4	5
Daily worked hours		92	72	70	66	72	98	88
Workdays		1	1	1	1	1	1	1
Week hours		92	72	70	66	72	98	88
WCEs		1+11/12	1+1/2	1+11/24	1+3/8	1+1/2	2+1/24	1+5/6

From the employee's viewpoint, the opportunity of working part-time, in 4- or 6-hour blocks, allows other family or personal activities. This opens the door to hire: students, women raising children, caregivers and other population segments who need to work but do not have the option of a full schedule.

Table 9. Comparison of results.

	WCEs	**Payroll savings**
Scenario 1 (reference)	17	
Scenario 2 (one-day contracts)	16 + 1/3	3.92%
Scenario 3 (4, 6 or 8-hour schedules)	12 + 1/2	26.47%
Scenario 4 (full flexibility)	11 + 5/8	31.62%

Under systemic disruptions, company's resilience may improve by hiring people under limited hours of working days, or less working days, thus increasing operational efficiency without losing service quality.

Some of the challenges involved are: a) a larger number of persons in payroll increases control complexity, although this is manageable by modern information technology solutions; b) Supervision is more difficult as servers may change constantly; and c) It is a change in paradigm for managers both in operations and in people management.

Even though the mathematical model presented in the numerical example assumed equal hourly payment regardless of the hour and the day of the week, the model could be easily adapted to include different rates according to time and weekdays, like Sundays or third shifts.

4. Further research

Further research pends ahead: a) to analyze a larger number of sets (hours per day and hours per working day) depending on particular industries; b) transversal studies on the social impact of implementing these flextime solutions, including effects on family life, job satisfaction or other; c) feasibility of flexible labor laws, where such part-time jobs are not accepted.

References

[1] A. Seers, Leadership and flexible organizations: Organizational structures, In G. B. Graen (ed.) *New Frontiers of Leadership*, Information Age Publishing, Greenwich, CT, 2004, pp. 1.

[2] M. F. J. Martens, F. J. N. Nijhuis, V. B. M. P. J. and J. A. Knottnerus. Flexible Work Schedules and Mental and Physical Health. A Study of a Working Population with Non-Traditional Working Hours. *Journal of Organizational Behavior,* Vol. 20, 1999, pp. 35.

[3] H. Boekraad, W. Buitelaar and R. Vreeman. Van arbeidsproces naar arbeidsbeleid (From labour process to labour policy). *Te Elfder Ure,* Vol. 4, 1988, pp. 6.

[4] R. J. Thompson, S. C. Payne and A. B. Taylor. Applicant attraction to flexible work arrangements: Separating the influence of flextime and flexplace. *Journal of Occupational & Organizational Psychology,* Vol. 88, 2015, pp. 726.

[5] A. Ertas. Understanding of Transdiscipline and Transdisciplinary process. *Transdisciplinary Journal of Engineering & Science,* Vol. 1, 2010, pp. 48.

[6] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, W. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 753-762.

[7] S. Lattanzio, et al., Transdisciplinarity Within the Academic Engineering Literature*, International Journal of Agile Systems and Management*, 2020, Vol. 13(2), pp. 213-232.

[8] E.E. Kossek, L.B. Hammer, T. Thompson and L.B. Burke, *Leveraging Workplace Flexibility for Engagement and Productivity*, SHRM Foundation, 2014.

[9] F.J.N. Nijhuis, M.L.H.G. Lendfers and R. Bullinga. Health effects of flexibilisation of work. *News from EFPPA,* Vol. IV, 1990, pp. 11-14.

[10] H. W. TenDam. Managerial Flexibility: A Strategic Asset. *Leadership & Organization Development Journal,* Vol. 8, 1987, pp. 11-16.

[11] S. L. Grover and K. J. Crooker. Who appreciates family-responsive human resource policies: The impact of family-friendly policies on the organizational attachment of parents and non-parents. *Personnel Psychology,* Vol. 48, 1995, pp. 271-288.

[12] W. J. Casper and L. C. Buffardi. Work-life benefits and job pursuit intentions: The role of anticipated organizational support. *Journal of Vocational Behavior,* Vol. 65, 2004, pp. 391-410.

[13] L. Rhoades and R. Eisenberger. Perceived organizational support: A review of the literature. *Journal of Applied Psychology,* Vol. 87, 2002, pp. 698-714.

[14] T.D. Allen, R.C. Johnson, K.M. Kiburz and K.M. Shockley, Work-Family Conflict and Flexible Work Arrangements: Deconstructing Flexibility, *Personnel Psychology,* 2013, Vol. 66(2), pp. 345-376.

[15] J. A. Meyer, *Examining workplace flexibility across work and family domains*, PhD thesis, University of Tulsa, 1997.

[16] B. B. Baltes, T. E. Briggs, J. W. Huff, J. A. Wright and G. A. Neuman. Flexible and compressed workweek schedules: A meta-analysis of their effects on work-related criteria. *Journal of Applied Psychology,* 1999, Vol. 84, pp. 496-513.

[17] S. A. Rogier and M. Y. Padgett. The Impact of Utilizing a Flexible Work Schedule on the Perceived Career Advancement Potential of Women. *Human Resource Development Quarterly,* 2004, Vol. 15, pp. 89-106.

[18] J. Pierce, J. Newstrom, R. Dunham and A. Barber, *Alternative work schedules*, Allyn & Bacon, Boston, 1989.

[19] C. L. ter Hoeven and W. van Zoonen. Flexible work designs and employee well-being: Examining the effects of resources and demands. *New Technology, Work and Employment,* 2015, Vol. 30, pp. 237-255.

[20] D. T. Hall and V. A. Parker. The role of workplace flexibility in managing diversity. *Organizational Dynamics,* 1993, Vol. 22, pp. 5-18.

[21] J. Soo Jung. The Relationships of Flexible Work Schedules, Workplace Support, Supervisory Support, Work-Life Balance, and the Well-Being of Working Parents. *Journal of social service research,* 2009, Vol. 35, pp. 93-104.

[22] J. Badaracco, *The Knowledge Link: How Firms Compete Through Strategic Alliances*, The Free Press, Boston, 1990.

[23] G. Onken-Menke, S. Nüesch and C. Kröll. Are you attracted? Do you remain? Meta-analytic evidence on flexible work practices. *Business Research,* 2018, Vol. 11, pp. 239-277.

[24] J. Barney. Firm resources and sustained competitive advantage. *Journal of Management,* 1991, Vol. 17, pp. 99-120.

[25] K. Begall, M. Mills and H.B.G. Ganzeboom, Non-Standard Work Schedules and Childbearing in the Netherlands: A Mixed-Method Couple Analysis. *Social Forces,* 2015, Vol. 93, pp. 957-988.

[26] N. Balbo, F. C. Billari and M. Mills. Fertility in Advanced Societies: A Review of Research. *European Journal of Population / Revue européenne de Démographie,* 2013, Vol. 29, pp. 1-38.

[27] K. L. Brewster and R. R. Rindfuss. Fertility and Women's Employment in Industrialized Nations. *Annual Review of Sociology,* 2000, Vol. 26, pp. 271-296.

[28] K. M. Collins. Stress and departures from the public accounting profession: A study of gender differences. *Accounting Horizons,* 1993, Vol. 7, pp. 29-38.

[29] N. H. Mohamad and F. Said. Integer Linear Programming Approach to Scheduling Toll Booth Collectors Problem. *Indian Journal of Science and Technology,* 2013, Vol. 6, No. 5, pp. 1-6.

[30] H. E. Miller. Personnel scheduling in public systems: a survey. *Socio-Economic Planning Sciences,* 1976, Vol. 10, pp. 241-249.

[31] F. Trigos, A. R. Vazquez and L. E. Cárdenas-Barrón. A simulation-based heuristic that promotes business profit while increasing the perceived quality of service industries. *International Journal of Production Economics,* 2019, Vol. 211, pp. 60-70.

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Study on Job Shop Scheduling for Keeping the Requested Shipping Sequence by Production System Modeling and Backward Simulation

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Abstract. In the field of high-mix low-volume production, to keep shipping deadline of each order is one of key factors due to the reason for make-to-order production. However, this type of production has a enormous number of parts to be handled, complicated work procedures, and many restrictions on production resources. Therefore, it is difficult to make an optimal production plan considering shipping deadline and efficient usage of production resources. In this paper, the objective is to create work plans which meet the due date with short lead times as much as possible in a job shop type production line. First, we propose the method how to model and represent the complex data of an entire factory structure. Then, based on this model, it was proved that we can obtain the production plan with short lead times that emphasizes compliance with the sequence of product shipping by backward discrete event simulation. Furthermore, the effectiveness of the proposed method and the validity of the obtained production plan are confirmed by using actual factory processes and real data.

Keywords. Job Shop Scheduling, Backward Simulation, Shipping Sequence, Production Modeling

Background

In high-mix low-volume production, to keep shipping deadline of each order is one of the major issues in production management. For solving this issue, it is important to create a realistic and optimal production schedule considering shipping deadline of each order and efficient usage of production resources. Such job-shop type factories have huge complex project architecture due to the large number and variety of parts and processes. For example, each product has a unique procedure and workload for manufacturing. In addition, production resources including workers and robots have many restrictions and differences in their capabilities. For these reasons, it is difficult to create a realistic and optimal production schedule considering the requested shipping sequence and shipping deadline of each order and efficient usage of production resources.

There have been many studies on scheduling problems focusing on shipping deadline. Morinaga et al. proposed a production scheduling method using a genetic algorithm for

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multi-objective optimization of weighted shipping delays and equalization of the workload of set-up personnel [1]. Camino R. Vela et al. combined a tabu search procedure using nearest neighbor search with a genetic algorithm to maximize due date satisfaction under uncertain task durations and flexible shipping deadline [2]. J.Lohmer et al. presented a model formulation of the distributed job-shop scheduling problem with due date consideration and proposed adapted greedy heuristics as well as a genetic algorithm to solve large problem instances [3]. These studies propose an optimization algorithm of job-shop scheduling problems with shipping deadline added to the objective function.

In a situation where the shipping deadline has been determined, establishing the production plan in reverse is often adopted. This method is commonly referred to as backward simulations. Lynch and Vaandrager conducted a study on schedule planning using forward and backward simulation [4]. They established the production plan through backward simulations on plans involving several processes, and equipment allocation and verification were performed through forward simulation. Musselman et al. defined the schedule planning system and information flows through forward and backward simulations of APS (the Advanced Planning and Scheduling System) in an overall enterprise information system [5]. In addition, studies have been conducted on applying backward simulation-based production planning to semiconductor processes, which have batch production and Make-to-Stock (MTS) characteristics [6] [7]. Zhu et al used backward simulation to establish production plans for steelworks, which include several processes in their production flow [8]. Most existing studies performed backward simulations that focused on industries with fixed processes and facilities. In production simulations with fixed facilities, a single simulation model that focuses on the facilities is used. However, in high-mix low-volume production, all designs and characteristics of the products to be produced are different, and they undergo different processes and require different facilities. It is difficult for establishing the production plan in high-mix low-volume production to apply these studies.

On the other hand, the Resource-Constrained Project Scheduling Problem (RCPSP) [9], one of the most challenging combinatorial optimization scheduling problems, has been the focus of a great deal of research. This involves the scheduling of project activities subject to precedence and resource constraints to meet the objectives in the best possible way. Nouri N. et al. proposed an efficient nature-inspired ABC algorithm for solving the RCPSP by using three types of honey bees [10]. Ripon K. et al. considered RCPSPs with known deterministic renewable resource requirements but uncertain activity durations, to approach based on the robust optimization concept [11]. However, these studies deal with very simple problems compared to the real problems, because the optimizing calculation cost is too heavy for utilizing these methods in the real field.

With the optimization approach, only the production planners can understand it, but not the production managers and factory workers, and they are not able to respond well to sudden situations. From the perspective of production managers, it is necessary to have a scheduling method that makes it easy to make plans again when some troubles occur in the field. Optimization methods that take a lot of computational time may sometimes be inappropriate because troubles frequently occur in the production field. And, solutions obtained by optimization methods are not always satisfactory for the field. From factory workers' point of view, they would prefer to adopt easy-to-understand working rules rather than having to check a work plan every time. The assignment solution obtained by the optimization method does not have clear rules such as dispatching rules, which are often unacceptable to workers. Therefore, it is necessary to have a transdisciplinary scheme that allows information sharing among production planners, production managers, and factory workers, who have their own individual disciplines for operational reasons. In this study, we focus on a factory where products are produced in all different processes and facilities. Then we approach the scheduling planning to ship the products in the required sequence. We propose the factory modeling method using nodes and links, and backward simulation that can be achieved by simply reversing the links to satisfy the requested sequence.

1. Proposed Method

1.1. *System modeling of target production project*

All data reproducing a factory consists of four models: product model, workflow model, workplace model, and team model. These models will be the input information for the discrete event simulation described below.

The product model represents information related to products to be manufactured in the target production project. Each product has its dependent relationship with a workflow described below.

The workflow model represents a workflow for expressing a unique work procedure required to produce a target product. First, since this workflow is composed of multiple tasks. All tasks can be created from the information of the production model and target domain knowledge. Each task has the attribute of work amount and a dependency on others.

The workplace model represents information about a workplace and facilities in the workplace. A workplace is a variable used to express the limit of the area where products and facilities can be placed. First, define each workplace, the number of products that can be placed in this workplace, tasks that can be handled in this workplace, and facilities that this workplace has. The number of workers in a workplace can be constrained by dependency between the workplace ,and facilities. Next, define each facility and skill value for each task handled by it. If the skill value is set to 0, it means that the facility is not able to perform the corresponding task.

The team model represents information about an organizational team and workers for a target production project. First, define each team, tasks that the team corresponds to, and workers who belong to the team. Next, define each worker, skill value for each task, and facility that can be handled.

1.2. *Simulation system*

Next, we propose the discrete event simulation system to create a work plan using these models in the previous section. The proposed simulation system is developed based on the previous study[12]. The method for performing a task in this simulation is that the remaining work amount of each task is reduced for each step based on skill values of assigned facilities and workers, and status is updated. (NONE: cannot start, READY: can start, WORKING: work in progress, FINISHED: work completed). The specific procedure of simulation is following:

1. Initialize the simulation setting.
2. Extract of tasks which states are READY or WORKING.

3. Place products that are dependent on the extracted tasks in corresponding workplaces.
4. Extract available workers and facilities.
5. Allocate workers and facilities based on the task priority rule.
6. Perform the task
7. Determine the end of the simulation

As an initial setting to start the simulation, set the state of head tasks to READY and other tasks to NONE. In step 2, extract tasks in the READY or WORKING state. In step 3, the products depending on the READY tasks are placed in the workplace according to the workplace model. If the corresponding workplace is not available, the target product will stay at the same workplace as at time t-1. The products depending on WORKING tasks are placed in the same workplace as at time t-1. In step 4, available workers and facilities that are not allocated or working at the current time are extracted. In step 5, according to the task priority rule, workers and facilities with skill values for the corresponding task are allocated. The task priority rule is adopted to a dispatching rule called TSLACK (Total Slack Time) [13]. This rule performs the task included in a workflow that is on the critical path preferentially. Specifically, the smaller SLACK of the task calculated by the Critical Path Method [14], the higher its priority. Slack(t) of task j at time t is calculated as in equation (1) using the latest start time $LST_j(t)$ and the earliest start time $EST_j(t)$.

$$Slack(t) = LST_j(t) - EST_j(t) \tag{1}$$

If a resource is allocated to the task, the state of this task becomes WORKING and updates the remaining work amount of the task based on the skill value of the resource. If the remaining work amount is 0 in this update, the task state is set to FINISHED. If all preceding tasks are FINISHED, the state of a task becomes READY. When the states of all tasks are FINISHED, the simulation is terminated. If not, advance time t by one step and go back to step 2. The simulation result outputs the end time of the simulation, the state of each model at each time, and the tasks that each resource has assigned.

As an exception to the above simulation flow, auto task can be defined. Auto task allows automatic task performance without the need to assign facilities or workers. For example, it can be used to adjust the time interval between the input time of one product to the production line and the input time of the next product.

1.3. *Backward simulation*

Traditionally, forward scheduling methods have been used mainly for solving production scheduling problems by using simulation techniques. These methods allocate jobs in advance according to the process steps along with the time flow. However, it is not suitable for creating a schedule that aims to improve shipping sequence compliance. Because forward scheduling methods, which use a discrete event simulation following a time axis, cannot control the end time of work for each product. Therefore, this paper adopts the backward simulation as a scheduling method. In this method, the due date of each targeted product is starting time of the process and simulate in opposite direction from the real-time flow. To perform backward simulation using the simulation system described in section 1.2, it is necessary to modify the workflow model. Figure 1 describes how to model the backward simulation method by comparing it with the forward simulation method. This figure considers a work plan in which N products are shipped in the requested sequence.

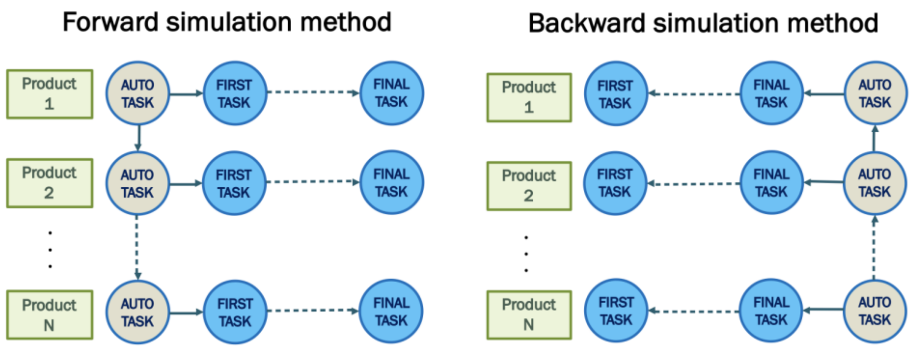

Figure 1. Comparison of the two methods.

First, as for the forward simulation method, simulation start time is when Product 1(the product with the highest requirement sequence) is put into the production line. Next, define auto task and set this work amount taking into account the relationship between input time intervals for each product. Then, add auto task before the first task, and create a workflow by linking tasks with each other in the direction of the actual procedure. On the other hand, as for the backward simulation method, simulation start time is when Product N (the product with the lowest requirement sequence) is shipped. Next, define auto task to adjust shipment timing between products. Then, add auto task after the final task, and create a workflow in the opposite direction of the forward simulation method.

2. Case Study

In order to verify the validity of the proposed method, a case study is conducted using the structure and product data of a real construction machinery production project. This case study assumed that this factory should manufacture 20 products with a different deadline considering the requested shipping sequence on a certain day. Figure 2 shows the overview of the target production project.

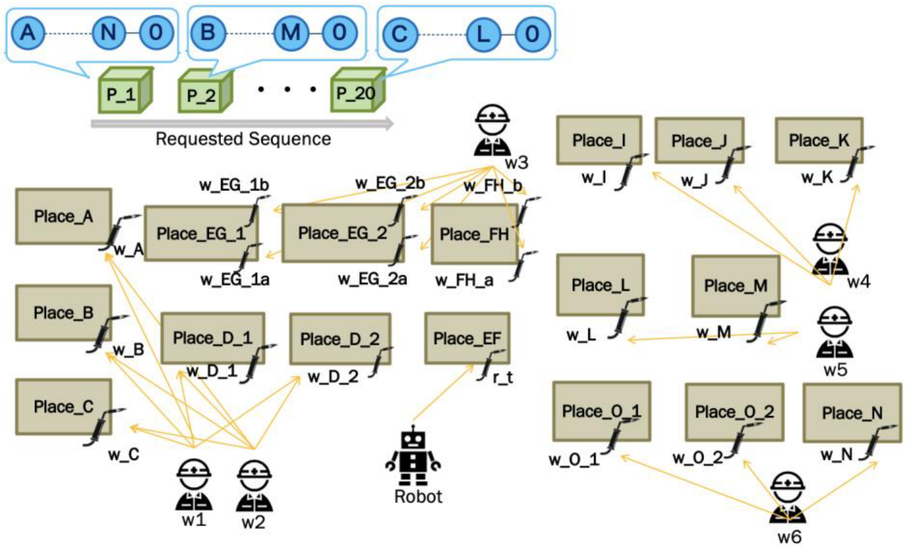

Figure 2. Overview of target production project.

First, define each product according to the product model by giving it a unique name for example "P_1". The requested shipping sequence is determined according to the number "1" through "20" at the end of the product name in this case study. Since each of the 20 products has a different completion process, they have their own workflows as shown in Figure 2. Next, define 15 different tasks from "A" to "O" in this factory. For each product, create a workflow that prioritizes the tasks required to ship it. The work amount for each task is determined independently. In order to keep only the requested shipping sequence, the work amount of auto task for each product is set 0.

Each product is placed on a jig tool and workers use a welding machine on it to manufacture. In this factory, there is a workplace dedicated to robots where humans cannot enter. A jig tool is modeled as a workplace and a welding machine as a facility. Based on the floor map of the factory, define all workplaces and facilities and their dependencies. In this case study, a robot is modeled as a worker like a human, not as a facility and the robot's workplace has a facility dedicated to the robot. For example, the workplace "Place_FH" has two facilities, "w_FH_a" and "w_FH_b". We can constrain the number of workers who can work in the same workplace by the number of welding machines.

Next, the task name following a workplace name "Place_" shows the dependency between them on which task can be performed in each workplace. For example, the workplace "Place_FH" can deal with the task "F" and "H". The dependency between a facility and a task is the same as the dependency between the workplace to which the facility belongs and the task. Skill values of each facility are set to 1 for the task related by the arrow, and 0 for the others. For example, the facility "w_FH_a" has a skill value of 1 for the task "F" and "H", and a skill value of 0 for others, which means "w_FH_a" can deal with "F" and "H".

This factory is operated by six human workers and one robot worker. As the feature of this factory, for the task "E" and "F", it is possible to choose to be performed either by human workers or robot worker. 7 workers named "w1" to "w6" and "Robo" are defined in Table 1. The dependency between the team and tasks is defined as this team is targeted to work from the task “A” to “O”. Since the worker “Robo” can work at 2.5 times the human work efficiency, the skill value is set to 2.5.

Table 1. Worker Skill info.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Robo	0	0	0	0	2.5	2.5	0	0	0	0	0	0	0	0	0
w1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
w2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
w3	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
w4	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
w5	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0
w6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1

Finally, arrows connecting a worker and a facility in Figure 2 show the dependency between them regarding which facility each worker can handle. Since both the worker “w3” and “Robo” have skill of the task “E” and “F”, they may be assigned to the same workplace if only modeling in Table1. However, human workers can work together in the same workplace, but the robot cannot work with other workers. This constraint can be modeled by specifying the facility that can be handled by “Robo” and “w3”.

The above resource constraints and process characteristics of the factory are modeled and simulated by using a python discrete event simulation package called pDESy [15] that we have developed. Figure 3 shows a Gantt chart for expressing the Gantt chart of each product by executing the backward simulation. The orange periods indicate that work in progress and the gray periods express the time when the product is stagnant in the workplace. From Figure 3, it can be said that the 20 products are completed in the required sequence. If each product is manufactured based on this result, it can be shipped in the required shipping sequence.

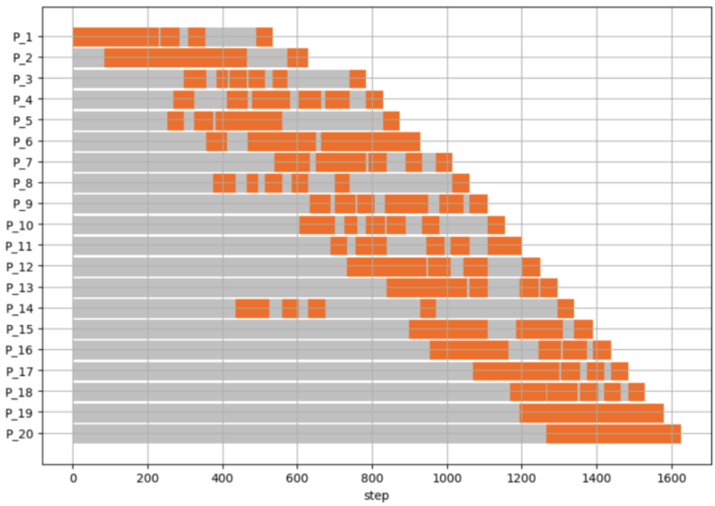

Figure 3. Gantt Chart for Case Study.

3. Discussion

This section compares the commonly used forward scheduling methods with the proposed backward simulation method for the same case to validate the production plan obtained with our proposed method. The forward simulation results performed by using pDESy are shown in the Gantt chart of Figure 4.

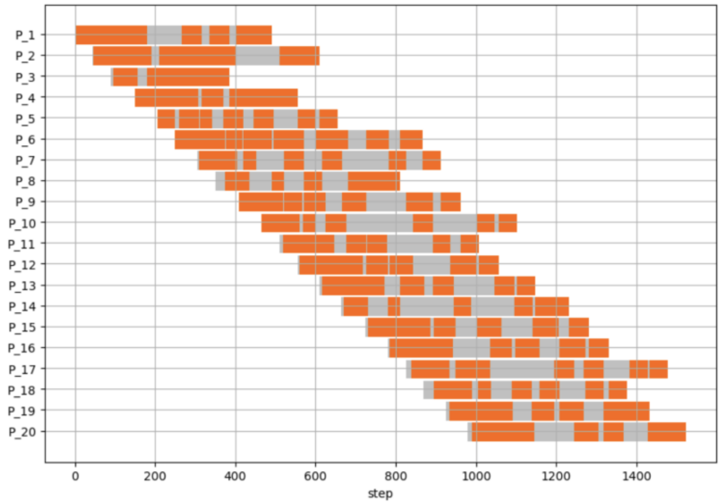

Figure 4. Gantt Chart for forward scheduling.

For comparing the results of forward and backward simulation, the following four KPIs are used.

- Lead time (*LT*)
- Total waiting time of workers (*Total FT*)
- Total stagnating amount of products (*Total ST*)
- Compliance value (*CV*)

In order to calculate the KPI correctly, it is necessary to evaluate the time period when products exist on all tasks. The lead time (*LT*) is defined as the period from the time when the first product in the completion sequence is shipped to the time when the 10th product in the completion sequence is shipped in this paper. Next, *Total FT* is the total amount of time that each worker in a team waits between completing a task and starting the next task. Then, *Total ST* is the total amount of time that each product stagnates in the workplace between the end of the task in progress and the start of the next task. Finally, the compliance value (*CV*) indicates how well the 10 products shipped comply with the requested shipping sequence. *CV* for a product (p_x) is calculated as in equation (2) using the requested shipping ranking of p_x (*Requested* S_{p_x}) and completion ranking of p_x by simulation output results (*Shipping* S_{p_x}). In other words, a smaller value indicates that products are completed in the requested sequence.

$$CV = \sum_{x=1,2,,,,10} \left| Requested\ S_{p\_x} - Shipping\ S_{p\_x} \right| \tag{2}$$

Table 2 shows the results of comparing the same case study between the backward and forward types using KPIs defined above.

Table 2. Backward and Forward Results.

	LT [min]	Total FT [min]	Total ST [min]	CV
Backward	621	805	2230	0
Forward	622	554	2129	11

From the comparison, the production plan obtained from the backward method has a very good compliance value, even though the lead time is almost the same as obtained from the forward simulation method. However, the waiting time of workers and the stagnating amount of products are higher. In the forward simulation, tasks flowing to the production line are performed one after another by free workers without considering the future which results in an incorrect shipping sequence. When the backward simulation results are viewed in the direction of the time axis, it appears that the workers and products are made to have free time. Therefore, it is thought that products can be completed in the required sequence by providing a buffer and making adjustments, such as intentionally stagnating tasks in the backward simulation or forcibly giving workers free time.

In order to show that our method can be applied to other cases, we also investigated other 5 days' cases. The results are summarized in Table 3. From Case 2 to Case 5, the results were generally the same as the one in the case study. In Case 6, the compliance value of forward simulation result was 0 because the same type of products were produced continuously on that day. From these results, it can be said that the proposed method can be applied to other cases in this factory .

Table 3. Results of other 5 days' cases.

	LT		Total FT		Total ST		CV	
	FS	BS	FS	BS	FS	BS	FS	BS
Case 2	557	596	402	749	2158	2673	8	0
Case 3	521	556	496	798	1552	1984	5	0
Case 4	458	501	449	702	1387	2043	8	0
Case 5	553	598	734	849	1626	2239	8	0
Case 6	505	516	334	578	1111	1611	0	0

4. Conclusion

This paper proposed a method of job-shop scheduling considering keeping the requested shipping sequence of each product by system modeling of target production project and executing backward process simulation. Firstly, we modeled complex production project by using the product model, workflow model, workplace model, and team model. From these models, proposed method can create a production plan for keeping requested shipping sequence by backward simulation. The proposed method was applied to the case study of the actual factory process of manufacturing multiple types of products. Results show that the backward simulation result is superior to the forward simulation result cosidering the comparison of lead time, total wating time of workers, total stagnating amount of products and compliance value. From this results, it can be said that proposed method is effective as a production planning method for keeping the requested shipping sequence in a job-shop type production line.

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References

[1] Morinaga, M. Nagao and M. Sano, Optimization of flexible job-shop scheduling with weighted tardines and setup-worker load balance in make-to-order manufacturing, *2014 Joint 7th International Conference on Soft Computing and Intelligent Systems (SCIS) and 15th International Symposium on Advanced Intelligent Systems (ISIS)*, Kitakyushu, Japan, 2014, pp. 87-94.

[2] Camino R. Vela, Sezin Afsar, Juan José Palacios: Evolutionary tabu search for flexible due-date satisfaction in fuzzy job shop scheduling, *Computers and Operations Research*, 2020, Vol.119, pp.1-19.

[3] J. Lohmer, D. Spengler and R. Lasch, Multi-factory Job Shop Scheduling with Due Date Objective, *2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, Singapore, Singapore, 2020, pp. 79-84.

[4] Lynch, N., Vaandrager, F., Forward and backward simulations. *Inf. Comput*. 1995, 121 (2), pp. 214-233.

[5] Musselman, K., O'Reilly, J., Duket, S., Supply chain planning: the role of simulation in advanced planning and scheduling. *Proc. 2002 Winter Simul. Conf.* , 2002, pp.1825-1830.

[6] Park, B.C., Park, E.S., Choi, B.K., Kim, B.H., Lee, J.H., Simulation based planning and scheduling system for TFT-LCD fab. *Proc. 2002 Winter Simul. Conf.* , 2008, pp.2271-2276.

[7] Seo, J.C., Chung, Y.H., Kim, B.H., Park, S.C., Backward capacity-filtering for electronics Fabs. *Prod. Plann. Contr.* , 2016, 27 (11), pp. 925-933.

[8] Zhu, D.F., Zheng, Z., Gao, X.Q.. Intelligent optimization-based productio planning and simulation analysis for steelmaking and continuous casting pro- cess. *Int. J. Iron Steel Res.*, 2010, 17 (9), pp.19-30.

[9] W. Herroelen, E. Demeulemeester, B. De Reyck, Resource-constrained project scheduling: A survey of recent developments, *Computers & Operations Research*, 1998, Vol.25, Issue.4, pp. 279-302.

[10] N. Nouri, S. Krichen, T. Ladhari, and M. Labidi, Solving the Resource-Constrained Project Scheduling Problem Using ABC Algorithm, *The 5th International conference on modeling, simulation and applied optimazation,* 2013.

[11] R.K. Chakrabortty, A.Sarker, D.L. Essam: Resource constrained project scheduling with uncertain activity durations, *Computers & Industrial Engineering*, 2017, Vol. 112, pp 537-550.

[12] T. Mitsuyuki, K. Hiekata, G. Takuya, Evaluation of Project Architecture in Software Development Mixing Waterfall and Agile by Using Process Simulation, *Journal of Industrial Integration and Management*, 2017, Vol. 2, No. 2, 1750007.

[13] T. Mitsuyuki, K. Hiekata, H. Yamato, Design of production strategy considering the cutting peak demand of electricity in the shipbuilding industry, *Journal of Marine Science and Technology*, 2014, Vol.19, No.4, pp.425-437.

[14] A.G. Mercier, *The Critical Path Method : its fundamentals*, Institutional Archive of Naval Postgraduate School,1965.

[15] pDESy, https://github.com/pDESy/pDESy

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Product Lifecycle Management and Sustainable Development in the Context of Industry 4.0: A Systematic Literature Review

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Abstract. The Fourth Industrial Revolution and its disruptive technologies are emerging massively. With various motivations for its implementation such as elevation of speed, reducing costs, mitigating errors, and other different factors, more and more technology are being employed to solve business problems and increase profit. Through the years, product lifecycles have been shorted as a good reason to reduce production costs and give to consumers the experience of replacing goods in shorter periods. This linear cycle of "produce-use-dispose" reached a massive success in the last decades, but have started to show lack of sustainability for consumer and industry. This work aims to conduct a Systematic Literature Review about the future challenges for Product Lifecycle Management and Sustainable Development, considering the context of Industry 4.0. The expected outcome for this study is to find elements that can support the use of 4.0 technologies in Product Lifecycle Management with a strong background for Sustainable Development.

Keywords. Product Lifecycle Management, PLM, Industry 4.0, 4th Industrial Revolution, Sustainable Development, Sustainability, Transdisciplinary.

Introduction

The Fourth Industrial Revolution and its disruptive technologies are emerging massively. Everyday refinement of software, equipments, new applications, and performance record is becoming a reality for various enterprise profiles: from small business, start-ups to large multinational industries, every enterprise has been looking for technology to accelerate the main lesson from the classic production concepts: do more with less effort [1].

With various motivations such as elevation of speed, reducing costs, mitigating errors, and other different factors, more and more technology are being employed to solve business problems, generate innovation and increase profit [1][2]. Financial sustainability is the primary justification for all these outcomes, for which an organisation would not need to face economic challenges or if the desire to enlarge its profitability. It seems that technology has been supporting companies to reach these financial goals, and this objective solely would justify the investment [3].

However, through the years, product lifecycles have been shorted as a good reason to reduce production costs and give consumers the experience of replacing goods in shorter periods. This linear cycle of "produce-use-dispose" had its massive success in the last two centuries [4][5]. Following this manufactures productivity demand, it is possible to realise changes in the consumer's behaviour contributing to the growth of the contemporary global problems such as pollution, wasting, economic disparities among other negative effects [3].

Thankfully to the broad availability of information, consumers are more conscious about their choices, which means that scrutinising a product has increased considerably. Further, digitisation motivates consumers to access innovations such as sharing economy [6]. Some manufacturers have then adopted green initiatives and sustainable approaches to reach more consumers, especially to compete in international markets [7] [3].

Other elements that corroborate the need for a shift for this company's profiles are technology adoption. Historically, technologies helped society development, productivity and economy. However, the speed of technological spreading in the last industrial revolutions are incomparable to the exponential proportions that the Fourth Industrial Revolution has already reached [8].

There are several initiatives to adopt 4.0 Industry: elements such as real-time data collection for the decision have been a good application in IT-enable PLM manufactures to foster cleaner production and achieve sustainable development [9] [10].

Moreover, climate change induced by the highest levels of pollution produced indiscriminately by enterprises and individuals summed to globalisation questions has been causing by environmental unbalance and brand-new challenges such as covid-19 pandemics. All these factors create imbalanced life conditions pressuring the manufacturing industry to respect the planet boundaries [11], to pay attention to energy consumption, to plan and execute more ethical operations attending global concerns, such as about pollution threats, which calls for a more environmental-friendly production mode between other sustainability challenges [12] [9].

The changes that this revolution is bringing supported by disruptive technologies are among the biggest challenges of this time [13]. The application of these technologies used with fair purposes can help solve cleaner production problems and achieve higher sustainability maturity. Different types of industries are combining technology and sustainability applied to product lifecycle to achieve corporate sustainability and competitiveness [14] [15]. Industry 4.0 presents a significant opportunity to achieve the goals of sustainable manufacturing and achieving the objectives of the circular economy [16].

These elements indicate that there are no more reasons to keep wheeling the same vicious circle of producing for financial purposes only. And it makes clear the demand for a shift in product lifecycles supported by responsible innovation, with technological applications focused on sustainable development and in all stages of Product Lifecycle, not just for profit.

This paper aims to conduct a literature review to map the research landscape in themes related to how to use Fourth Industrial Revolution technologies to promote Sustainable Development promoting inputs for Product Lifecycle Management. The remainder of this paper is structured as follows: In Section 1, the background is presented. Section 2 illustrates the used scientific method. Finally, Section 3 summarizes the conclusions and outlook.

1. Background

The Fourth Industrial Revolution characterised in details by Schwab in 2016 [8], indicating that the digital technologies based on computers, software and networks are working in more comprehensive approaches, with more integration, sophistication and robustness, which is transforming economy society globally. With the same premise, Industry 4.0 - a term that first appeared in Hannover Fair in 2011 - intends to use digital technologies to create intelligent factories. The convergence of digital information is necessary in order to integrate physical and digital systems to operate globally and flexible. More than achieve disruptive productivity levels, the 4.0 Industry has as goals more intelligent operations and personalisation of products and services. In other words, technologies have to support disruptive innovation for all types of industries, as we have been presenting in the last years [8].

The rise of technologies, sustainability opportunities, cost reduction and user experience, has produced many initiatives to offer incremental or disruptive innovations including collaborating industry-university-government [17] [18]. However, previous studies indicate that disruptive innovation is the opposite of sustaining innovation [6]. While very positive effects are expected, such as new models development and innovations, improvements in quality and productivity, some not desired effects might occur to society in general, such as an increase of inequalities, polarisation of social power and more [8]. This trade-off brings the necessity to introduce sustainable development concepts and practices to balance the adoption technology that seems so urgent in the agendas of Product Lifecycle.

The term sustainability is not a closed concept. It emerged in the public policies context at the end of the 80s as "development that meets the needs of the present without compromising the ability of future generations to meet their own need" [19]. Since then, its concepts have encompassed more application areas extending its meaning for areas not initially planned [20][21]. Therefore, the concepts have been unfolding to corporative environments, bringing out its benefits and shaping new fields of study and applications. The organisational definitions of sustainability in the engineering literature have been more encompassing and have explicitly incorporated the macro view of social, environmental, and economic dimensions by defining organisational sustainability [22].

In a precise definition, Product Lifecycle Management (PLM) [23] is the commercial activity of managing the products of a company throughout its lifecycle, from the first idea of a product until it is removed and discarded most effectively. Further, Product Lifecycle Management may mean a technological solution that encompasses different and complementary tools to promote collaboration between stakeholders to support the Product Lifecycle's effective management [24]. Although Product Life Cycle Management concepts are more commonly found in traditional manufacturing companies, their concepts can also be found in other business profiles such as startups [25].

It seems that these three approaches brought lots of advantages and some disadvantages. However, it seems that the overlap, or a more comprehensive integration of the Fourth Industrial Revolution, Sustainable Development to Product Lifecycle Management, may promote innovation, more robust outcomes in a long-term business perspective.

2. Method

2.1. Systematic Literature Review

2.1.1 Search phase and criteria of selection

This paper aims to identify the state of the art of the thematics that direct this research which main themes are: "Fourth Industrial Revolution", "Product Lifecycle

Management", and "Sustainable Development". A systematic literature review (SLR) was conducted to achieve the identification of so-called knowledge boundaries. The SLR method was chosen because of its concept of a systematic, explicit and reproducible method for identifying, evaluating and synthesizing the existing body of completed and published work produced by researchers, academics and professionals [26] and [27].

The method consisted of a structured search of the themes "Fourth Industrial Revolution", "Product Lifecycle Management", and "Sustainable Development", and its synonyms or analogue concepts. All the combinations of the keywords and synonyms resulted in 88 strings for search, performed within of the two more relevant databases: Scopus and Web of Science.

The selected documents are in according to the following steps and their respective criteria to respect the scope of the present research:

a) Step 1: search of keywords; b) Step 2: the selection of articles published in the English Language; c) Step 3: the selection of original articles and exclusion of other types of documents such as conference papers, abstracts, book chapters; d) Step 4: the selection of articles that match three keywords in all fields and the removal of duplicated articles; e) Step 5: preliminary reading: abstract reading to meet the scope; f) Step 6: content analysis of the most relevant articles according to the described criteria above. The Systematic Literature Review sequence method is depicted in the seven steps, as shown in figure 1.

b)

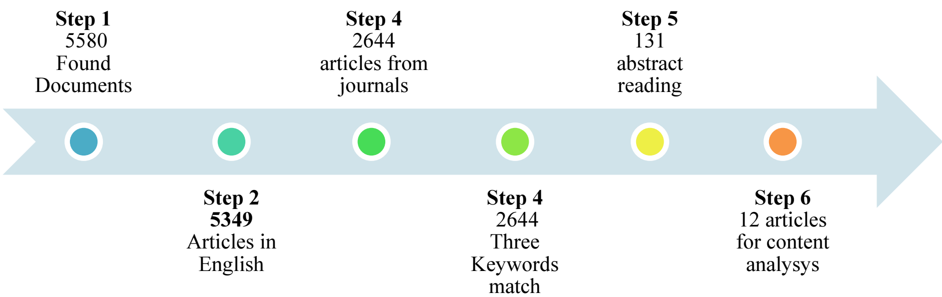

Figure 1. Systematic Literature Review Method

The first raw search result in 5580 documents. Posteriorly, the articles were rigorously selected to meet the scope of this research. Finally, 12 articles were select for meeting all the criteria to have their content thoroughly analysed as described in the next section.

2.1.2 Content analysis

The 12 most relevant articles found in the systematic literature review will be analysed in this section. For this step, the method consists of profoundly reading the articles in order to map all the elements and characteristics related to the themes: Fourth Industrial Revolution", "Product Lifecycle Management", and "Sustainable Development."The table summarises the contribution of the 12 articles for this study.

Table 1. SLR content analysis.

Authons and year	Contributions	Limitations	Applications	4 IR	PLM	SD
Lai, Lin & Wang (2015) [15]	A framework to improve strategic corporate social responsibility improving the innovation capability.	The high-level framework suggests detailed unfolding.	Inputs for improvement of Organizational Factors, R&D Factors, Environment Factors, and to intensify collaborations university-industry.	√	√	√
2. Zhang et. al (2017) [9]	Big data analytics applied to PLM to promote Cleaner Production.	The technology applied to PLM has its limitations for replication.	Analytical architecture applied for PLM, considering all technologies.	√	√	√
3.Bradley et. al (2018) [5]	Total life cycle cost model to support decisions in Circular Economy and Sustainable Manufacturing implementations.	The mathematical approach may limit the replications.	Comprehensive analysis.	√	√	√
4. Lee et. al (2018) [6]	Brainstorming sessions with scholars resulting in an advance template to answer questions related to 4th IR, Open Innovation and Sustainability.	Open innovation as the primary approach to solving the issues detected.	Discussion of a comprehensive approach of correlated themes may support future research of subtopics.	√	√	√
5. Gu et. al (2019) [28]	Architecture for extending producer responsibility in the 4th IR context.	Lack of information shared between stakeholders.	Approach considering legal requirements, products lifecycle and system of industry 4.0 The ease of replication.	√	√	√
6. Park, Shin & Kim (2017) [13]	Social responsibility model for evaluation of corporate social responsibility in the 4th IR era. Open quality approach.	Case of application.	The evaluation model is generic and appliable to a different context.	√	√	√
7. Lekan, et. al. (2020) [14]	Construction technologies to encourage sustainability goal 9 – Industry innovation and infrastructure.	Building constructions and SDG 9.	Roadmap for achieving life cycle sustainability goas with the support of 4.0 technologies	√	√	√
8. Silk et. al. (2020) [29]	Decision support – a techno-economic framework to overcome cleaner production barriers.	Resource recovery application and information flows between stakeholders.	Economical approach for sustainability.	√	√	√
9. Rajput & Singh (2020) [18]	Industry 4.0 model for cleaner production and circular economy.	The model for deterministic demand does not include the reverse supply chain.	Productivity and energy consumption.	√	√	√
10. Bai et. al. (2020) [1]	Assessment framework for application and sustainability implications based on the Sustainable Development Goals (ONU).	The implications of implementation for different types of industry.	Relations between the SDGs and 4.0 technologies.	√	√	√
11.Tiwari and Khan (2020) [10]	Framework for sustainability and accounting report in Industry 4.0.	The incipient maturity of artificial intelligence. Small scale industries.	Three levels of implementation of 4.0 Industry.	√	√	√
12. Bag et. Al (2021) [16]	4.0 Industry adoption for 10 Rs in manufacturing to achieve Sustainable Development.	Generalised results.	Practical factors to cope with 4th IR, PLM and Sustainable Development.	√	√	√

2.1.2 Discussion

The discussion was strutured into 5 basic topics (Organisational models, Goverments, Technologies, Product Life Cycle and Sustainability topics):

a) Organisational models

To guarantee innovation capabilities, enterprises must maintain good strategies for standard domains such as organisational strategy, research and development technology. More than that, it is necessary to complement many critical factors, such as uncertainty and stakeholders in the environment [15]. For some authors [14], these factors are often the catalyst that accelerates organisation and systems development. In this context, the catalyst could be classified as a factor that influences success, often described as critical success factors, [14] that are well described in different approaches in these 12 articles studied. Given that, according to some studies, innovation and sustainability are straight connected. Furthermore, innovation capability directly influences the enterprise capability to implement or improve sustainability [15].

On the other hand, to deal with sustainability in the context of industry 4.0, some authors discuss complementary approaches to organisational models. Transitions from organised economy to entrepreneurship and innovation orientation, economic policies, emphasis on open-design are profiles that may replace traditional economies enterprises. Moreover, businesses should be more creative and resilient to cope with uncertain scenarios. There is a massive growing need for creative solutions to apply for technologies development and specially focused on improving products and services that facilitate the consumers' routines [12].

Nevertheless, more than list the factors, the authors Park et al. suggest an assessment tool for effective enterprise planning and execution of 4.0 Industry and sustainability strategies for product lifecycle. Firstly, the most important factors to be evaluated are leadership and strategic planning from the direction's perspective. Secondly, the authors [13] proposed two categories of systems to be observed: a) Sustainability aspects based on ISO 26000, such as organisational governance, human rights, labour practices, the environment, fair operations practices, consumer issues, community engagement. Moreover, still complementing the systems category, but now aligned with the 4th Industrial revolution, the elements to be evaluated are management quality and responsibility, social value operation, corporate social value, and open data/open quality management. Further, the evaluation process closes with the last block of elements: performance results, financial results, significant process, and customer satisfaction results [13].

Other paper studied proposes a systematic computer-aided framework that evaluates the techno-economic aspects and the environmental potential of a specific initiative such as resource recovery initiatives. According to the authors [30], it is necessary to obtain a good quality of information flows between different stakeholders, such as industrial, society and policymakers. Based on this information, the framework supports an evaluation that may assist overcome the barrier of multidimensional problems and provide solutions and justifying choices in technology readiness, economics, and sustainability [30].

With the understanding of the complexity of digital transformation when overlapped with sustainable productions transition, some authors believe in using frameworks to contemplate all information necessary to make decisions in different stages of implementation or improvement. Additionally to the framework, the techno-economic and sustainability model may maximise the evaluations and decision support addressing the circular economy's implementation challenges, resource recovery, and waste management properly [30].

While this last presented framework is based [30] in sustainability and digital transformation goals that match from inside industry to outside, other work seeks to create strategies to match broad external goas as stated by Sustainable Development Goals - United Nations Organisation considering global industry influences in sustainability in supply chains, products and process [1]. The adoption of 4.0 Industry technologies might well not be uniform by industries, and each enterprise needs to choose its best path to achieve sustainability goals (social, environmental and economic). However, a framework can support the decision in different stages: a) evaluating 4.0 technologies for implementation, assisting practitioners, and helping technology roadmaps development [1].

Another proposal of framework encompasses the characteristics of two different theories of operations management: Practice-Based View (PBV) and Dynamic Capability View and considers how technologies of the 4th Industrial Revolution may support the implementation of 10 R's (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover) [14]. Finally, the success in an endeavour might be achieved by respecting a sequence of factors: 1st) The Establishment of the disruption need; 2nd) The localisation of areas where disruption is needed; 3rd) Rightly instituting methodology to use for the adoption and identification of the possible constraints and barriers; 4th) Personnel training and retraining; 5th) The Set-up of reasonable remuneration and reward mechanism; 6th) The Effective monitoring and control system, and the consolidation of progress achieved and forecast towards enhanced performance [14].

New combinations of business models and cooperation between established firms and startups emerge [12]. The importance of Product-Service System solutions as well-integrated business models and the convergence between the real and virtual world is growing up.

The use of 4.0 technology with sustainability purpose may bring clear economic and environmental benefits [9], but not only. Another possible approach it conduces changes in product line through corporate responsibility innovation to aggregate benefits immediately realised by consumers. Pay attention to the demands of altruistic consumers may lead to significative changes to the product line. This group of consumers have been pushing companies to act more engaged in sustainability purposes [3].

b) Governments

As parameters to evaluate the implementation of disruptive technologies in the construction industry can be the economic and commercial impact, the influence of the research on policymakers, and contribution to research knowledge.

More fluidity to capital, collective initiatives to fund projects, the extension of the entrepreneurial role to governments, once their policies are crucial to induce eco-innovation systems and effective industrial clusters in response to the 4th Industrial Revolution [12]. The government role is to use the technologies with combined strategies with the private sector to promote better and online essential education to support the changes. More overture to co-creation between government and civil society is required to develop more comprehensive solutions – which also includes work closely of universities and firms [12].

Some authors suggest Desing Thinking as an excellent approach to promote effective collaboration and contemplate stakeholders' interests. This methodology would help to develop comprehensive solutions based on human needs according to their role in society: government, citizen, university, firm [12].

c) Technologies

From the perspective of technology implementation, the approximation between stakeholders is crucial to pursue innovation and to discuss large technical development projects actively [12]. When considered threats derived from climate change, new technologies implementation approaches need to consider their impact on sustainability's transformation process. Achieving this innovation with privileges sustainability required all stakeholders' active participation to more transparency in all stages [12].

The consense of the convergence of technologies to promote comprehensive solutions is straightforward. Even if the technologies are the same, their application may be diverse, which means that some technologies may present different maturity levels for some areas or industry. [29]

It is not the scope of this work list all technologies and its application, but select some concepts and approaches to deal with technology seem more compelling. For example, systems should be flexible – which means focusing without losing flexibility [12].

The durability and customisation of products supported by the service-driven and big data-based manufacturing mode, for example, may increase the product lifetime, reduce the amount of the product in circulation in combination with maintenance and refurbishment operations. Further, the technologies allow the identification of new markets and the product will be more competitive in the market and more profitability for the enterprises who adopt this type of technology approach [9].

d) Product Lifecycle

Product lifecycle data consists of structured, semi-structured and unstructured data. However, several non-real-time data is stored to provide reliable and complete raw data support on further data analysis [9]. Additionally, while there are various set of philosophies and tools that may support the manufacturing to a sustainability transition, some industrial environments factors as process complexity and process uncertainty are more critical, demanding advanced production management paradigms [9], which may work in consonance with technologies and have some alignments with sustainability strategies such as cleaner production or corporate social responsibility.

Still considering the product lifecycle perspective, the economic model may support sustainable manufacturing and circular economy vision. One of the works demonstrated that implemented in the early stages would provide information to support decision-making.

On the other side, better experience implementing Extended Producer Responsibility (EPR) Programs with support Industry 4.0 in Product Lifecycles may be found to support the integrated architecture with specific attention on promoting information sharing. Information asymmetry may represent a significant barrier to implementing EPR. However, the comprehensive approach may reshape the industry's paradigms – at least as shown in the case of the electrical and electronic equipment. [28]

About the primary objective, the definitions, applications and potential impacts of Industry 4.0 are introduced as the starting point of this work. Industry 4.0 reshapes the EEE industry's paradigms, as intelligent factories have been set up, and it also offers new opportunities for product development and EPR implementation [28].

e) Sustainability Topics

The authors of the studied works agree that sustainability is a crucial factor for innovation, competitiveness and survival in these uncertain times. However, there are many barriers to integrating technologies, which have their implementation challenges when considered isolated.

Lack of information and knowledge about technologies and sustainability, availability of appropriated equipment, human resources engagement and lack of skills are some of the main challenges faced by PLM for Sustainability adopters [9].

Despite the potential economic and environmental benefits that Cleaner Production (CP) strategy can provide, the implementation of the CP program continues to face problems and barriers, for instance, an insufficient supply of equipment and information, lack of information about clean technologies, available procedures, and organisational capabilities, as well as organisational barriers such as resistance to change [29].

Implement or improve isolated one of these strategies: Industry 4.0, PLM or Sustainability configures a big challenge. Moreover, to move in the three goals at the same time seems to be an enormous challenge. However, the 12 texts indicate that there are many possibilities to obtain successful implementation if every enterprise is ready to choose the work method that better fits its profile.

3. Conclusion

This article has presented a Product Lifecycle Management and Sustainable Development in the context of Industry 4.0 by a Systematic Literature Review. This study's expected outcome is to find elements that can support the use of 4.0 technologies in Product Lifecycle Management with a strong background in Sustainable Development. As the preliminary mapping of the main thematics and challenges, this research does not intend to cover a complete and deep content analysis that is characteristic of a Systematic Literature Review in this paper. However, the analysis of content, even preliminarily, allowed us to identify the main forces driving the 4th Industrial Revolution to PLM with sustainability purposes.

With a base on the study of the 12 selected articles, it is possible to conclude that there is a great movement of industries and enterprises for Disruptive Innovation, which might be supported by one of two of these strategies: Digital transformation and/or Sustainability Transition. With the continuity the research, the authors will propose a framework for transition of sustainability and digital transformation.

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References

[1] C. Bai, P. Dallasega, G. Orzes, J. Sarkis. Industry 4.0: technologies assesment: a sustainability perspective. *International Journal Of Production Economics*. 2020, 229.

[2] M. Ameli, S. Mansour, A. Ahmadi-Javid. A simulation-optimization model for sustainable product design and efficient end-of-life management based on individual producer responsibility. *Resources, Conservation and Recycling*. 2019, Vol. 140, pp.246–58.

[3] H. Xu, Corporate social responsibility, product innovation, and product line. *Nankai Business Review International*, 2020, Vol.11(2), pp. 171–90.

[4] L. Hetemaki, M. Hanewinkel, B. Muys, M. Ollikainen, M. Palahí, A. Trasobares. *Leading the Way to a European Circular Bioeconomy Strategy*. European Forest Institute, 2017, https://efi.int/publications-bank/leading-way-european-circular-bioeconomy-strategy, accessed July, 3 2021.

[5] R. Bradley, IS. Jawahir, F. Badurdeen, K. Rouch. A total life cycle cost model (TLCCM) for the circular economy and its application to post-recovery resource allocation. *Resources, Conservation and Recycling*. 2018, Vol. 135, pp.141–9.
[6] M.H. Lee, J.H.J. Yun, A. Pyka, D.K. Won. F. Kodama, G. Schiuma, et al. How to respond to the Fourth Industrial Revolution, or the second information technology revolution? Dynamic new combinations between technology, market, and society through open innovation. *Journal of Open Innovation: Technology, Market, and Complexity*. 2018, Vol. 4(3), 21.
[7] N. Kawai, R. Strange, A. Zucchella. Stakeholder pressures, EMS implementation, and green innovation in MNC overseas subsidiaries. *International Business Review*, 2018, Vol.27(5), pp. 933-946, https://doi.org/10.1016/j.ibusrev.2018.02.004.
[8] K. Schwab. A quarta revolução industrial. Trad. Daniel Moreira Miranda, Edipro, 2016.
[9] Y. Zhang, S. Ren, Y. Liu, S. Si. A big data analytics architecture for cleaner manufacturing and maintenance processes of complex products. *Journal of Cleaner Production*. 2017, Vol.142, pp.626–41. Available from: http://dx.doi.org/10.1016/j.jclepro.2016.07.123
[10] K. Tiwari, M.S. Khan. Sustainability accounting and reporting in the industry 4.0. *Journal of Cleaner Production*. 2020, Vol. 258, Available from: https://doi.org/10.1016/j.jclepro.2020.120783
[11] M.Z. Hauschild, S. Kara, I. Røpke. Absolute sustainability: Challenges to life cycle engineering. *CIRP Annals*, 2020, Vol. 69(2), pp.533–53.
[12] S. Kim, J. Lee. Accounting treatment of R&D for environmentally responsible firms: Evidence from south korea. *Sustainability (Switzerland).* 2020, Vol. 12(8), pp.1–16.
[13] S.H. Park, W.S. Shin, K.J. Kim. Assessing a social responsibility model for sustainable company growth in the Fourth Industrial Revolution. *International Journal of Quality and Service Sciences*, 2019, Vol. 11(3), pp. 334–45.
[14] A. Lekan, C. Aigbavboa, O. Babatunde, F. Olabosipo, A. Christiana. Disruptive technological innovations in construction field and fourth industrial revolution intervention in the achievement of the sustainable development goal 9. *International Journal of Construction Management*. 2020, pp.1–12.
[15] W.H. Lai, C.C. Lin, T.C. Wang. Exploring the interoperability of innovation capability and corporate sustainability. *Journal of Business Research*. 2018, Vol. 5;68(4), pp. 67–71. Available from: http://dx.doi.org/10.1016/j.jbusres.2014.11.043
[16] S. Bag, S. Gupta, Kumar S. Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development. *International Journal of Production Economics*. 2021, 231.
[17] M. M. Oliveira,. B. R. Leite, M. Rudek, O. Canciglieri Junior,. Evaluation of the Impact of Open Innovation and Acceleration Programs on Research and Development Performed by Universities. *Advances in Transdisciplinary Engineering*, 2020. Vol. 14, pp. 92 - 101, DOI 10.3233/ATDE200065.
[18] S. Rajput, S.P. Singh. Industry 4.0 Model for circular economy and cleaner production. *Journal of Cleaner Production.* Vol. 277, 2020. Available from: https://doi.org/10.1016/j.jclepro.2020.123853
[19] World Commission on Environment and Development (WCED). *Our Common Future*. Oxford University Press, New York. 1987.
[20] T. Kuhlman, J. Farrington. What is Sustainability? *Sustainability*. 2010, Vol.2(11), pp. 3436–48. Available from: http://www.mdpi.com/2071-1050/2/11/3436
[21] P. Glavič, R. Lukman. Review of sustainability terms and their definitions. *Journal of Cleaner Production*. 2007, Vol.15(18), pp.1875–85.
[22] C.R. Carter,. and D.S. Rogers. A framework of sustainable supply chain management: moving toward new theory. *International Journal of Physical Distribution & Logistics Management*, 2008, Vol. 38(5), pp. 360-387.
[23] J. Stark, *Product lifecycle management*. vol.1, pp.1-29. Springer, Cham, 2015.
[24] F. Ameri, D. Dutta. Product lifecycle management: closing the knowledge loops. *Computer-Aided Design and Applications*. 2005 Jan 1;2(5), pp. 577-90.
[25] B. R, Leite. M. M. Oliveira, M. Rudek, Szejka, A, O. C. Junior, Startup Definition Proposal Using Product Lifecycle Management. *Product Lifecycle Management Enabling Smart X*, Springer, Cham. 2020, pp. 426-435.
[26] M.F. Muller, F. Esmanioto, N. Huber, E.R Loures, O. Canciglieri. A systematic literature review of interoperability in the green Building Information Modeling lifecycle. *Journal of Cleaner Production*, 2019, Vol. 223, pp. 397–412.
[27] A. Fink, *Conducting research literature reviews: From the internet to paper*. Sage, Thousand Oaks, 2019.
[28] F. Gu, J. Guo, P. Hall, X. Gu. An integrated architecture for implementing extended producer responsibility in the context of Industry 4.0. *International Journal of Production Research*. vol. 57(5), 2019, pp.1458–77.
[29] D. Silk, B. Mazzali, C.L. Gargalo, A.M. Pinelo, I. Udugama, S.S. Mansouri. A decision-support framework for techno-economic-sustainability assessment of resource recovery alternatives. *Journal of Cleaner Production*, 2020, Vol. 266, 121854.
[30] M. M. Oliveira B. R. Leite, O. Canciglieri Junior. Universities Best Practices in Open Innovation and R&D. *International Conference on Production Research*, 2020, Bahía Blanca, Argentina.

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Dynamic Modeling of Resource Allocation for Project Management in Multi-Project Environment

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Abstract. A challenge in project management in a multi-project environment concerns sharing human resources across projects. Generally, project-based organizations share resources to regulate and plan the project portfolio. This resource allocation process can be elevated through the estimation of required resources by assessing different strategies. Two strategies, static and dynamic, have been applied for resource allocation and compared project performance during this work. Our contribution focuses on how a resource-constrained and schedule-constrained project management policy can meet the planned project performance. Switching resources through dynamic allocation ensures that a project can be delivered on time even when there is no free resource capacity and hiring new staff. Besides, productivity changes as resources are switched among projects back and forth by exploring the gap between the actual and the expected completion dates that affect project performance. Three example projects portfolio has been analyzed employing a system dynamics simulation model. The aim is to plan and control the projects' progress in a multi-project environment by analyzing human resources changes, which will help portfolio managers decide optimal resource allocation.

Keywords. Human resource allocation, Multi-project environment, System dynamics, Transdisciplinary

Introduction

While working in a multi-project environment, project managers generally face problems regarding resource allocation to ensure the timely execution of projects since projects are complex and dynamic. This study focuses on human resource allocation by applying static and dynamic allocation strategies to share resources from a fixed shared resource pool. Considering these resource allocation strategies, we developed a system dynamics (SD) model. This study's primary insight is that projects are unfolding in a multi-project environment frequently switch resources between projects that become a root cause of schedule pressure. Working under schedule pressure and fixed resources shows how resources can be allocated through these allocation strategies to handle project performance.

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In a multidimensional project environment, projects are often related to each other. Digitization is specified by considering various interfaces and end-to-end processes represented as an integrated and integrative discipline[1]. All procedures must be driven forward, focusing on planning and controlling the entire project environment rather than individual projects. This situation increases the importance of multi-project management (MPM), which focuses on selecting, planning, controlling, and monitoring the entire project environment [1]. Although several projects are handled simultaneously in a multi-project environment, the projects may vary in size, required skill, and different stages of completion but use the resources from the same resource pool [2, p. 1]. Hence, managers responsible for resource allocation often get into difficulties regarding the proper distribution of their resources and confirm the projects' timely execution [3]. A different environmental situation may cause variation in resource management policy in MPM. A common approach for solving resource allocation issues in a multi-project environment in the literature assumes a resource sharing policy among different projects forming a sharing resource pool [4].

This study analyzes human resource allocation strategies in a multi-project environment and figures out how these resource allocation strategies affect project performance. A system dynamics (SD) model has been developed to model human resource allocation in a multi-project environment. We assumed some conditions to obtain project performance through our simulation- first, no free resource capacity; second, no hiring new staff; third, switching resources to the concurrent projects affects productivity.

The contribution of this work is to address resource allocation decision problems with simulation studies. We have compared two different resource allocation strategies and analyzed the resource buffer sizing in a multi-project environment. The simulation results provide necessary decision-making implications for resource allocation strategies, which will help managers form decisions about optimal resource allocation.

We structured the paper as follows. Chapter 1 considers literature reviews that imply the desirable scope of importance of resource allocation strategies for concurrent projects in a multi-project environment. Chapter 2 describes the methodology and the process of application in a multi-project environment. Chapter 3 explored result analysis. Based on the exploration, we made a discussion in chapter 4. Finally, chapter 5 represents the conclusion.

1. Literature Review

1.1. Multi-project management(MPM)

Project management is a complex task as it involves complexity, uncertainties, and many activities, even in a single project [5][6]. MPM defines where multiple projects are implemented concurrently, and usually, the projects are lead by one project manager [6][7]. The projects involve in a multi-project environment are often intertwined due to interdependencies among inputs, outputs, and sharing of specialized resources [4][8]. Since multiple projects are unfolded concurrently in a multi-project environment, different issues may arise for successful project execution. Many studies have worked on several matters regarding MPM. These studies have discussed resource allocation issues [3][4][9][10], project scheduling issues [4][9], project delays as a result of managerial problems [4][10]. All these studies have focused on organizational design and the management of the projects.

This study focused on resource allocation problems in a multi-project environment. Often sharing the same resources to concurrent projects make the allocation problem complex since it creates interdependencies among projects. Due to these interdependencies, a resource problem in one project may cause a problem for another project. Hence, the proper resource allocation plan is crucial for the better performance of the project organization.

1.2. Multi-project management and approaches

For the timely execution of the concurrent projects in a multi-project environment considering challenges of interdependencies, project priority, and resource capacity, the researchers have addressed several approaches. A heuristic operational research approach through optimization algorithms' involvement has been discussed [11][12]. A method regarding resource sharing policies with dedicated & core teams and shared resource pools has been explained [10][13]. The main focus is dealing with conflicts among project management, resource management, and portfolio management. Multi-agent-based decentralized decision-making policy design methods have been developed concerning multi-project environments [9][14].

1.3. Resource allocation in a multi-project environment

One principal challenge in a multi-project environment is how to allocate resources to ascertain the timely execution of all planned projects. Usually, to increase the available resource utilization, project managers tend to distribute all the resources at the beginning of the cycle of all planned projects. But this process doesn’t focus on uncertainties involved in project execution. A multi-project environment requires a dynamic and efficient way of determining resource allocation and a pragmatic set of delivery schedules for projects, especially when resources need to switch during ongoing projects [15]. Using resources from a shared resource pool and having interdependencies among projects creates difficulties for project managers about how the resources should be allocated and distributed [16]. Several types of research have proposed and discussed methods for resource allocation, focusing on MPM. A bottom-up approach for resource allocation has been defined to minimize duration in the presence of uncertainty [17]. A system dynamics simulation model has been developed to simulate the effects of resources allocated projects which arrived late and contributed to design schedule-driven project management policy[4]. A decision support system has been developed to mitigate resource competition of autonomous local decisions [9].

[4] work is related to our study, but the focus is different. Their work has focused on schedule pressure by considering the delay only for the first projects to obtain planned project milestones in the long-term and contributing to illuminating short-term logic for tardy projects. In our study, we reproduced project behavior by considering the delay for all the concurrent projects as a long-term effect and obtained the outcomes of project execution in the presence of delay and fixed resource capacity. We considered rework and its impact on the project progress mechanism's performance to reproduce project behavior that has not been considered in the prior work. Considering these, we developed an SD model and then analyzed the simulation results to explore project performance.

2. Research methodology

2.1. Overview of a dynamic model for human resource allocation

The overview of the proposed methodology has shown (Figure 1). In a multi-project environment, a set of projects run concurrently. Hence, the project manager assigns resources to each project based on its necessity and deadline and switches the resources from one project to another as needed. Tasks are developed for each project concurrently, shown through the causal loop diagram (CLD). The CLD for this work represents the interrelation among the project development process parameters considering a multi-project environment. A system dynamics (SD) simulation model has been developed based on the resource allocation process and causal mapping for task development. After developing the simulation model, several runs have been done to obtain resource allocation and project performance in a multi-project environment.

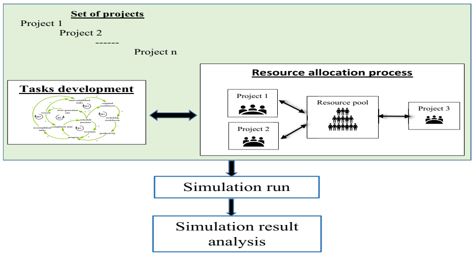

Figure 1. Overview of the proposed methodology.

2.2. The conceptual model

2.2.1. Causal loop diagram (CLD)

In this section, the process described above is illustrated.

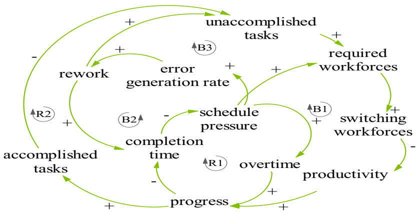

Figure 2. CLD for task accomplishment.

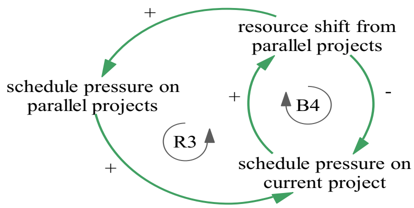

Figure 3. CLD showing the impact of schedule pressure for resource allocation in multi-projects.

Figure 2 depicts the dynamics of effective parameters of project tasks development and resource allocation regarding various reinforcing and balancing loops represented as causal loop diagram (CLD). A CLD in system dynamics is used to model complex relationships with feedback among different parameters involved. In the CLD, the (+) sign represents that both variables are affected in the same way; the (-) sign defines both variables are affected in a reverse manner. The overall reinforcing loop is denoted with **'R,'** and the balancing loop is indicated with **'B.'** In figure 2, the reinforcing loop R1 shows how progress is affected by schedule pressure and affects completion time. Another reinforcing loop, R2, shows the relationship between project task accomplishment and the required workforces, which causes workforces switching and affects productivity. For balancing loops, B1 shows the relation between schedule pressure and its impact on workforces, and loop B2 shows the effect of schedule pressure on rework and completion time. Another balancing loop, B3, represents rework with unaccomplished tasks, which eventually affects project completion time. While talking about schedule pressure, the loops R3 and B4 in figure 3 shows how the schedule pressure is affected due to resource switching.

2.2.2. Project progress mechanism and resource allocation

Figure 4 is used as a project progress mechanism and shown as a stock-flow diagram to determine the project progress rate and track project task accomplishment. Each project consists of tasks referred to as original work to do that needed to be accomplished for project execution. When the tasks are completed, they are referred to as work done. This work done is measured through the flow progress rate. When tasks begin to develop, it contains an error generated through the flow rework generation and then initially moves to the stock undiscovered rework. Rework is an error-based task that is needed to be developed again to complete project execution. After stored in the stock undiscovered rework, rework is discovered with time through the flow rework discovery and then proceeds to another stock rework to do. Rework to do increases the number of unaccomplished tasks and requires more time to accomplish.

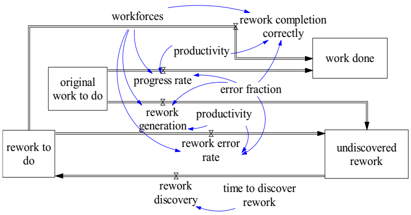

Figure 4. Project progress mechanism.

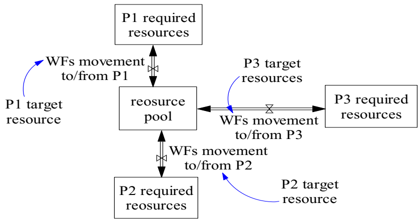

Figure 5. Stock-flow diagram of the resource allocation process.

Resource allocation to several projects in a multi-project environment has been shown as a stock-flow diagram (Figure 5). Once a project arrives, the project manager will capture resources from the concurrent projects considering the gap between the actual and the expected completion date of the concurrent projects. The movement of the resources to the projects will be done through the shared resource pool.

2.2.3. Model Boundary

The model boundary considered for the developed model of this work is shown (Figure 6). The changes of these boundary variables have a significant impact on model behavior as well as project performance. Since the simulation model is developed based on several assumptions, the model's endogenous and exogenous variables are defined and then performed the sensitivity analysis by changing the boundary assumptions to obtain the model behavior.

Figure 6. Model boundary.

2.2.4. Simulation results analysis

We simulated three different projects to reproduce a multi-project environment and obtained the performance through project progress, completion time, and resource allocation by switching resources between projects. Based on the causal loop diagram, project progress mechanism, and resource allocation process, we developed the simulation model using the Vensim tool and then run and analyze the simulation results.

3. Simulation results and analysis

3.1. Resource allocation strategies

Project development in a multi-project environment often experiences several challenges that might be attained through contextual factors-resource availability, project scope, time, client expectations, etc. In regards to these, resource allocation processes are impacted by different strategies. Considering projects' deadlines and required resources, two strategies have been applied and discussed in this work.

3.1.1. Dynamic resource allocation strategy

Dynamic resource allocation allows allocating the resources to projects dynamically by switching them among projects and keeping down completion time and cost [18]. Since in a multi-projects environment, several projects happen concurrently, the projects can be started any time after getting approval. While assessing a dynamic resource allocation strategy, we considered two different situations of the projects beginning.

i. A gap between the projects (considering delay): In this case, a delay has been considered while starting the projects. During the simulation run, we have considered delays for project 2 and project 3. Project 1 has been started at the due time.
ii. All projects start simultaneously (without delay): Projects will start simultaneously, and the resources will be distributed at the beginning based on the requirements.

3.1.2. Static resource allocation

In this allocation process, each project is developed separately as a single project environment. After finishing one project, the next project will begin.

3.2. Project data

Table 1. Input parameters for simulation run.

Parameters	Input values
Number of projects	3
Project scope	200 tasks (for each)
Resources	30 persons
Nominal productivity	0.05 task/person/day

As previously mentioned, three projects have been considered to analyze the resource allocation process and its impact. For each project, the scope is assumed to the same. Therefore, the initial run of the model was conducted under the initial conditions (Table 1).

3.3. Results analysis

3.3.1. Dynamic resource allocation (considering gap)

Focusing on this state while simulating the designed projects to reproduce a multi-project environment, a gap has been considered, representing the project's delay. This system's situation often increases schedule pressure on the project and becomes a reason for the other projects' resource shifting.

As mentioned, the delay has been considered for project 2 and project 3. Hence when project 1 begins, all the resources are allocated to project 1, as they are all available at that time. On the other hand, when project 2 schedules to unfold concurrently with project 1 after a certain period, it captures some of the resources from project 1 (Figure 7) but didn't get the desired number of resources since project 1 still ongoing. These situations increase schedule pressure both for project 1 and project 2. To tackle these circumstances, workforces need to do overtime at times, keeping the deadline.

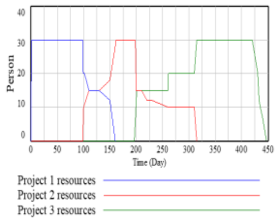

Figure 7. Resource allocation to each project.

In a later stage of the simulation, the beginning of project 3 captures resources from project 2 and creates the same situations as previous projects. In the meantime, project 1 execution process is completed, and the resources are allocated to other projects. This dynamic behavior of resource allocation simulates that the management process has no alternative but to capture resources from other projects and happen concurrently. Switching resources to and from the concurrent projects are happened by calculating the gap between the actual and the expected completion time. This circumstance causes the shifting of the resources several times and occurs oscillation in resource allocation (Figure 7). The shifting of resources from one project to another negatively affects productivity. This effect on productivity increases schedule pressure and affects the overall progress of the projects. Figure 8 and figure 9 represent the project progress rate and the cumulative progress for each project.

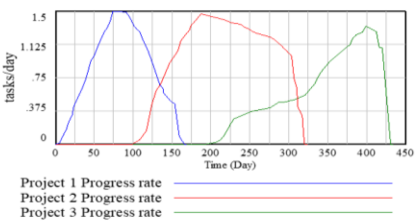

Figure 8. Projects' progress rate.

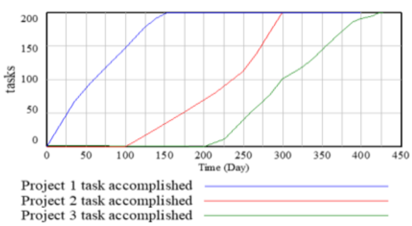

Figure 9. Cumulative progress of each project.

3.3.2. Dynamic resource allocation (projects starting at the same time)

In the multi-project environment, when all the projects begin to unfold simultaneously, resources are distributed to all projects as per requirements. Since in this work, it is assumed that all the projects' scope is equal, then resources are distributed equally to all projects. As the resource capacity is fixed, projects often don't get the required resources following the deadline, and workforces need to do high overtime for project completion in time (Figure 10). Since we considered equal project scope for each project, we obtained the same performance for each project (Figure 11).

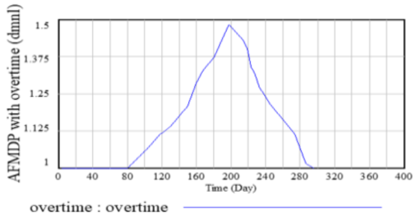

Figure 10. Overtime impact.

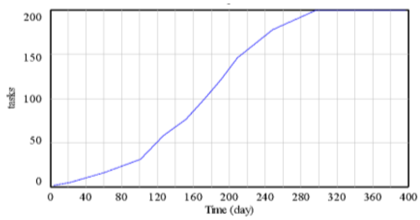

Figure 11. Cumulative progress of each project without delay.

3.3.3. Static resource allocation

In this allocation strategy, projects are assumed to be unfolded one after another. This environment usually works as single project development and can be effective if the completion time is flexible and high. In this process, since projects happen singularly, the project manager allocates all the resources to one project until completion. This effect reduces the schedule pressure and makes the project execution process easier (Figure 12).

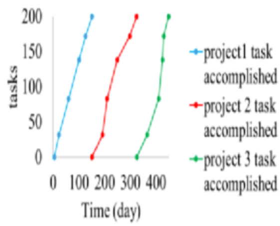

Figure 12. Cumulative progress of each project.

Since multiple projects need to be handled in a multi-project environment and the elapsed time for each project has to be considered seriously, a static allocation strategy cannot be an excellent way to implement this environment.

The simulation results have been explained both for dynamic allocation with delay and static allocation. The obtained resource allocation results act as a helpful paradigm to access the interaction among variables involved in project performance and the effects of managerial decisions for resource allocation in a resource-constrained and schedule-constrained multi-project environment.

4. Discussion

This work exhibits an approach of resource allocation for a multi-project environment sustained on switching resources to concurrent projects with dynamic allocation, affecting the multi-project environment's potential to accomplish planned project milestones. This outcome is beneficial where a fixed shared resource pool is used, and the resource capacity for each project is designated from that fixed shared resource pool. This work explores that several factors happened when the project manager emphasizes completing all projects on time. When one project losses resources, schedule pressure increases for that project. And when several projects have schedule pressure simultaneously, resources switch back and forth in response to the project deadline's priority and thus affect productivity. These dynamic allocation consequences operate the schedule pressure in a reinforcing loop yielding a sensible state to deliver the project successfully. The results obtained from the analysis are consistent with [4], where it has also mentioned schedule-pressure is self-reinforcing. With the simulation results, our central contribution shows that the projects developing in a multi-project environment can be delivered on time considering delay and fixed resource capacity. The dynamic allocation process works as a better strategy against total completion time. The first option- allocation considering gap- performs better than the other option. In this case, since a delay happened, so by this meantime, the maximum number of resources can be allocated to the ongoing project, and a large number of tasks can be accomplished before switching resources with high progress. The arrival of new projects causes resource switching and increases schedule pressure. In this allocation process, one issue occurs to the productivity of the resources. When the resources are switched from one project to another, it adversely affects productivity since the project goal is different. The second option of dynamic allocation, when all the projects start simultaneously, requires a longer completion time. The reason for taking a long time is the fixed resource capacity, and at the same time, all projects are active. Hence resources must be distributed to all the projects from the beginning, allocating fewer resources, but often the productivity remains high since switching doesn't happen frequently. They need to do overtime to lower the schedule pressure as well as complete the project. Equality among projects and resource availability are identified as high-performing portfolios in MPM [19]. Hence when the resource capacity is fixed and not having enough availability for each project, the understanding of dynamic allocation could be an excellent way to handle the project execution process, which has been obtained through this study. Another contribution involves experimenting with two different resource allocation strategies separately, explaining how the resources can be handled in different situations and achieve the project milestone without having the worst effect. Another consequence of this work is that the SD modeling has been done based on the rework cycle (Figure 4). The rework cycle focuses on downstream work through which error-based tasks are identified. The project execution process is completed counting all unaccomplished tasks that cover the testing phase of a project.

Any line of employment relies heavily on human resources. While working in a multi-project environment, each project has a distinct aim that necessitates a different set of skills. As a result, the human resources in a multi-project scenario are knowledgeable with a wide range of capabilities. Hence, this study will have a significant impact on the field of transdisciplinary engineering.

5. Conclusion

This paper presents an approach for a multi-project environment where each project's resource capacity is determined from the fixed shared resource pool. The resources are eventually shared among projects based on necessity. An essential aspect of this work lies in its usefulness to the decision-makers at various managerial levels while deciding on resource allocation in a multi-project environment. The application of both static and dynamic allocation processes has been explained clearly. Based on the simulation results and overall contribution of this study, it can be said that the simulation provides a stylish representation of the flow of resources in a multi-project environment. In making visible to project managers how they can best meet the resource concerns, this study might contribute to decision-making for resource allocation to reduce schedule pressure and improve project performance.

Acknowledgment

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References

[1] N.N., *Multi-project Management*, Passcon Consulting Solutions with Passion, 2018.

[2] C. B. Jørgensen, *Human resource allocation practices in multi-project organizations: A case study of human resource allocation practices and the contextual conditions that shape them*, Master's thesis, University of Agder, Norway, 2015.

[3] T. Ben-Zvi and T. G. Lechler, *Resource allocation in multi-project environments: Planning vs. execution strategies*, Portland International Center for Management of Engineering and Technology, Portland, OR, 2011, pp. 1-7.

[4] K. Yaghootkar and N. Gil, The effects of schedule-driven project management in multi-project environments, *International Journal of Project Management*, 2012, Vol. 30, pp. 127–140.

[5] C.M.d.M. Mota, A.T. d. Almeida, and L.H. Alencar, A multiple criteria decision model for assigning priorities to activities in project management, *International Journal of Project Management*, 2009, Vol. 27, pp. 175–181.

[6] M.C.J. Caniëls and R.J.J.M. Bakens, The effects of Project Management Information Systems on decision making in a multi project environment, *International Journal of Project Management*, 2012, Vol. 30, pp.162–175.

[7] P. Patanakul and D. Milosevic, The effectiveness in managing a group of multiple projects: factors of influence and measurement criteria, *International Journal of Project Management*, 2009, Vol. 27, pp. 216–233.

[8] M.A. Kaulio, Project leadership in multi-project settings: Findings from a critical incident study, *International Journal of Project Management*, 2008, Vol. 26, pp. 338–347.

[9] F. Li, Z. Xu, and H. Li, A multi-agent based cooperative approach to decentralized multi-project scheduling and resource allocation, *Computers & Industrial Engineering*, 2021, Vol. 151, 106961.

[10] Z. Laslo and A.I. Goldberg, Resource allocation under uncertainty in a multi-project matrix environment: Is organizational conflict inevitable?, *International Journal of Project Management*, 2008, Vol. 26, pp. 773–788.

[11] T.R. Browning and A.A.Yassine, Resource-constrained multi-project scheduling: Priority rule performance revisited, *International Journal of Production Economics*, 2010, Vol. 126, pp. 212–228.

[12] J. Xu and C. Feng, Multimode Resource-Constrained Multiple Project Scheduling Problem under Fuzzy Random Environment and Its Application to a Large Scale Hydropower Construction Project, *The Scientific World Journal*, 2014, 463692.

[13] H. Chen, G. Ding, J. Zhang, and S. Qin, Research on priority rules for the stochastic resource constrained multi- project scheduling problem with new project arrival, *Computers & Industrial Engineering*, 2019, Vol. 137, 106060.

[14] S. Adhau, M.L. Mittal and A. Mittal, A multi-agent system for distributed multi-project scheduling: An auction-based negotiation approach, *Engineering Applications of Artificial Intelligence*, 2012, Vol. 25, pp. 1738–1751.

[15] L.D. Dye and J. S. Pennypacker, Project Portfolio Management and Managing Multiple Projects:Two Sides of the Same Coin?, *Proceeding of the Project management institute Annual seminars & Symposium*, Houston, 2000, pp. 7-16.

[16] Blomquist, T., & Müller, R., Practices, Roles, and Responsibilities of Middle Managers in Program and Portfolio Management, *Project Management Journal*, 2006, Vol. 37, pp. 52-66.

[17] L.D. Long and A. Ohsato, Fuzzy critical chain method for project scheduling under resource constraints and uncertainty, *International Journal of Project Management*, 2008, Vol. 26, pp. 688-698.

[18] T. Linnenberg, C. Derksen, A. Fay, and R. Unland, Cross-Domain Energy Savings by Means of Unified Energy Agents, *Emerging Applications of Software Agents in Industry*, 2015, pp. 247-268.

[19] R.G. Cooper, S.J. Edgett, and E.J. Kleinschmidt, Benchmarking Best NPD Practices-II, *Research Technology Management*, 2004, Vol. 47, pp. 50-59.

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Reference Model as Support for the Implementation of Agriculture 4.0

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Abstract. Agriculture is facing increasing challenges due to several factors such as population growth, climate change, and variation of prices practiced by the market. It has been looking for ways to improve profitability and agricultural efficiency through better management control based on information and knowledge generated on the farm in its specific context. Innovative technologies and solutions have been applied as an alternative for the collection and processing of this information with the fourth industrial revolution, which is generated by systems, equipment, markets, and agents involved in agricultural production. Transforming this data collected in the field into valuable data that supports better decision-making is essential. Through a literature review, it was established that the artifact to be developed in this project corresponds to an information model over an agricultural scenario. Following the Design Science Research (DSR) methodology, to reach this objective will be necessary to develop three artifacts. In this article, the first artifact is presented: a model that provides a systemic view and characterizes Agriculture 4.0.

Keywords. Agriculture 4.0, Farm 4.0, Reference Model, Transdisciplinary Engineering

Introduction

Technological advances have been driving drastic changes in industries since industrial revolutions started [1].Thus, several technologies are available for Industry 4.0 to achieve its objective related to continuous improvement, greater efficiency, safety, and operations productivity [1], [2].

As in industry, the agricultural sector is being transformed with the use of these new technologies. From Industry 4.0, Agriculture 4.0 appeared, offering new opportunities through the availability of interconnected and intensive technologies, which arise from Industry 4.0 [3].

Agriculture is considered highly unpredictable due to the high dependence on weather and environmental conditions (i.e., rainfall, temperature, humidity), uncertain events (i.e., animal diseases, pests), and market price volatility. For this reason, there is a great need to use technologies and data analysis to help farmers about the conditions and risks of their farms, enabling them to take appropriate and timely measures to protect their crops [4].

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With the advent of intelligent machines and sensors, the amount and types of data have grown dramatically. Thus, these data are increasingly guiding agricultural processes [5]. Technological solutions (i.e., Bluetooth, Global Positioning System - GPS, Radio Frequency Identification - RFID) combined with communication between operators and agricultural machines at all levels of collaboration make it feasible to create a self-optimizing structure [6]. According to [7], current sensors provide very accurate data, and the actuators are capable of managing irrigation, changing weather conditions, or even enrich the soil with the necessary nutrients.

Thus, farmers are interested in business models that support revenue generation from data captured through IoT technologies [8]. From the data collected and generated by various devices and communication technologies, it is possible to build knowledge bases that store complex and unstructured information. However, a model with information in an organized and complete way, that provides relevant knowledge, can be used universally and implements smart agriculture is still a challenge [9], [10].

According to [11] it is possible to perceive the inexistence of works focused on the agricultural area that consider creating a model that characterizes Agriculture 4.0. It is also possible to notice the absence of a model that depicts, in an integrated and universal way, all the farm-oriented agents to Agriculture 4.0, with all technologies and relations between them. Besides, was identified the need to create an information model across a generic agricultural scenario enabling data analysis and event prediction to anticipate decision making.

In this context, this article presents the first artifact of extensive research, in partnership with a company that produces agricultural equipment, which aims to develop an information model across a generic agricultural scenario, capable of selecting and interpreting agricultural implements sensors data. The objective of this paper is to propose an Agriculture 4.0 reference model through the adaptation of The Reference Architectural Model Industry 4.0 (RAMI 4.0).

This article is structured in four sections. Section 1 presents a theoretical foundation necessary for the understanding of the research. The following section describes the methodological aspects considered. In Section 3 the development of the proposed reference model is presented. Section 4 presents the final considerations and conclusions about the work and suggests recommendations for future work.

1. Theoretical Background

1.1 Industry 4.0

Source [12] considers Industry 4.0 a manufacturing revolution that presents a new perspective for the industry combining new technologies to obtain maximum performance with minimum use of resources. This movement has led companies to rethink how they manage their businesses and processes, allowing for real-time production planning and control [13].

To implement Industry 4.0, vertical and horizontal integrations of all its principal functions are necessary, giving rise to a new way for companies to position themselves in the value chain and manage their production. This integration, combined with the emergence of new technologies, allows productive systems to be more efficient since they are more responsive and predictive. Thus, Industry 4.0 is not just a digitization movement but a combination of diverse technologies based on innovation [2].

Several reference models represent industry 4.0, such as The Industrial Internet Reference Architecture (IIRA), The Stuttgart IT - Architecture for Manufacturing (SITAM), The Reference Architectural Model Industry 4.0 (RAMI 4.0), among others.Reference models are sets of interconnected and clearly defined concepts developed by specialists to understand the interactions between entities in an environment [14].

Between the existing architecture reference models for industry 4.0, the most known and used is RAMI 4.0 [15]. Illustrated in Figure 1, this model, developed in Germany [16], is an adaptation and expansion of the Smart Grid Architecture Model (SGAM) to meet requirements 4.0 [14].

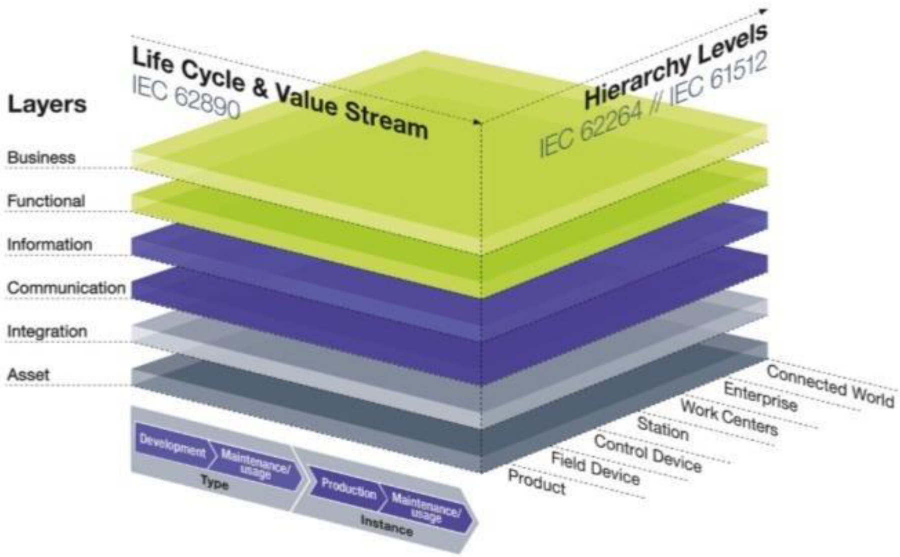

Figure 1. RAMI 4.0 [24]

RAMI 4.0 aims to group and represent different aspects of the industry in a unique model, describing the most important aspects of intelligent production systems with an architectural view of Industry 4.0[15], [17], [18]. According to [14], this model provides a reference for a basic 4.0 architecture system, serving as a basis for analyzing its relationships and details.

RAMI 4.0 is a three-dimensional model developed based on horizontal and vertical integration and end-to-end engineering. The horizontal axis (at the right of Figure 1) represents the hierarchy levels, i.e., the layers of integration of a business control system (enterprise, work centers, station, and control device) and three other layers to support the smart concept. The Field Device layer allows controlling equipment and systems in an intelligent way (use of sensors). The Product layer represents the interdependence between the products to be manufactured and the production equipment. The Connected World layer, on the other hand, allows the representation of the expansion of factory limits, with the institution of partnerships and collaborative networks [14], [17], [19].

The left horizontal axis - Life Cycle and Value Stream - shows the production cycle and the product life cycle [17]. Finally, the vertical axis (Layers) represents the hierarchical layers for information, decomposing and representing perspectives (i.e., data

maps, behaviors) of physical entities. Thus it defines the structure of information and communication technologies for industry 4.0 [14], [17].
Thus, RAMI 4.0 integrates vertically and horizontally concepts, end-to-end engineering, and life cycle [19]. Also, the model allows the division of processes into packages, facilitating communication and data processing. This model subdivides a complex system with internal connections into smaller and easier to deal with subsystems [15].

The combination of technologies results in the development of intelligent factories that use resources in a highly efficient way and can adapt quickly to different market scenarios [12]. In this context, the changes and technologies present in Industry 4.0 influence the way companies in the agricultural sector walk in the market. same sense. Thus, with great potential for growth and productivity, the agricultural sector has been adopting and adapting these same technologies, giving rise to the so-called Agriculture 4.0 [20].

1.2 Agriculture 4.0

Currently, Agriculture 4.0, as well as Industry 4.0, has all processes connected to the cloud. Thus, Agriculture 4.0, also called smart agriculture or digital agriculture, is defined as Industry 4.0 of the primary sector [3], [6], [21], [22].

The development of technologies such as systems and data transmission has led to radical changes in the agricultural work environment in recent years. These changes updated systems information, markets, and agents involved in the production, so it is necessary to provide information for decision-making related to production and strategic and managerial issues [23]. Figure 2 presents the progress made in agriculture resulting from the leading industrial revolutions.

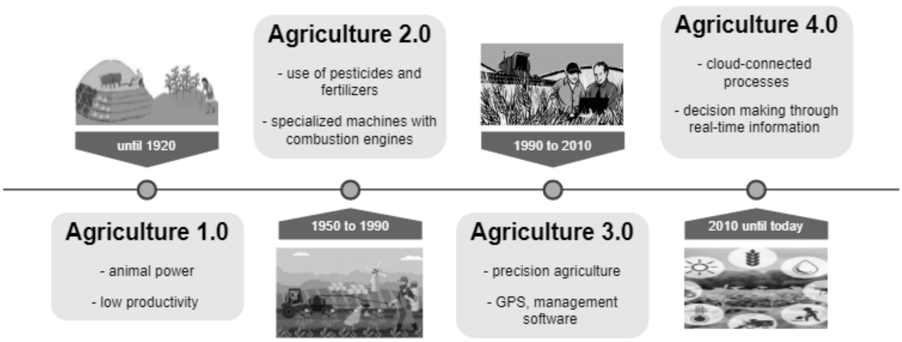

Figure 2. Agricultural progress

Although smart farming and precision farming are often indistinguishable treated, they are thoroughly different [24]. Precision agriculture allowed intelligent agriculture emergence. Intelligent agriculture uses the collection, processing, and analysis of data in real-time, automating agricultural procedures. Thus, allowing the improvement of operations, management, and decision making [4].

Unlike precision agriculture, which takes into account only the variability of the field, intelligent agriculture goes further, including the entire agricultural production cycle, aiming to improve context and situation awareness triggered by real-time events [25]. Combining digital agriculture and precision farming technologies will be possible to reduce costs and maximize yields and profits [24].

According to [26], digital agriculture has relevant information to deal with challenges related to climate change, such as water scarcity, and environmental problems, which make food production more difficult and expensive. Decision-making and agricultural planning can be further supported, leading to more effective and efficient agriculture [27].

Agriculture 4.0 means the use of technologies to increase profitability and sustainability in agriculture [28]. Companies that supply agricultural products have sought to offer alternatives to collect and process information [29]. Machines are equipped with sensors that measure data in their environment and evaluate the machine's behavior. Thus, big data technologies play an essential role in this development [5], [30].

[5] state that digital agriculture has been driven by the rapid development of cloud computing and the internet of things, using information and communication technology in the cyber-physical management of farms. It can also be said that Agriculture 4.0 is the application of technology systems with big data and precision in agriculture [26], [28].

Digital agriculture provides several improvements as the increase of harvest efficiency, risks minimizing, costs reducing and profitability increasing, and improving decision-making management [27]. The application of modern information and communication technologies (ICT) increases the production and financial return and reduces the environmental impact in the agricultural sector. [31]. According to [27] The use of technologies such as cloud computing, remote sensing, the internet of things, data-driven agriculture, and Big data analysis is the basis of Smart agriculture.

2 Methodological Aspects

The present research is based on the Design Science Research (DSR) approach. DSR aims to improve the perception of professionals in their fields so problems can be solved [32], [33]. Thus, this approach assists in the development of artifacts that attempt to solve observed problems, make research contributions, evaluate solutions and communicate results [33]. Artifacts are designed in order to change something in a system, aiming to solve problems or improve performance, are defined as methods, models, constructions, and instantiations [34].

According to [35], the development and application of an artifact acquire knowledge and understanding of a problem and its solution. Thus, this research presents a model as the artifact to be designed. Models are sets of propositions or statements that describe and represent a real scenario [34].

The DSR approach defines six steps that must be followed to create a consolidated artifact. These steps are: (*i*) problem definition and motivation; (*ii*) definition of the Solution objectives; (*iii*) Design and development; (*iv*) Demonstration; (*v*) Evaluation; and (*vi*) Communication. Figure 3 presents a flowchart with these phases.

Figure 3. DSR steps. Adapted from [28].

This article will present only three steps of the DSR approach. The other phases are yet to be performed in future research.

Phase 1 - Problem identification and motivation: The first step of the DSR is related to the identification of an application context of the solution. The main objective at this stage is to direct the researcher to solve an existing problem.

Phase 2 - Definition of the Solution objectives: In this second step of the DSR the objectives expected to solve the problem.

Phase 3 - Solution design and development: This stage is correlated to the construction of the artifact. Therefore, this phase includes the development of three models that integrate and form the complete artifact.

3 Results and Discussion

This section presents the results obtained in this research, which follow the steps of DSR described in methodological aspects, giving the deliverables obtained in the first three steps of this approach.

3.1 Problem Identification and Motivation

At this step, meetings with members of this project's partner company were carried out. In the context of an intelligent farm, the integration levels of the technologies adopted by the company in their products were identified. Besides, a literature review about the research topic was performed, to obtain a conceptual basis on the subject, assist in identifying research already carried out and its results achieved, detecting trends and research gaps on the topic in question.

Based on that previous study carried out by the authors [11], [36], it was accomplished that researches related to Agriculture 4.0 do not present a systemic view, deal with the subject in a restricted way, seeking to find isolated solutions. Also, companies that provide agricultural equipment are equipping their products with sensors that can collect various types of data, but these data are not used to generate information useful, either to improve the overall productivity of the farms [11], [36].

3.2 Definition of the Solution objectives

The objectives to solve the problem are expected in this second step of the DSR. Thus, after conducting the literature review, it was established that the artifact to be developed in this project corresponds to an information model over an agricultural scenario

The model must capture data related to maintenance in existing databases and powered by IoT, making possible the objective of controlling and predicting the need for equipment maintenance can be achieved, assisting predictive decision making.

Product and maintenance engineers predict and schedule the maintenance of agricultural equipment taking into account scenarios that approximate their real working conditions in the field. However, equipment is used in regions with very different climates, which have particularities related to the ambient temperature and humidity that often make this maintenance schedule a failure.

To predict the need for maintenance, and as a consequence, to increase the availability of equipment, the artifact to be developed will focus on data captured by sensors present in equipment, which can be related to component failure. Thus, enabling predict the need for maintenance and consequently promote an increase in equipment availability.

3.3 Solution design and development

To achieve the objective defined in the second step of the DSR will be necessary to develop three artifacts. In this article, the first one is presented, the other two are still being developed.

So the first artifact is presented in this article. It was created as an initial phase to support the construction of the other artifacts, as well as the development of the information model, which is the main objective of this project.

Thus, the first artifact was created: a model that provides a systemic view and characterizes Agriculture 4.0.

This reference model of Agriculture 4.0 was proposed based on an Industry 4.0 model already existing in the literature, the RAMI 4.0, incorporating its principles and adapting them to the agricultural reality. As can be seen in Figure 4, the proposed model considers three dimensions.

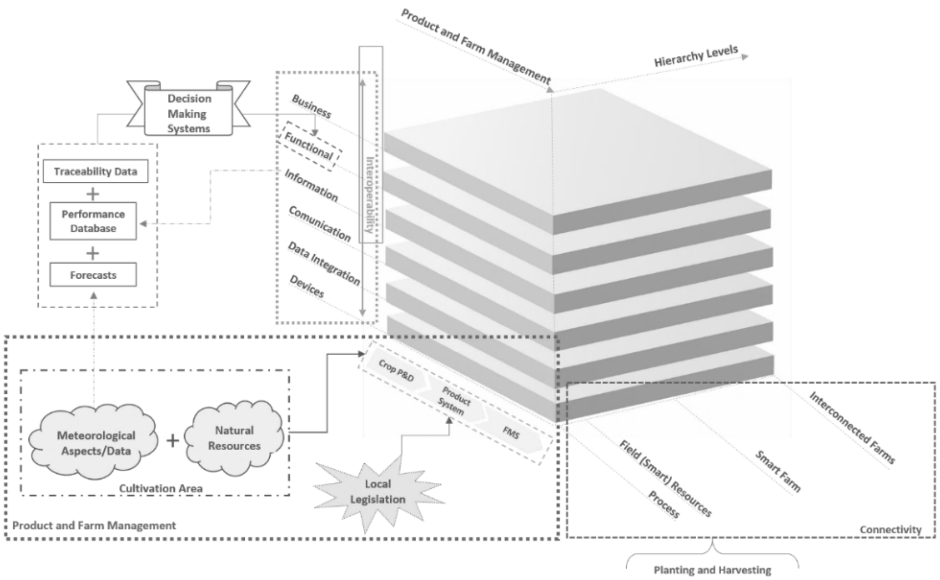

Figure 4. Reference Model for Agriculture 4.0

The horizontal axes represent the hierarchical levels and the agricultural production cycle. On the right horizontal axis of the reference model, all processes involved in agriculture are considered, from planting to harvest, emphasizing the concept of connectivity. Thus, this axis represents the processes and equipment data collection through the relationship between equipment and intelligent systems (i.e., sensors).

The smart farm concepts are also represented in this dimension, considering all the equipment and systems interconnected. Finally, the Interconnected Farms layer, which is related to RAMI 4.0 Connected World layer, aims to represent the expansion of farm limits, with partnerships institution and collaborative farms network.

On the left horizontal axis of the model - Product and Farm Management - the development and production of plantations and management systems are presented. The cultivation place legislation must be considered in the agricultural production system and was highlighted in the model. Two other important aspects were considered: meteorological data of the cultivation region and its natural resources. Meteorological data (i.e., precipitation and temperature) and natural resources data (i.e., soil type and pests) must be combined to support the decision to choose the crop and its production.

As RAMI 4.0 model, the vertical axis represents the hierarchical layers for information. However, the proposed model highlights the interoperability between them In this axis, it is possible to identify the representation of support systems for decision-making, depending on data traceability and equipment performance, and forecasts derived from meteorological databases. Thus, Functional and Information hierarchical layers are highlighted in the model.

Figure 5 presents a preview of the model that is being transcribed in SysML language in the Enterprise Architect software, which is still in the development phase.

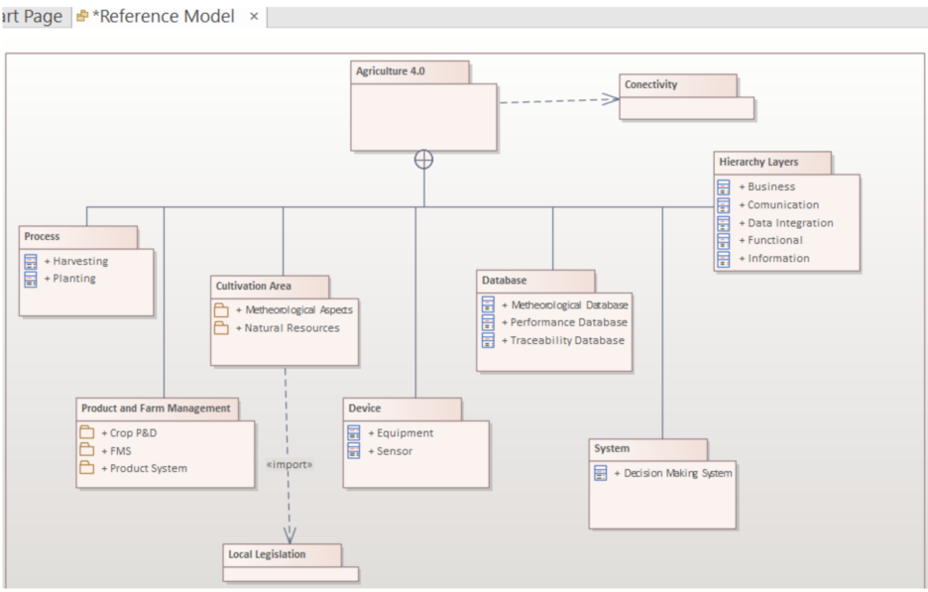

Figure 5 - Agriculture 4.0 - Reference Model

4 Conclusions and Future work

The reference model for Agriculture 4.0 proposed was developed considering the particularities linked to the agricultural scenario. It provides a view and describes the most important aspects of smart agriculture production systems. Thus, the reference model developed in this work allows the direction of a generic vision of Agriculture 4.0 and will serve as a basis for the development of the other steps to achieve the general objective of the research.

Hence, after the reference model creation, as future work, a model that depicts all the agents of a farm-oriented to Agriculture 4.0 - Farm 4.0 will be developed, representing all technologies and relations between them in an integrated and universal way. Thus, it will be possible to operate a systemic view of the farm.

After modeling Farm 4.0, an information model over a generic agricultural scenario that enables data analysis and events prediction to anticipate decision making will be developed. This information model should capture the data generated in one of the information flows represented in the Farm 4.0 model to control and predict the need for equipment maintenance, assisting decision making in a predictive manner. Enterprise Architecture software and cloud computing will be used to make it possible to elaborate the model by structuring layers of information.

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References

[1] M. Rüßmann *et al.*, Industry 4.0: The future of productivity and growth in manufacturing industries, *Bost. Consult. Gr.* , 2015, Vol. 9, No. 1, p. 54–89.

[2] P. M. N. Coelho, *Rumo à indústria 4.0*, MThesis, University of Coimbra, 2016.

[3] I. Kovács e I. Husti, The role of digitalization in the agricultural 4.0–how to connect the industry 4.0 to agriculture?, *Hungarian Agric. Eng.*, 2018, No. 33, pp. 38–42.

[4] A. Kamilaris, F. Gao, F. X. Prenafeta-Boldu, and M.I. Ali, Agri-IoT: A semantic framework for Internet of Things-enabled smart farming applications, in *2016 IEEE 3rd World Forum on Internet of Things, WF-IoT 2016*, 2017, pp. 442–447.

[5] S. Wolfert, L. Ge, C. Verdouw, and M.-J. Bogaardt, Big Data in Smart Farming – A review, *Agric. Syst.* , 2017, Vol. 153, pp. 69–80.

[6] I. Zambon, M. Cecchini, G. Egidi, M. G. Saporito, and A. Colantoni, Revolution 4.0: Industry vs. agriculture in a future development for SMEs, *Processes*, 2019, Vol. 7, No. 1, 36.

[7] M. A. Zamora-Izquierdo, J. Santa, J. A. Martinez, V. Martinez, and A. F. Skarmeta, Smart farming IoT platform based on edge and cloud computing, *Biosyst. Eng.*, 2019, Vol. 177, pp. 4–17.

[8] O. Elijah, T. A. Rahman, I. Orikumhi, C. Y. Leow, e M. N. Hindia, An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges, *IEEE Internet Things J.* , 2018, Vol. 5, No. 5, pp. 3758–3773.

[9] I. Mohanraj, K. Ashokumar, and J. Naren, Field monitoring and automation using IOT in agriculture domain, *Procedia Comput. Science*, 2016, Vol. 93, pp. 931–939.

[10] R. R. Shamshiri *et al.*, Research and development in agricultural robotics: A perspective of digital farming, *Int. J. Agric. Biol. Eng.*, 2018, Vol. 11, No. 4, pp. 1–14.

[11] J. Iaksch, E. Fernandes, and M. Borsato, Digitalization and Big Data in Smart Farming– Bibliometric and Systemic Analysis, *Advances in Transdisciplinary Engineering*, 2020, Vol. 12, pp. 115-124.

[12] S. S. Kamble, A. Gunasekaran, and S.A. Gawankar, Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives, *Process Saf. Environ. Prot.*, 2018, Vol. 117, pp. 408–425.

[13] A. Sanders, C. Elangeswaran, and J. P. Wulfsberg, Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing, *J. Ind. Eng. Manag.*, 2016, Vol. 9, No. 3, pp. 811–833.

[14] M.A. Pisching, M.A.O. Pessoa, F. Junqueira, D.J. dos Santos Filho, and P.E. Miyagi, An architecture based on RAMI 4.0 to discover equipment to process operations required by products, *Comput. Ind. Eng.*, 2018, Vol. 125, pp. 574–591.

[15] M. Resman, M. Pipan, M. Šimic, and N. Herakovič, A new architecture model for smart manufacturing: A performance analysis and comparison with the RAMI 4.0 reference model, *Adv. Prod. Eng. Manag*, 2019, Vol. 14, No 2, pp. 153–165.
[16] F. Aziz, S. Samsudin, N. Nambiar, E. Li, R.Y. Zhong, Industry 4.0 in New Zealand dairy industry, *International Journal of Agile Systems and Management*, 2019, 12(2), pp. 180-197..
[17] A. Rojko, Industry 4.0 concept: background and overview, *Int. J. Interact. Mob. Technol.* , 2017, Vol. 11, No. 5, p. 77–90.
[18] K.M. Alam and A. El Saddik, C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems, *IEEE Access*, 2017, Vol. 5, pp. 2050–2062.
[19] M. Adolphs, P., Bedenbender, H. Dirzus, D. Ehlich, M. Epple, U. Hankel, M. Wollschlaeger, *Reference Architecture Model Industrie 4.0 (RAMI 4.0)*. VDI/VDE and ZVEI, 2015.
[20] I. Husti, M. Daroczi, e I. Kovacs, Message from ‘Industry 4.0’ to agriculture, *Towar. Sustain. Agric. Biosyst. Eng. Univ. Nonprofit Ltd., Mosonmagyaróvár, Hungary*, 2017, p. 63–78.
[21] F. Strozzi, C. Colicchia, A. Creazza, and C. Noè, Literature review on the ‘Smart Factory’concept using bibliometric tools, *Int. J. Prod. Res.*, 2017, Vol. 55, No 22, pp. 6572–6591.
[22] J.-H. Huh and K.-Y. Kim, Time-based trend of carbon emissions in the composting process of swine manure in the context of agriculture 4.0, *Processes*, 2018, Vol. 6, No- 9, 168.
[23] D. Pivoto, P. D. Waquil, E. Talamini, C. P. S. Finocchio, V. F. Dalla Corte, and G. de Vargas Mores, Scientific development of smart farming technologies and their application in Brazil, *Inf. Process. Agric.* , 2018, Vol. 5, No. 1, pp. 21–32.
[24] S. Suakanto, V.J.L. Engel, M. Hutagalung, and D. Angela, Sensor networks data acquisition and task management for decision support of smart farming, in *2016 International Conference on Information Technology Systems and Innovation, ICITSI 2016 - Proceedings*, DOI: 10.1109/ICITSI.2016.7858233.
[25] S. Himesh *et al.*, Digital revolution and Big Data: A new revolution in agriculture, *CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour.* , 2018, Vol. 13, DOI: 10.1079/PAVSNNR201813021.
[26] S. Rotz *et al.*, The Politics of Digital Agricultural Technologies: A Preliminary Review, *Sociol. Ruralis*, 2019, Vol. 59, No. 2, pp. 203–229.
[27] Ö. Köksal and B. Tekinerdogan, Architecture design approach for IoT-based farm management information systems, *Precis. Agric.*, 2019, Vol. 20, No. 5, pp. 926–958.
[28] B. Ozdogan, A. Gacar, and H. Aktas, Digital agriculture practices in the context of agriculture 4.0, *J. Econ. Financ. Account.*, 2017, Vol. 4, pp. 184–191.
[29] P. P. Ray, M. Mukherjee, and L. Shu, Internet of Things for Disaster Management: State-of-the-Art and Prospects, *IEEE Access*, 2017, Vol. 5, pp. 18818–18835.
[30] A. Kamilaris and A. Pitsillides, Mobile Phone Computing and the Internet of Things: A Survey, *IEEE Internet Things J.*, 2016, Vol. 3, No. 6, pp. 885–898.
[31] G.C. Rains and D.L. Thomas, *Precision farming: An introduction*, University of Georgia, Griffin, 2009.
[32] K. Peffers, T. Tuunanen, M.A. Rothenberger, and S. Chatterjee, A design science research methodology for information systems research, *J. Manag. Inf. Syst.*, 2007, Vol. 24, No. 3, pp. 45–77.
[33] H.A. Simon, *The sciences of the artificial*. MIT press, Boston, 2019.
[34] D.P. Lacerda, A. Dresch, A. Proença, and J.A. V Antunes Júnior, Design Science Research: método de pesquisa para a engenharia de produção”, *Gestão & produção*, 2013, Vol. 20, No. 4, pp. 741–761.
[35] R.H. Von Alan, S.T. March, J. Park, and S. Ram, Design science in information systems research, *MIS Q.*, 2004, Vol. 28, No. 1, pp. 75–105.
[36] J. Iaksch, E. Fernandes, and M. Borsato, Digitalization and Big data in smart farming–a review, *J. Manag. Anal.*, 2021, pp. 1–17.

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Tracking Underground Metro Cars with Low-Cost Acceleration Sensors

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Abstract. Subways and other rapid transit systems are marked symbols of the modern metropolis. As a transdisciplinary service, accurately and safely positioning and tracking the metro trains helps the passengers to plan their travels and provides the operators with auxiliary information about the trains to enhance the metro system's resilience. However, many general-purpose positioning technologies, such as Global Navigation Satellite Systems (GNSS) and Wi-Fi signals, do not apply to the situations of underground metro trains. In this paper, we propose a two-stage framework for automatic real-time tracking of metro cars implemented only with low-cost accelerometers, saving the expense for complicated infrastructures. In the off-line stage, reference maps are developed for station-to-station track sections using the onboard acceleration data. To handle the missing data and uncalibrated consumer-grade sensors, Gaussian process regression (GPR) is adopted to denoise and interpolate the online acceleration readings, followed by the application of the Kalman filter algorithm to track the cars in real-time with the help of the reference map. We tested the proposed system in Wuhan Metro Line 2, and the results showed that our system achieved an error below 5% in positioning.

Keywords. Positioning and tracking, acceleration sensors, Gaussian process regression

Introduction

Since its birth in 1863 in London, England, the subway has become the most efficient and convenient public transport means for commuters in many metropolitan areas in the world. And the trend of its rapid growth sustains in recent years along with urbanization in the emerging economies. For example, in 2019 alone, China added over 800 kilometers to the mileage of its subway systems. There are many critical applications for the real-time positioning and tracking of metro trains, including control and positioning of repair trains (and other engineering vehicles), autonomous locomotives, collision warning systems, diagnosis and maintenance of abnormal defects, etc. In the meantime, the passengers are keen to know their whereabouts after getting on board for many possible reasons. However, even given its role to ensure the safe and efficient operations of the metro systems, the real-time positioning and tracking of metro vehicles remain a challenging problem.

Conventionally, most vehicular positioning systems rely on global navigation satellite systems (GNSS) such as the global positioning system (GPS) to provide the basis for positioning, navigation, and timing (PNT) services. Regardless of the advantage of high precision, high-speed, and availability in all-weather, the GPS-based positioning

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suffers in complex environmental conditions (e.g. tunnels and forests). However, a majority of metro lines contain a large portion of tunnels. As an alternative, the inertial measurement unit (IMU) also serves as the fundamental sensory technique for mobile objects' positioning. In particular, the high-precision IMUs provide proper localization and good autonomy at an extra cost. The advances in micro-electro-mechanical systems (MEMS) brought the trade-off between performance, size, and cost, making the acceleration sensors integrated into today's mainstream smartphones. Due to their affordability, we may install consumer-grade IMUs on the metro cars to collect the data needed in the positioning applications.

Data fusion of multiple sensor signals proves to improve the positioning performance by compensating for the drawbacks of a single sensor. Autonomous vehicles usually take advantage of a collection of sensors, like GPS receivers, frontal and lateral video cameras, LiDARs, and many more [1]. In addition to heterogeneous sensors, a priori knowledge can also be integrated to achieve higher positioning accuracy. Various forms of maps and visual landscapes give critical information to adjust the sensor's prediction. Kalman filter algorithm and particle filter algorithm are two widely used data fusion techniques. Aiming at reducing the uncertainty of error covariance and state noise in the system, the Kalman filter integrates the model-based prediction and the state measurement. [2] introduced a sensor fusion method for unmanned surface vehicle navigation based on fuzzy adaptive Unscented Kalman filter (UKF). [3] surveys the research on train positioning with the fusion of GNSS, INS, and Doppler radar signals. Also, surveillance images help to detect the position of a vehicle and can be integrated into the tracking system [4]. Recent research showed the application of some deep learning models in vehicle positioning, and [5] specifically examined the problem of inertial system drift with the help of a deep neural network.

Unlike other solutions that depend on the fusion of several different types of sensors (for example, making available extra information in case one type of sensor fails or severely degrades), in this investigation, we develop a metro car tracking and positioning framework using only low-cost MEMS acceleration sensors. The acceleration readings collected by the low-cost IMUs usually contain significant noise, are compromised by nonlinear gains, and suffer zero-shift errors. To solve these problems, we collect the data from multiple sensors for redundancy to alleviate the negative impacts in the absence of expensive labor-demanding sensor calibration. More specifically, we face two major challenges in the tracking of metro cars: first, the sensory readings are susceptible to unreliable wireless link and might be missing from time to time; second, it is impractical to obtain the real-time speed and distance observations in a realistic operating metro system, and thus we can only find sparse feedback information at the stations. The main contributions of our work include: by placing Bluetooth Low Energy (BLE) beacons at the station platforms, we develop a framework to track the relative displacement of metro cars between stations, using only the accelerometer readings; to handle the problem of lacking real-time speed and distance measurement, we design a simple reference map learned by optimization with the observed acceleration data and the fixed terminal conditions on velocity and displacement. The fusion of IMU data and map matching improves the positioning performance.

The rest of this paper is organized as follows. In Section 1, we briefly review the recent development in the related areas; and then in Section 2, we introduce the denoising and tracking algorithms along with the creation of the reference map. Section 3 discusses the setup of the experiments, data acquisition, and experimental results. Section 4 concludes the current research and provides remarks on our future investigation.

1. Related Work

A positioning and tracking system allows its users to estimate an object's location within a constrained space, with the help of a variety of sensors including those embedded in smartphones and other mobile devices. In typical outdoor environments, GPS has found extensive success in locating stationary and moving objects [6]. In a challenging environment where the GPS signal does not work well, or some special needs have to be satisfied, IMU provides complementary or alternative solutions, without the need for expensive infrastructure. Since MEMS has made remarkable progress recently, IMU becomes an important component in many positioning applications. But the IMU is susceptible to measurement noise, external disturbances, and needs integration over time to estimate the speed and distance states, so the system relying on IMU alone suffers from accumulative errors. Therefore, people exploit particular forms of learned knowledge together with the IMU measurement to jointly improve the positioning results [7]. Visual features, magnometers, and maps help correct the estimation drifts of the IMU [8, 9, 10]. [11] proposed to track the surface train by integrating the BeiDou navigation satellite system and an inertial navigation system and taking odometer and track map matching to compensate for the INS degradation and the blocked BDS signals.

Indoor positioning scenario extends the selection of sensor technologies: Wi-Fi, BLE, UWB, light, and ultrasound signals all bear the underlying information for distance estimation. While some parameters like Angle of Arrival and Time of Arrival need a specialized device to analyze, Wi-Fi and Bluetooth Received Signal Strength Indicators can be detected by regular smartphones [12, 13]. Fingerprinting maps the radio signal strengths to the coordinates of a location. Once the offline radio map gets established, matching the observed RSSIs with the entries in the fingerprints generates the online position prediction.

Both Gaussian process regression and Kalman filter are Bayesian approaches that learn the uncertainty from the temporal samples and derive the optimal decision based on statistical assumptions [14, 15]. In [16], the authors adapted GPR to denoise the CT images taking advantage of the temporal labels. While the non-parametric nature of the Gaussian process makes GPR apply to plenty of functions, the computational load grows fast when the data size increases. [17] introduced a recursive version of GPR, enabling the online regression incorporating new data. By iterative model-based forecast and data assimilation, the Kalman filter facilitates the integration of the information from different sources, and thus applies to the fusion of sensor data and other evidence reflecting the states of interest. The classic Kalman filter theory makes assumptions on the linearity of the system dynamic and Gaussian distribution of the errors. As the Kalman filter variants, extended Kalman filter (EKF) and error-state Kalman filter (ESKF) propagate the state distribution by the first-order linearization of the nonlinear system [18]. On the other hand, the Unscented Kalman Filter (UKF) is a derivative-free alternative only using a deterministic sampling approach to represent the state distributionwith a set selected sample points [19, 2]. Various forms of the Kalman filters are extensively used in multi-sensor fusion for positioning and tracking applications. To overcome the problem of high nonlinearity, in [5], the authors proposed a multi-sensor fusion algorithm for underwater vehicle localization by a radial basis function (RBF) neural network augmented ESKF.

Though people have made solid progress in tracking and locating mobile objects, most solutions in the related research rely on multiple advanced sensors to obtain reliable measurements and sophisticated site survey for the reference fingerprints.

2. Proposed Method

2.1. System Architecture

Table 1 summarizes the workflow of the proposed underground metro car tracking system. The system's hardware consists of the accelerometers, Bluetooth Low Energy (BLE) beacons, and the onboard computer equipped with a BLE probe. Several IMU/BLE devices are attached to the interior walls of a metro car. Each IMU sensor samples the three-dimensional accelerations at a predetermined frequency, and the built-in BLE unit then broadcasts the readings. On the platform of each station, separate BLE beacons are fixed to identify the station.

Instead of estimating the train's absolute position through complex measurement infrastructure, in this study, we only attempt to determine the train's location relative to its previous full stop at a station using the low-cost accelerometers. To simplify, we treat a subway train as a longitudinal rigid body and further approximate a car as a particle. Then the moving train is constrained by a one-dimensional track. Therefore, we only need to solve a one-dimensional dynamic problem, i.e., finding the trains' displacement and velocity. Given the subway track details, this one-dimensional solution can be converted to a three-dimensional earth frame, and then the train can be marked with the absolute coordinates. In the data acquisition setup, the sensors periodically send the three-axis acceleration data through BLE connections to a smartphone or a computer for processing. In a realistic situation, the passengers might be blocking the wireless signal's propagation paths in a crowded metro car. Because the BLE broadcast is prone to interference, there is no guarantee that the probe receives every message transmitted by the BLE beacons. Therefore, besides the measurement noise and variable zero shifts, we also need to handle the data-missing problem. Assuming the underlining properties about acceleration's smoothness and continuity, as shown in Figure 1, we apply Gaussian process regression (GPR) to interpolate in case of missing data. Additionally, we adopt the Kalman filter algorithm to handle the inertial drifts and estimate the train's states by look up the speed and displacement references in a learned map.

Table 1. Metro car online positioning algorithm

Inputs	Offline reference maps for all subway sections
Step 1	Section identification: read platform beacon's ID, find the corresponding section
Step 2	Model-based prediction: use the current GPR result as input to the dynamic model, update the state estimates
Step 3	Map-matching: use the segment of historical and current data to search for the closest reference point, return the matched result
Step 4	Fusion: apply Kalman filter to update the state prediction and parameters
Outputs	Predicted state values

As stated before, we deploy just a simplified type of IMUs (without gyroscopes) in the positioning and tracking of metro cars to save cost. Since the sensors only measure the three-axis accelerations at low precision, different sensors may disagree on the estimates of velocity and displacement as the accumulative errors grow over time. To obtain a better system state estimation, we need to introduce an independent feedback mechanism to provide additional evidence on the train's location. The metro operator has to comply with a strict protocol to serve the public, and therefore a train properly running between two stations stays in three modes: accelerating, maintaining, decelerating. Each stage presents a similar pattern that will be repeatedly followed in the same subway section. We take advantage of these patterns to find the train's mode for the improvement of state prediction. However, since it is unrealistic to survey the running trains for state annotations, we derive the reference patterns by optimizing the functionals satisfying the terminal conditions as well as being in line with the observed data.

2.2. Gaussian process regression and signal preprocessing

Gaussian process regression is a machine learning method using nonparametric models based on strict statistical theory instead of specific domain knowledge. Using Gaussian process regression for interpolation, not only can we predict the optimal acceleration value at each time instant, but we can determine the uncertainty of the data as well. As required by car tracking, we need to estimate the longitudinal acceleration value $a(k)$. First, a set of data measured by the IMUs is selected. Then, this data set is taken as the training set of Gaussian process regression, to denoise the original signal and interpolate for the missing ones.

The critical component in Gaussian process regression is the covariance among variables. The most common forms of covariance functions include Gaussian kernel, linear kernel, and periodic kernel. In this paper, we use the Gaussian kernel functions in the following form:

$$\kappa(x_i, x_j) = \sigma^2 \exp\left(-\frac{||x_i - x_j||_2^2}{2l^2}\right),$$

where parameters σ and l controls the shape of the curve fitting the observed data points, in particular, the scaling factor l influences the curve's smoothness.

Gaussian distribution can be used to estimate the mean value and covariance, and the mean value is taken as the predicted longitudinal acceleration value at each moment, and the covariance is taken as the uncertainty.

$$f(x) \sim \mathcal{N}(\mu(x), \kappa(x, x))$$

where $\mu(\cdot)$ represents the mean function, returning the mean value of each dimension; $\kappa(\cdot,\cdot)$ is the covariance function, representing the correlation of data points.

2.3. System dynamic model

Let $s(k)$, $v(k)$, and $a(k)$ represent the displacement, velocity, and acceleration of the metro car respectively at time instant k; let ω_s and ω_v represent the system noise contained in the displacement and velocity at time k; and denote the sampling period T. The state can be modeled in the vector form:

$$\begin{bmatrix} s(k) \\ v(k) \end{bmatrix} = \begin{bmatrix} 1 & T & \frac{T^2}{2} \\ 0 & 1 & T \end{bmatrix} \begin{bmatrix} s(k-1) \\ v(k-1) \\ a(k-1) \end{bmatrix} + \begin{bmatrix} \omega_s(k-1) \\ \omega_v(k-1) \end{bmatrix}$$

We rewrite the state equation as,

$$X(k) = \Phi(k, k-1)X(k-1) + Ba(k-1) + W(k-1)$$

where the state vector $X(k) = [s(k), v(k)]^T$, $\Phi(k, k-1)$ is the state transition matrix from time point $k-1$ to instant k. Given the current state and the measured acceleration value, we may derive the next state prediction using the system model.

2.4. Reference map generation and online matching

Since there is no direct measurement available for the car's velocity and displacement in between two stations, we have to find an additional estimation of $s(k)$ and $v(k)$ independent of the ones predicted by the model. Moreover, for the same reason, we cannot take fingerprinting-like site survey on a running train. Alternatively, we generate a reference state-acceleration map for the subway section between two consecutive stations using an optimization scheme.

Let $A = \{a(k)|0 \leq k \leq K\}$ be the measured acceleration data in a section, we know that the state starts at $[0,0]^T$ and the velocity goes back to 0 after a train comes to a full stop. In our system setup, the BLE beacons installed on the platforms give us a clear indicator of a station's identity. Denote the unknown reference states as $Z = \{z(k) = [s(k), v(k)]^T | 0 \leq k \leq K\}$. Hence we have the terminal conditions $z(0) = [0,0]^T$ and $z(k) = [dist, 0]^T$, where $dist$ is the known distance between two stations. Within all functionals Z, we require the reference to hold a few important properties: smoothness, conforming to the observation and meeting the terminal conditions.

Consequently, we find the values Z^* for by optimizaing the constrained quadratic form:

$$\min \sum_k ||z(k) - x(k)|| + \alpha ||z(k) - z'(k)||$$

$$s.t. \qquad z(0) = [0,0]^T, z(K) = [dist, 0]^T$$

where $x(k)$ is the state propagated by the model using A, $z'(k)$ is the Gaussian weighted average of the reference states in a specified time interval, and parameter α balances the importance of data term and smoothness term. This quadratic problem can be solved with the simple matrix operations.

We project the data in A into a d-dimensional delayed coordinate phase space P to make the data points $p(k) = [a(k), a(k-1), ..., a(k-d+1)]^T$ spread in that space. The movement of the train is divided into three portions along the time axis: speed-up, gentle change, and slow-down. The center of each portion is calculated then. In the online stage, we first find the coarse match of the measured data by searching the shortest distance to the portion centers; subsequently, we refine the match by the shortest distance to a phase space point within the selected portion. The state in Z^* corresponding to that point is returned as the state estimation. Now we have established a reference map for the section as a mapping $P \to Z^*$.

In practice, the two-step reference map lookup requires little computation and storage because a subway section contains the observation data sampled at low frequency in the period lasting only a couple of minutes.

2.5. Kalman filter and data fusion

Kalman filter is a recursive linear estimator. Relying on the periodic observations of the state, it continuously estimates the state value changes over time. The recursive steps involved in the Kalman filter algorithm of distance and speed estimation include: predicting the new state using the dynamic model and the previous state; then using the reference map match result to correct the prediction for the optimal estimation of the next state; finally updating the parameters in the dynamic state equation.

Then Kalman filtering can be expressed as the following process:

(1) Temporal updating

$$X(k,k-1) = \Phi(k,k-1)X(k-1)$$
$$P(k,k-1) = \Phi(k,k-1)P(k-1)\Phi^T(k,k-1) + \Gamma Q(k-1)\Gamma^T$$

(2) Measurement updating

$$X(k) = X(k,k-1) + K(k)(Z(k) - HX(k,k-1))$$
$$K(k) = P(k,k-1)H^T(HP(k,k-1)H^T + X(k,k-1))$$
$$P(k) = (I - K(k)H)P(k,k-1)$$

where, $X(k,k-1)$ represents the predicted value of the state based on information available at time $k-1$, $K(k)$ is the Kalman gain, and $P(k,k-1)$ represents the error covariance with respect to $X(k,k-1)$; $P(k-1)$ is the estimation error variance matrix at time k; H is the sensor measurement matrix, I stands for the identity matrix, and $Z(k)$ represents the reference map matching values at instant k.

The positioning and tracking routine works as follows: given the initial state $X(0)$ of the metro car and the arbitrarily set initial error $P(0)$, the optimal state estimation $X(k)$ is achieved with the update of Kalman gain $K(k)$ based on the sensor measurement. As mentioned earlier, the consumer-grade low-cost sensors may have different uncalibrated zero shifts, therefore, we deploy multiple sensors at the same time, and take the average value of the online GPR processed reults as the acceleration input.

3. Experiment Results

We tested the tracking system in Wuhan Metro Line 2. Wuhan Metro Line 2 is the first metro line crossing the Yangtze River via a tunnel in China. Wuhan Metro Line 2, starting from Tianhe Airport Station and ending at the Fozuling station, has a length of 60.8km, with 38 stations in total. The number of daily average passengers is over 100,000.

Four low-cost MEMS accelerometers with built-in BLE transmitters were attached to the walls inside a car. A laptop computer connected with a signal receiver (probe) was used to collect the acceleration data. Both accelerometers and BLE units were commercial off-the-shelf products. In the experiments, three accelerometers were installed in the front, rear, and middle of the car on the same side, and the fourth one was installed in the middle of the car on the other side. The tests were carried out in 24 sections (between 25 stations). Throughout the experiments, we set the sampling frequency of the accelerometer to 1 Hz. To verify the effectiveness of this method, we conducted field tests in Wuhan Metro Line 2 and placed the beacon on the platforms of all stations of line 2 to identify the stations. The field tests were performed between December 2020 and March 2021 at different times of the day, and on different days in a week. In the actual experiments, our probe might fail to receive all data from a single beacon, but the redundancy in multiple sensors ensured at least one measurement be successfully received per second.

Figure 1 displays the GPR smoothing result for a sensor's measurements in a section. The stages were partitioned by the end and the start of the steepest slope representing the beginning of decelerations. In Figure 2, we can find that the averaging outcome of the multiple sensors' readings has almost corrected the zero drifts. The coarse match of the reference map depends on the comparison of distances from the current IMU data to the centers of learned modes. By projecting to the high-dimensional space, each point in the phase space represents a segment of acceleration history.

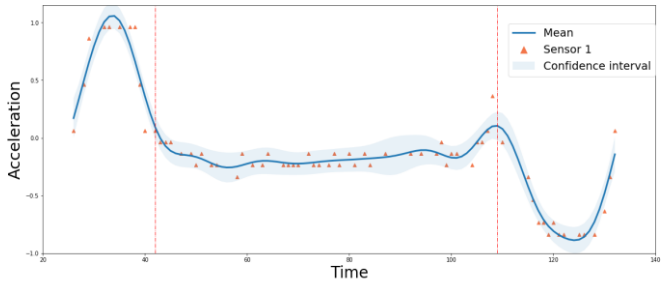

Figure 1. GPR result for a single sensor (acceleration in m/s^2, time in second)

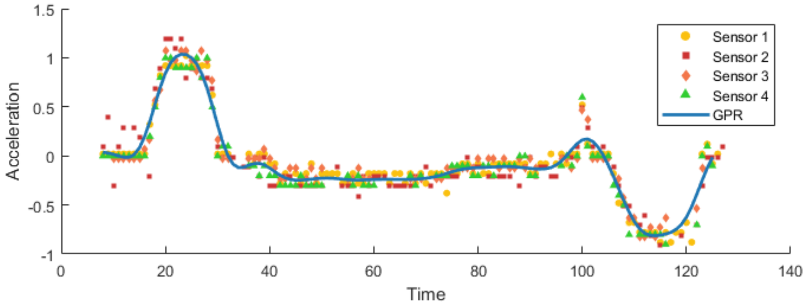

Figure 2. Sensor measurments and the GPR result (acceleration in m/s^2, time in second)

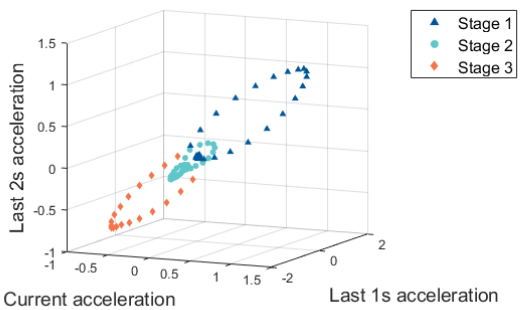

Figure 3. Phase space representations of points in different stages (only showing 3 dimensions)

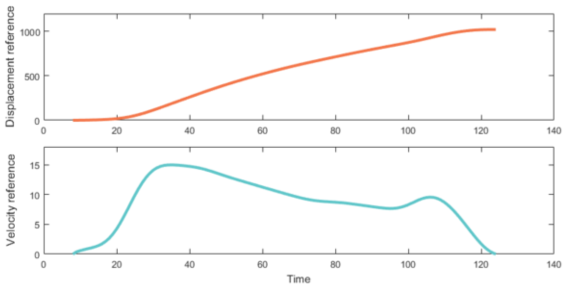

Figure 4. Reference displacement (m) and velocity (m/s)

Figure 3 shows that the points in different modes spread over a big area except for those in the speed-maintaining stage. In Figure 4 are the reference maps for speed and distance. There was a fluctuation in periods for the trains running between two stations, as found in our tests.

As illustrated in Figure 5, the model-based prediction depending only on IMU drifts severely over time. The fusion of IMU and reference map matching helps contain the estimate errors.

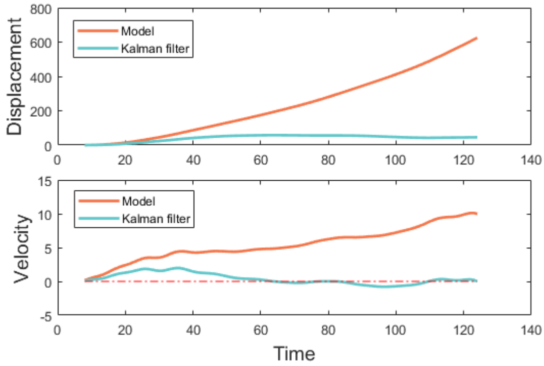

Figure 5. Prediction errors of displacement (m) and velocity (m/s)

Table 2. The predicted states at the end of each section

Section		1	2	3	4	5	6	7	8
v (m/s)	**Predicted**	0.03	0.26	0.09	0.15	0.06	0.19	0.28	0.08
s (m)	**Actual**	1021	1999	1603	2038	1059	1487	1368	817
	Predicted	975	1957	1582	2066	1050	1464	1315	815

Section		9	10	11	12	13	14	15	16
v (m/s)	**Predicted**	0.05	0.65	0.43	0.25	0.12	0.05	0.23	0.19
s (m)	**Actual**	1009	1317	1442	794	1613	951	1238	1418
	Predicted	982	1251	1395	800	1577	936	1202	1386

Section		17	18	19	20	21	22	23	24
v (m/s)	**Predicted**	0.01	0.23	0.16	0.01	0.33	0.39	0.44	0.16
s (m)	**Actual**	966	1168	930	966	3292	897	1543	946
	Predicted	953	1112	905	953	3205	889	1499	922

In the experiments, we randomly picked the data collected from one trip as the training set to learn the reference map and tested the proposed online tracking algorithm with the rest of the data. The cross-validation results listed in Table 2 indicate that the data fusion framework presented a distance estimation within a 5% error range, and the predicted velocity was close to 0 when the train stopped (with RMSE of about 0.4m/s).

4. Discussion and Conclusions

In this work, we proposed a framework for tracking underground metro cars, which can be extended into similar scenarios like a coal mine. Tracking and positioning metro trains are the foundation for many location-based services, including assisting the decision-making for the metro operators. Real-time positioning requires a balance among several factors, most importantly, cost and performance. In the proposal, we only deployed the consumer-grade low-cost acceleration sensors and BLE beacons in cars and on platforms. To confront the accumulative errors introduced by IMU and the dynamic model, we designed a reference map that took advantage of the train's moving patterns in a between-station track section. By applying a simple Kalman filter to integrate the model-IMU prediction and the map-matching outcome, we achieved a positioning accuracy at the error below 5% on arriving at the next stop. In the future, we will focus on improving the dynamic model and refining the online reference map for better tracking results.

References

[1] G. Wan, X. Yang, R. Cai and et al, Robust and Precise Vehicle Localization based on Multi-sensor Fusion in Diverse City Scenes, In: *2018 IEEE International Conference on Robotics and Automation (ICRA)*, Brisbane, QLD, Australia, 2018, pp. 4670-4677.

[2] W. Liu, Y. Liu and R. Bucknall, A Robust Localization Method for Unmanned Surface Vehicle (USV) Navigation Using Fuzzy Adaptive Kalman Filtering, *IEEE Access*, 2019, Vol. 7, pp. 46071-46083.

[3] J. Otegui, A. Bahillo, I. Lopetegi and et al, A Survey of Train Positioning Solutions, *IEEE Sensors Journal*, 2017, Vol. 17, No. 20, pp. 6788–6797.

[4] Y. Zhang, B. Song, X. Du and et al, Vehicle Tracking Using Surveillance With Multimodal Data Fusion, *IEEE Transactions on Intelligent Transportation Systems*, 2018, Vol. 19, pp. 2353–2361.

[5] N. Shaukat, A. Ali, I. Javed and et al, Multi-Sensor Fusion for Underwater Vehicle Localization by Augmentation of RBF Neural Network and Error-State Kalman Filter, 2021, *Sensors*, 21, 1149.

[6] H. Kim and I. Lee, Localization of a CAR Based on Multi-sensor Fusion. ISPRS - International Archives of the Photogrammetry, *Remote Sensing and Spatial Information Sciences*, 2018, vol. 621, pp. 247–250.

[7] H. Zhao, Z. Wang, S. Qiu and et al, Heading Drift Reduction for Foot-Mounted Inertial Navigation System via Multi-Sensor Fusion and Dual-Gait Analysis, *IEEE Sensors Journal*, 2019, Vol. 19, no. 19, pp. 8514-8521.

[8] S. Qiu, Z. Wang, H. Zhao and et al, Inertial/Magnetic Sensors Based Pedestrian Dead Reckoning by Means of Multi-Sensor Fusion, *Information Fusion*, 2018, Vol. 39, pp. 108–119.

[9] D. Li, W. Yang, X. Shi and et al, A Visual-Inertial Localization Method for Unmanned Aerial Vehicle in Underground Tunnel Dynamic Environments, 2020, *IEEE Access*, Vol. 8, pp. 76809-76822.

[10] G. Huang, Z. Hu, Q. Tao and et al, Improved intelligent vehicle self-localization with integration of sparse visual map and high-speed pavement visual odometry, In: *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering*, 2021, Vol. 235, pp. 177-187.

[11] W. Jiang, S. Chen, B. Cai and et al, A Multi-Sensor Positioning Method-Based Train Localization System for Low Density Line, *IEEE Transactions on Vehicular Technology*, 2018, Vol. 67, No. 11, pp. 10425-10437.

[12] C. Zhou, J. Yuan, H. Liu and et al, Bluetooth Indoor Positioning Based on RSSI and Kalman Filter, *Wireless Pers Commun*, 2017, Vol. 96, pp. 4115–4130.

[13] H. Huang, C. Hsieh, K. Liu and et al, Multi-Sensor Fusion Approach for Improving Map-Based Indoor Pedestrian Localization, *Sensors*, 2019, Vol. 19, no. 17, 3786.

[14] S. Roberts, M. Osborne, M. Ebden and et al, Gaussian processes for time-series modelling, *Philosophical Transactions of the Royal Society A*, 2013, 371: 20110550.

[15] S. Miah, E. Milonidis, I. Kaparias and et al, An Innovative Multi-Sensor Fusion Algorithm to Enhance Positioning Accuracy of an Instrumented Bicycle, *IEEE Transactions on Intelligent Transportation Systems*, 2020, Vol. 21, No. 3, pp. 1145-1153.

[16] F. Zhu, T. Carpenter, D. Gonzalez and et al, Computed Tomography Perfusion Imaging Denoising Using Gaussian Process Regression, *Physics in Medicine and Biology*, 2012, Vol. 57, no. 12, N183-198.

[17] M. Huber, Recursive Gaussian Process: On-Line Regression and Learning, *Pattern Recognition Letters*, 2014, Vol. 45, pp. 85–91.

[18] D. Jeon and H. Choi, Multi-sensor fusion for vehicle localization in real environment, In: *2015 15th International Conference on Control, Automation and Systems (ICCAS)*, Busan, Korea (South), 2015, pp. 411-415.

[19] H. Li, H. Guo, Y. Qi and et al, Research on Multi-Sensor Pedestrian Dead Reckoning Method with UKF Algorithm, *Measurement*, 2021, Vol. 169, 108524.

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Aspects on a Digitalized Industrialization Process: Are There Challenges to Overcome?

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Abstract. Increased possibilities to utilize digital tools in the industrialization process where a product move from conceptualization toward mass production is challenged with how to develop resilience in such process. Several digital tools such as CAD, CAE, Production flow analysis, assembly analysis, and off-line programming of robots and CNC machines are commonly used in industry for both product development and production. There are also many good initiatives such as computational multidisciplinary design optimization or design automation in the aircraft industry to integrate such digital tools and increase the efficiency of the generating and distributing of information. However to maximize the benefit of digitalization, a fully digitalized platform is required where all parties including the product development team, manufacturing resources, suppliers, and even customers can contribute efficiently. Although establishing such a digitilized platform seems very promising, it confronts many challenges in a large firm. Hence, this paper, based on a theoretical outlook related to industrial observations, will explore challenges and opportunities related to the digitalization of product development and the manufacturing process.

Keywords. Digitalization, Product development, Manufacturing industry

Introduction

Product life cycle (PLC) encompasses the time from product introduction to the market until it is removed from the shelves and not possible to buy any longer. It has four stages - introduction, growth, maturity, and decline [1-3]. While some products may stay in a prolonged maturity state, all products eventually are phased out due to e.g., market saturation, increased competition, and decreased demand. However, many high-tech products are characterized by short PLCs. According to prior research [4], the products where designers spend more time on engineering and development have lengthier PLCs. These products, however, require continuous adjustment and updates with changing customer requirements [4], which increases the need for the ability to manage different variants with flexibility both in the design as well as manufacturing process [5].

Development of a product with a long-life cycle e.g., aircraft; consist of a large number of interconnected activities, which are normally partitioned into several phases such as Design, Production, Operation, and Decommissioning [4],[6]. The design phase comprises market research, requirements specification, conception, design management, overall design (including design for X), and design of components. Production includes selection and development of production technologies, production planning and management, supply of materials and components, manufacturing, assembly, testing, and quality assurance. Operation includes the scheduling and management of the use of aircraft and its crew within a fleet; the maintenance and repair tasks and resources; and the logistics support tasks and resources. Decommissioning consists of safe disposal and recycling of components and/or materials.

The current practice is to consider each phase of the lifecycle separately managed by different teams of specialists, often from different organizations, with limited interactions between them [4] or that the different organizations are coordinating all communication in a network [7]. Based on observations in the studied company, there is no central lifecycle management team charged with coordinating all activities from product idea to its disposal and recycling. Moreover, each phase of the lifecycle is normally supported by stand-alone computer systems, such as computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), enterprise resource planning (ERP), and various production and logistic schedulers, which are rarely fully compatible with each other and never integrated into a single lifecycle system. This contributes to key lifecycle activities with no connections between them, and thus delays the useful flow of information, particularly feedback from manufacturing, assembly, operation, maintenance, and support to design. Consequently, designers have no real-time access to data on failure analysis, which is necessary to understand the relationship between failures and design decisions. Nevertheless, the safety record of the aircraft industry is excellent. That is why manufacturing companies that develop products with long life cycles strive to improve management of the complexities while maintaining or improving current levels of safety. This example that has been observed, links to the challenge of linking different tools to support transdisciplinary interaction across different phases in a design phase [8] as well as between different phases in the PLC and keep an excellent safety record in the aircraft industry.

With an increase of digitalization during production, it becomes easy to gather information during the production phase and provide immediate input to what is going on with a product in operations [9-10]. From a production system perspective, it is common to use simulation software e.g., production flow analysis, assembly analysis, and off-line programming of robots and CNC machines [11]. However, companies that move towards full digitalization and automation of engineering processes that are necessary for integrated product and production development face various challenges [10]. That is why; this paper explores challenges and opportunities related to the digitalization of product development and manufacturing process. The industrialization process is a part of the production phase and it is associated with all the activities that are necessary to prepare a product for production [12], [13]. The success of an industrialization process is affected by how well product and production development are integrated [14].

1. Product development and digitalization reform

Manufacturing industries in general and the aerospace industry particularly are trying to improve product profitability by streamlining the product development process (PDP). One trend is that companies implement novel PDPs for more innovative products with less development time. However, this is a challenge for industries dealing with complex products that consist of thousands of parts, design routines, design evaluation points, where product development takes more than 10 years. Hence, digitalization seems like one of the most important solutions at hand. However, the digitalization of a complex PDP in a large company is challenging and not straightforward. Furthermore, digitalization is a general word that can be interpreted differently in various contexts. Nowadays almost all companies benefit from digitalization to some degree. In this study, fully digitalized PDP is referred to as a process where all parties such as design engineers, manufacturing teams, and even external parties can contribute. A fully digitalized platform includes many software tools that need to be managed appropriately. This requires many interdisciplinary and transdisciplinary collaboration within the organization that may not be easily achieved [8],[15]. It has been proven beneficial to integrate manufacturing knowledge, suppliers, and customers early into a design process [16-21]. This helps to decrease the probability of problems later in the development process. Typically, PDPs used in manufacturing industries consist of linear or transitional phases and routines, as well as decentralized information flow. In this approach, the product information increases and transfers to later stages as the product develops. However, it is not so efficient to involve more parties in the product development with less interruption. Therefore, a data-centric approach is proposed to evolve more information (external parties) into the product development process efficiently. It has been proven that many advanced PDP techniques such as multidisciplinary design optimization (MDO), collaborative multidisciplinary design optimization (CMDO), and even Interdisciplinary design (ID) are more efficient using data-centric architecture [22-23]. In this approach, information from each discipline is collected in a database, which is accessible by other disciplines in the PDP. This is where Product Lifecycle Management (PLM) and Product Data Management (PDM) tools could be very helpful to track the information flow and facilitate the accessibility of such knowledge. The data-centric approach is used to facilitate communications among design teams, share information and manage complexity [24]. The fully digitalized PDP in this paper is referred to as a data-centric product development approach [24-26].

2. Smart manufacturing

The goal of smart manufacturing or its synonym “Industry 4.0” is to automate manufacturing processes, were fully integrated and collaborative manufacturing systems rapidly can respond to meet the demand and conditions. Frank et al. [9] explore the pattern about how emerging technologies related to "Industry 4.0" are implemented in the industry up until now, but also exploring the lack of understanding of how to implement these technologies. These emerging technologies, in combination with the increased digitalization, challenge the IT infrastructure [27], and if implemented they need to be managed concerning efficiency, productivity, and flexibility [28]. To manage Machine-to-Machine (M2M) communication and other Internet of Things (IoT) solutions, the traditional manufacturing environment is changing from material flow to information flow, which emphasizes the role of data management in the success of smart manufacturing [29]. However, elements related to organization and work procedures are not a primary concern in early industrial development phases [30], which indicates that a transition towards smart manufacturing must include more than just technical implementation.

3. Methodology

This study is based on observations of a research project at SAAB Aeronautics that was about the digital transformation of the PDP, from now on referred to as *Transform Project.* The project aimed at enhancing and speeding up the PDP using state of an art digitalization approach. The subject of observation was the Transform Project and its set up both technically and administratively. One of the authors of this paper was involved in the Transform Project as a domain expert and carried out the observations of the challenges and opportunities related to the transformation to fully digitalized PDP. The project team consisted of 2 conceptual engineers, 6 domain experts, and one project manager acting as a data architecture. The team used the PLM system to share data. The observations were carried from early brainstorming sessions and later throughout the project. Observations were carried out during weekly project meetings, daily e-mails exchanged between the project manager and the team members. Furthermore, observations took place during four training sessions, where team members got familiar with the software tools. During observations, notes were taken with a focus on challenges and opportunities during the digital transformation.

In addition to the observations, informal semi-structured interviews with four experienced professionals involved in digital transformation at SAAB Aeronautics were carried out [31]. The interviewees were two domain experts, a line manager, and the research coordinator. The informal interviews included questions about the informants' experience with the digitalization process, and what were the general challenges and opportunities involved in such a process.

The data analysis followed the steps prescribed by Miles et al., namely data condensation, data display, and conclusion drawing/ verification [34]. To triangulate the collected data, evidence from different key respondents and through different methods was collected. Through interviews and observations, challenges and opportunities with digital transformation were brought forward. To strengthen the internal validity, enfolding of literature during the analysis was carried out [35-36]. Contrasting literature to empirical findings was crucial for strengthening the external validity of this study.

4. Empirical material

4.1. Digitalization concept in the product development process

The observed challenges for the product development team were gathering/generating design information and its efficient sharing. It was observed that the team preferred to change the traditional sequential data access approach, see Figure 1, to a data-centric approach. The data-centric approach was proven to be efficient at SAAB. In this approach, the generated data was accessible upon all product generations to all design parties through a centralized data center. Concerning this approach, several challenges and possibilities were observed, see Figure 2.

Figure 1. Management of data in Decentralized PDP (conventional)

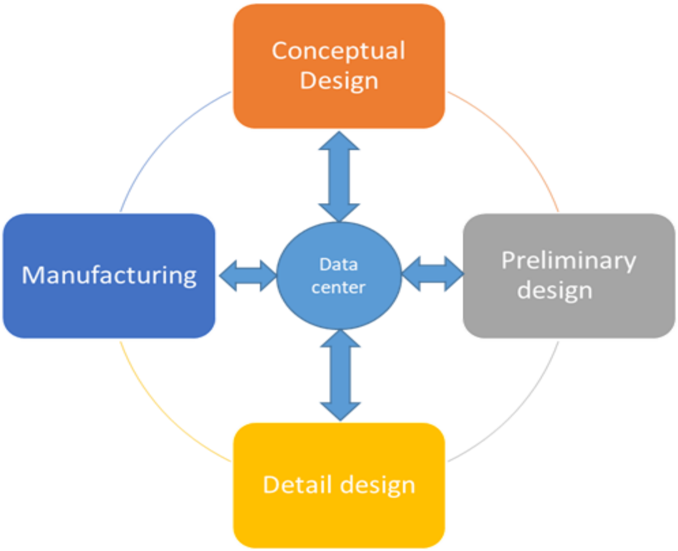

Figure 2. Management of data in Centralized PDP (future approach)

4.2. Project organization

Observation during the Transform Project showed tremendous organizational challenges where the interdisciplinary and transdisciplinary links between departments, divisions, and even product development groups were missing. SAAB used a decentralized organizational chart with many hierarchies. The project team as an issue when implementing a data-centric approach because various decisions had to be shared fast with all concerned employees pointed this. This was also confirmed during the interviews with the experienced professionals involved in digitalization transformation at SAAB. To avoid this organizational challenge, the project manager was acting as a data center. The role of the project manager was to share all managerial information among the team using daily email and weekly meetings. However, the observation showed that at the beginning of the project the team members had difficulties understanding each other due to a lack of knowledge about each other's domains. To increase integration the project manager set up weekly meetings where each domain expert provided knowledge about the domain, potentials, and limitations. Observations revealed that during one early meeting some domain experts complained about the unbalanced workload between their routine job and their involvement in the Transform Project. As a result, the project manager had to discuss this issue with all line managers requesting allocation of more time of the domain experts needed in the Transform Project.

4.3. IT infrastructure

Observation showed that the team faced many IT difficulties from hardware to software and cyber securities. Some of the project team members were not equipped with proper hardware capable of running the software efficiently. The team was faced with a cybersecurity problem early in the Transform Project, as it was not allowed to install new software on the existing IT infrastructure. This was a very important challenge that took weeks and hundreds of person-hours to solve. The team had to run a dedicated IT system locally to avoid the IT regulatory of the company. This provided many challenges for the team to overcome various IT problems. Another issue that had raised during the interview is the reliability of the new software and its generated results. The interviewee mentioned that it took about a year to decide if the used software in the Transform project was reliable enough to start with or not. Observations showed that the lack of knowledge of the experts about the new software was yet another challenge. As previously stated, the team manager set up training sessions for the project team members so that they could get familiar with the new tools.

Table 1. Summary of the findingS during observationS and interviewS

Aspect	Observations	Interviews
Digitalization concept	• Moving from sequential PDP to data-centric PDP	• Digitalization was necessary for information generation and distribution
Project organization	• Agile team for proof of concept was created	• Organizational changes were needed to remove decision-making bottlenecks • Lack of experts equipped with knowledge of digitalization was a concern
IT infrastructure	• Hardware update was required • A software update was required • A dedicated IT system was required • Training of the team member was required	• A software update was required to support a data-centric approach • Cybersecurity was a challenge • Reliability of the results was a challenge • Education and training of the engineers was a challenge

5. Analysis and discussion

The findings indicated that moving from semi-digitized PDP to fully digitalized PDP was not an easy task. During the digital transformation organizational challenges related to missing interdisciplinary and transdisciplinary links between departments, divisions, or product development groups could be encountered. The findings showed that old-fashioned organizational charts with many hierarchical levels could challenge the digital transformation aiming at centralization of the information flow and open-access information. Based on the findings, this study emphasizes that a centralized information flow platform may be promising for fully digitized PDP. The findings showed that applying fully digitalized PDP required specialized expertise. To achieve the required level of expertise a remedy was in-house training of employees, which was less costly and more efficient compared to hiring new employees. The lack of expertise in digital product architecture and integration is also stressed in the prior research [8].

One problem that might occur about the digital transformation is the employees' motivation. Introducing changes in organizations is not an easy task and employees could be reluctant and hesitant to the changes [43]. The related organizational challenge was the unbalanced level of digitalization for various departments, which needed to be taken into consideration when planning for digital transformation. This finding was in line [38] stressing the need for a review and update of work procedures as well as organizational development. Moreover, the findings showed that involving suppliers and customers in the digital transformation is important for companies that want to maintain relationships with external parties.

The findings showed that establishing a stable IT infrastructure to support digitalized PDP and manufacturing was not an easy task. Moving towards more advanced digital tools required machines with high computational capabilities and new hardware. Apart from the high cost, the hardware systems required training, support, maintenance, and more importantly continuous updating over a timeframe.

The conventional software was used as stand-alone and dedicated to a specific domain. However, the digital transformation required higher collaboration from other domain experts and therefore the architecture of the information flow had also to be changed. Fortunately, there are many advanced approaches such as MDO, PLM, and PDM, to integrate domain expert's knowledge into a knowledge-sharing platform [44]. However, the findings showed that there was a lack of expertise to efficiently deal with the new software, not just on the users' side (domain experts and engineers) but also on the support and services side.

Nowadays there are many commercial computational digital tools e.g., from MS excel to Matlab, CAD, and CAE which are used in the PDP [45]. However, the findings of this study showed that the integration of these tools to a centralized digital platform was challenging. Although there are some commercial integrator tools available such as ModeFrontier [39], Heeds [40], 3Dexperience [41], etc., the study showed that dealing with such tools was not an easy task in the industry. This was mainly because of the lack of extensive knowledge available in the industry.

Companies have experience with digital tools and are familiar with which tools are suitable for what tasks, what are the gains and the limitation and more importantly how reliable these tools are [46]. This is very valuable knowledge that companies gain over the years. The findings of this study showed that knowledge about the reliability of the tools and the creditability of the results was accumulated during many design iterations and validations. Therefore, changing the tools or the PDP in a well-established company with many years of experience was perceived as risky in terms of losing such reliability and creditability. The findings showed that there was a need to verify and validate the results of the new digital tools based on real use case data over time. In a fully digitalized PDP with many tools involved, this evaluation and validation was not an easy task as uncertainty in one tool may propagate to the others. Hence, companies that embark on a digital transformation journey need to have the capabilities to manage uncertainties and establish plans and methods for reviewing the design and outcomes of the tools.

6. Conclusions and outlook

The findings of this study are summarized in Table 1 and show that digital transformation brings several organizational and technical challenges.

To conclude, this study stresses that it is important to establish a clear vision for digitalization before the transformation process commences. A well-defined strategy to reach the vision for digitalization and new metrics that will capture progress towards that vision is needed. The vision has been defined under Industry 4.0 where front-end technologies consist of four dimensions: Smart Manufacturing, Smart Products, Smart

Supply Chain, and Smart Working [9]. To achieve this, it is required to employ four base elements as the Internet of Things, cloud services, big data, and analytics. This study puts forward that a digital vision needs to consider companies' existing core competencies and strengths.

Digital transformation requires not only selecting the right technology but also implementing this technology in a company's core. However, a company cannot get the full benefits of digitalization until reaching digital maturity [42]. Digital maturity is achieved when integration of the operations and human capital of a company is done successfully into digital processes and vice versa [42]. Digitally mature companies understand the importance of technology adoption. If an employee cannot benefit from the features and advantages conferred by digitalization, companies will not see a positive return on investment [30]. That is why, as this study points out it is essential to establish effective training for the employees to adopt the new digital tools.

Cybersecurity and reliability analysis is another important factor that digitally mature companies need to consider [27]. Digitalization without proper planning of the security and reliability of a system can attract malicious users who aim to infiltrate weaknesses within the systems for their gain, referred to as cybersecurity attacks.

This study also points out that there is a lack of a digital system architect who can have a holistic view and understand the different phases of the PDP process including data generation and dataflow. An architect should have a good understanding of a company's digital environment and the associated limitations and potentials. The role of an architect could be to help the domain expert to develop digital models that could efficiently be integrated into a company's centralized digital platform. This study points out a gap between the company's need for expertise, including a deep understanding of architecture technologies both on domain and integration levels, and the specialists at the work market. The identified gap put higher demands on the universities to develop specialists who are knowledgeable in managing this transdisciplinary challenge.

This study discusses plenty of challenges that could potentially reduce the importance of the benefits that companies could achieve by undertaking digital transformation using the right tools and processes. For example, by achieving a higher degree of integration of product development and manufacturing through digitalization companies have opportunities to smooth their industrialization process. Better integration will provide the opportunity for companies to deal with interdependencies of product engineers' and manufacturing engineers' tasks as early as possible in the development process and avoid potential engineering changes later in the PDP. It is important to detect the need for engineering changes as early as possible because product changes become more expensive and harder to manage the later they are implemented [13]. The opportunities for companies with digitalization are summarized below:

- Companies can keep or even increase their competitive advantage.
- Companies' management team can collect valuable information about assets, processes, products, and customers.
- Companies can retain market share less costly.
- Companies can gain higher profitability when more efficient processes are implemented.
- Companies can improve PDP, production efficiency, machine uptime, performance, and even consumed materials.

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References

[1] C.R. Anderson and C.P. Zeithmal, Stage of the Product Life Cycle, Business Strategy, and Business Performance, *Academy of Management Journal*, 1984, Vol. 27 No. 1, pp. 5-24.
[2] G. Day, The Product Life Cycle: Analysis and Applications Issues. *J of Marketing*, 1981, Vol 45(4), pp. 60-67.
[3] D.R. Rink and J.E. Swan, Product life cycle research: A literature review, *Journal of Business Research*, 1979, Vol. 7, (3), pp. 219-242.
[4] M. Price, D. Soban, C. Mullen, J. Butterfield and A. Murphy, A novel method to enable tradeoffs across the whole product life of an aircraft using value-driven design, *Journal of Aerospace Operations*, 2012, Vol.1(4), pp. 359-375.
[5] A. Oke, A framework for analyzing manufacturing flexibility, *Int. J. of Operations & Production Management*, 2005, Vol. 25, No. 10, pp. 973–996.
[6] S. Jones and G. A. Zsidisin., Performance implications of product life cycle extension: The case of the A-10 aircraft. *Journal of Business Logistics*, 2008, Vol. 29, pp. 189-214.
[7] K. Johansen, M. Comstock, M. Winroth, Coordination in collaborative manufacturing mega-networks: A case study, *In. J. of Engineering and Technology Management*, 2005, Vol. 22, pp. 226-244.
[8] M. Goudswaard, B. Hicks, L. Newnes, An Appraisal and Classification of the Transdisciplinarity of Existing Design Tools, *Advances in Transdisciplinary Engineering*, 2020, Vol. 12, pp. 50-59.
[9] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić and W.J.C. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 753-762.
[10] A. Schumacher and W. Sihn, A Strategy Guidance Model to Realize Industrial Digitalization in Production Companies. *J of Management and Production Engineering Review*, 2020, Vol. 11(3), pp. 14-25.
[11] K. Thoben, S. Wiesner and T. Wuest, Industrie 4.0 and Smart Manufacturing – A Review of Research Issues and Application Examples, *Int Journal of Automation Technology*, 2017, Vol. 11. pp. 4-19.
[12] Le Dain M., Calvi, R., & Cheriti S., Measuring supplier performance in collaborative design: Proposition of a framework. Journal of R&D Management. 41. 2010.
[13] Wlazlak P., Eriksson Y., Johansson G., & Ahlin P., Visual representations for communication in geographically distributed new product development projects, J of Eng Design, 30:8-9, 2019, pp.385-403.
[14] P. Wlazlak, K. Säfsten and P. Hilletofth, Original equipment manufacturer (OEM)-supplier integration to prepare for production ramp-up, *Journal of Manufacturing Technology Management*, 2019, Vol. 30, No. 2, pp. 506-530.
[15] O. Khan, T. Stolte, A. Creazza and Z.N. Lee Hansen, Integrating product design into the supply chain, *Cogent Engineering*, 2016, Vol. 3, Issue 1, 1210478.
[16] K.E. Gruner, C. Homburg, Does customer interaction enhance new product success?, *In. J. of Business Research*, 2000, Vol 49 (1), pp. 1-14.
[17] X Huang, G.N. Soutar, A. Brown, New product development processes in small and medium-sized enterprises: Some Australian evidence, *J. of Small Business Management*, 2000, Vol 40 (1), pp. 27-42.
[18] D.W. LaBahn, Early supplier involvement in customer new product development: A contingency model of component supplier intentions, *Journal of Business Research*, 2000, Vol. 47 (3), pp. 173-190.
[19] M. Swink, Threats to new product manufacturability and the effects of development team integration processes, *Journal of Operations Management*, 1999, Vol. 17 (6), pp. 691-709.
[20] S.P. Leo Kumar, Knowledge-based expert system in manufacturing planning: state-of-the-art review, *International Journal of Production Research*, 2019, Vol. 57 (15–16), pp. 4766-4790.
[21] M. El Souri, J. Gao, C. Simmonds, Integrating manufacturing knowledge with the design process to improve quality in the aerospace industry, *Procedia CIRP*, 2019, Vol 84, pp. 374-379.
[22] E. Safavi, *Collaborative Multidisciplinary Design Optimization for Conceptual Design of Complex Products*, PhD. dissertation, Linköping University, 2016, https://doi.org/10.3384/diss.diva-131792.

[23] S.J. Culley, B.J. Hicks, T.C. McAloon, T.J. Howard and Y. Reich, Dimensions of objectives in interdisciplinary product development projects, DS 68-2: *Proceedings of the 18th Int Conference on Engineering Design (ICED 11)*, Impacting Society through Engineering Design, Vol. 2: Design Theory and Research Methodology, Lyngby/Copenhagen, Denmark, 15.-19.08.2011, pp 256-265.
[24] D. Kohr, M. Ahmad, B. Alkan, M. Chinnathai, L. Budde, D. Vera, T. Friedli and R. Harrison, Proposing a Holistic Framework for the Assessment and Management of Manufacturing Complexity through Data-centric and Human-centric Approaches, *Proceedings of the 3rd International Conference on Complexity, Future Information Systems and Risk*, Madeira/Portugal, 2018, pp. 86-93.
[25] D. Zahay, A. Griffin, E. Fredericks, Sources, uses, and forms of data in the new product development process, *Industrial Marketing Management*, 2004, Vol. 33, Issue 7, pp. 657-666.
[26] W.D. Li and Z.M. Qiu, State-of-the-art technologies and methodologies for collaborative product development systems, *International Journal of Production Research*, 2006, Vol. 44:13, pp. 2525-2559.
[27] R. Ande, B. Adebisi, M. Hammoudeh, J. Saleem, Internet of Things: Evolution and Technologies from a Security Perspective, *Journal of Sustainable Cities and Society*, 2019, Vol 54, pp.10-16.
[28] E. Oztemel and E. Gursev, Literature review of Industry 4.0 and related technologies, *Journal of Intelligent Manufacturing*, 2020, Vol. 31, pp. 127–182.
[29] K. Schwab, *The Fourth Industrial Revolution*. Crown Publishing Group, New York, 2017.
[30] J. Wiklund, T. Baker and D. Shepherd, The age-effect of financial indicators as buffers against the liability of newness, *In. J. of Business Venturing*, Vol. 25(4), 2010, pp. 423-437.
[31] SAAB, SAAB Technologies, 2021, Accessed: 14.03.2021. [Online]. Available: www.SAAB.com
[32] FCAS, Future-Combat-Air-System, Accessed 14.03.21 [Online] available https://www.airbus.com/newsroom/stories/Future-Combat-Air-System-Owning-the-sky-with-the-Next-Generation-Weapons-System.html
[33] Open CPS, Accessed 14.03.2021. [Online] available https://opencps.eu/
[34] M.B. Miles, A.M. Huberman and J. Saldana, *Qualitative analysis: a methods sourcebook*. 3rd ed, SAGE, Los Angeles, 2014.
[35] M.K. Eisenhardt, Building theories from case study research. *The Academy of Management Review*, 1989, Vol 14 (4), pp. 532-550.
[36] C. Voss, N. Tsikriktsis and M. Frohlich, Case research in operations management. *International Journal of Operations and Production Management*, 2002, Vol 22 (2), pp. 195-219.
[37] S. Jamshed, Qualitative research method-interviewing and observation, *J. Basic Clin Pharm.*, 2014, Vol 5(4), pp. 87-88.
[38] J. Wiklund, T. Baker and D. Shepherd, The age-effect of financial indicators as buffers against the liability of newness. *Journal of Business Venturing*, Vol. 25(4), 2010, pp. 423-437.
[39] Modefrontier, the Multidisciplinary design optimization software, accessed 14.03.2021 [online] available https://www.esteco.com/modefrontier.
[40] Heeds, design exploration and optimization software, accessed 14.03.2021, [online] available https://www.redcedartech.com/index.php/solutions/heeds-software
[41] 3d experience, accessed 14.03.2021, [online] available https://www.3ds.com/3dexperience.
[42] I.V. Aslanova and A.I., Kulichkina, Digital Maturity: Definition and Model, In *Proceedings of 2nd International Scientific and Practical Conference "Modern Management Trends and the Digital Economy: from Regional Development to Global Economic Growth" (MTDE 2020)*, Yekaterinburg, Russia, 2020.
[43] P. Mugge, H. Abbu, T.L. Michaelis, A. Kwiatkowski and G. Gudergan, Patterns of Digitization: A Practical Guide to Digital Transformation, Research-Technology Management, 2020, Vol. 63:2, 27-35, DOI: 10.1080/08956308.2020.1707003.
[44] J. Gao, A.Y. Nee, An overview of manufacturing knowledge sharing in the product development process. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. 2018, Vol. 232(13), pp. 2253-2263, doi:10.1177/0954405418759375.
[45] T.J. Marion and S.K. Fixson, The Transformation of the Innovation Process: How Digital Tools are Changing Work, Collaboration, and Organizations in New Product Development, *Journal of Product Innovation Management*, 2021, Vol. 38.1, pp. 192-215.
[46] M. Eek, *On credibility assessment in aircraft system simulation*, PhD Thesis, Linköping University Electronic Press, 2016.

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Critical Operations Capabilities and Reshoring Drivers in a High-Cost Environment

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Abstract. Reshoring of manufacturing to high-cost environments has been gaining attention. Several drivers are usually involved in the reshoring process. This process also requires manufacturing companies to assess their capabilities in relationship to the reshoring drivers. However, the connection between the reshoring drivers and the capabilities that the manufacturing companies have in high-cost environments has received little attention. The purpose of this study is to investigate the connection between the reshoring drivers and critical capabilities, through a transdisciplinary approach. This study was conducted through a literature review. The first step included the investigation of existing literature related to operations capabilities. The second step included the investigation of existing literature related to reshoring drivers. The third step included an investigation of the link between the critical operations capabilities and the reshoring drivers derived from the literature. Both sets of critical operations capabilities and reshoring drivers were linked based on their respective definitions. The findings revealed that there is a connection between operations capabilities and reshoring drivers. This study contributes to the development of both reshoring and operations capabilities research streams, and to practice by identifying the specific operations capabilities that can drive reshoring.

Keywords. Capabilities, reshoring, literature review, transdisciplinary

Introduction

An extensive movement of manufacturing from high-cost to low-cost environments has taken place in the last three decades [1]. The key driver for this offshoring trend has been manufacturing costs [2]. Despite achieving reduced manufacturing costs, the offshoring decisions lacked a holistic perspective while evaluation leading to suboptimal decisions [3]. These offshoring failures and changes in manufacturing strategy have led to an intensified debate about reshoring, that is when companies decide to move manufacturing back to the home country [4].

The main goal for manufacturing relocations is to achieve a competitive advantage. The fundamental strategies implemented for creating a competitive advantage are referred to as cost-leadership and differentiation [5]. Differentiation is achieved by organizing the firm around how customer value is created and delivered efficiently, and

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how these processes can be coordinated and managed. This is supported by the operations capabilities that the firm develops over time [6].

Relocation decisions require both current and future analysis of operations capabilities [7]. Furthermore, a large number of drivers are involved in the decision [8]. Therefore, it is fundamental to understand the connection between the operations capabilities that a company wants to develop and the reshoring drivers that a company takes into consideration when moving manufacturing back to a high-cost environment. The connection between the two research streams, that is operations capabilities and reshoring, is relevant to both research and practice. However, this connection has not been sufficiently investigated in the literature. In order to better understand this connection, it is important to adopt a transdisciplinary approach that allows investigating cross-disciplinary boundaries [9] and present findings from two disciplines with different theoretical foundations aligning the thoughts from these two disciplines. The purpose of this study is to investigate the connection between critical operations capabilities and reshoring drivers.

1. Theoretical framework

1.1. Operations capabilities

The competitive advantage is formulated as part of the business strategy and is subsequently to be transferred to the functional operations strategy. Two core elements are central to the formulation of an operations strategy [10]. The first element (competitive priorities) is a statement of what the operations function must accomplish (referred to as the tasks, objectives or priorities) and can be defined as the capabilities that the operations unit must have in order to compete successfully, given its overall business strategy. The second element in the formulation of an operations strategy (operations decisions) is the pattern of decisions that a firm makes, which determine the actual capabilities of the operations system [11]. The competitive success of a firm depends on its ability to identify, develop and continuously improve operations capabilities that provide superior value to customers. These operations capabilities can be grouped in six dimensions which are cost, quality, time, flexibility, innovation and sustainability [6].

1.2. Reshoring drivers

Reshoring can be described as the return of manufacturing activities back to the home country [12]. Several decision criteria influence the reshoring decision and among them include drivers, enablers and barriers. Drivers are those decision criteria that cause a reshoring action [13]. The more common groups of drivers include manufacturing cost, product or process quality, company strategies, availability and proximity to resources, and global conditions [13]. Drivers can be categorised into different theoretical frameworks, however, not all of the drivers clearly fit into these frameworks [12].

1.3. Connection between operations capabilities and reshoring drivers

The topics operations capabilities and reshoring drivers come from two different research streams, having different theoretical foundations. However, these two different research streams have one common denominator which is related to achieving competitive advantage for companies in home country. On one side, critical operations capabilities are developed in manufacturing companies as to maintain and achieve a competitive advantage. When developing these capabilities, companies can build a stronger foundation for delivering a better value to the customer (through differentiation strategies) or deliver the same value more efficiently (through low-cost strategies). On the other side, the reshoring drivers reflect on why companies reshore their manufacturing (and other operations) to high-cost countries so that they maintain and achieve a competitive advantage. Therefore, the development of operations capabilities can be related to reshoring drivers for achieving competitiveness. Manufacturing companies implementing low-cost strategy might focus on capabilities in the cost dimension, while at the same time be more sensitive to changes such as increased supply chain cost as a result of reshoring decisions. However, there is a gap in the literature regarding the connection between reshoring drivers and critical operations capabilities, that contributes to the debate of strategy versus failure in reshoring decisions [7].

2. Research methodology

The research was conducted in three successive steps. In the first step, a systematic search was conducted to derive the critical operations capabilities for competitive manufacturing from the literature. In the second step, another systematic search was conducted to derive the reshoring drivers from the literature. In the third step, the critical operations capabilities and reshoring drivers were mapped and the connections were analysed. Different search strings were used for the two different research streams on the Scopus database (Table 1).

Table 1. Literature review characteristics

	Operations strategy	Reshoring
Aim	To derive critical capabilities for competitive manufacturing	To derive common reshoring drivers
Search string	("operations" OR "production" OR "manufacturing" OR "supply chain" OR "strategy") AND ("competitive priority" OR "performance objective" OR "manufacturing objective" OR "intended critical factor" OR "business priority" OR "strategic priority") OR ("competitive capability" OR "manufacturing capability" OR "strategic capability" OR "strategic dimension" OR "cumulative capability" OR "dynamic capability" OR "operational capability" OR "realized success factor" OR "competitive dimension") OR ("manufacturing strategy" AND "taxonomy")	"reshoring" OR "re-shoring" OR "reshore" OR "re-shore" OR "reshored" OR "re-shored" or "backshoring" OR "back-shoring" OR "backshore" OR "back-shore" OR "backshored" OR "back-shored" OR "Rightshoring" OR "Right-shoring" OR "Onshoring" OR "On-shoring"
Database	Scopus	Scopus
Search date	2021-01-31	2021-01-31

Search period	Until 2020	Until 2020
Initial sample	3404 (including duplicates)	1080 (including duplicates)
Inclusion criteria	English language journal papers that address critical capabilities for competitive manufacturing	English language journal papers that address reshoring drivers
Final sample	230	109
Synthesis	Data extraction and emerging coding (excel)	Data extraction and emerging coding (excel)
Output	27 Capabilities	41 Drivers

The initial sample included more than 3400 articles for the operations strategy stream and more than 1000 articles for the reshoring stream. After applying different inclusion and exclusion criteria, the final sample was narrowed down to 230 papers for the operations capabilities stream and 109 papers for the reshoring stream. A content analysis of the articles included in the final sample was conducted. This analysis allowed to create two different frameworks, one summarizing the operations capabilities and one summerizing the reshoring drivers. These frameworks were then merged to identify the connection and link between operations capabilities and reshoring drivers.

3. Findings

3.1. Critical operations capabilities for competitive manufacturing

In total, 27 critical capabilities for competitive manufacturing were identified in the literature review. The operations capabilities identified in the literature are organized in six dimensions and the definitions for each capability are provided in Table 2.

Table 2. Operations capabilities

Dimension	Capability	Definition
Cost	Cost efficiency	The ability to provide products at low cost
	Resource efficiency	The ability to maximize utilization of process resources (machinery and human)
	Process efficiency	The ability to maximize the output of the process
Quality	Product quality	The ability to provide high performance and durable products
	Service quality	The ability to provide high-performance services
	Process quality	The ability to provide products/services with consistent quality (conformance)
	Delivery dependability	The ability to deliver on time
	Brand quality	The ability to build a strong and positive company image
	Supplier dependability	The ability to select and develop reliable suppliers
Time	Delivery time	The ability to deliver within a short time frame
	Time to market	The ability to reduce time to market
Flexibility	Product flexibility	The ability to customize products based on customer requirements
	Product line flexibility	The ability to provide a wide range of products with different features
	Volume flexibility	The ability to respond to changes in market demand

	Production mix flexibility	The ability to change the product mix in manufacturing
	Labor flexibility	The ability of employees to perform different types of tasks
	Delivery flexibility	The ability to change delivery times and quantities within the agreed-upon delivery time
	Supplier flexibility	The ability to select and develop responsive suppliers
Innovation	Product innovation	The ability to develop and introduce new products
	Service innovation	The ability to develop and introduce new services
	Process innovation	The ability to develop and implement new processes
	Supply chain innovation	The ability to develop and implement new supply chain solutions
	Market innovation	The ability to find and exploit new markets and opportunities
	Technology innovation	The ability to develop and implement new technologies
Sustainability	Product sustainability	The ability to provide sustainable products
	Process sustainability	The ability to manufacture products in a sustainable manner
	Supply chain sustainability	The ability to source and deliver products in a sustainable manner

3.2. Reshoring drivers

In total, 41 reshoring drivers were identified in the literature review (Table 3). Note that some drivers are quite similar (e.g. different elements of cost reduction), but still represent potentially distinct effects considering the extended supply chain.

Table 3. Reshoring drivers

Driver	Definition
1. Favorable government incentives	The company seeks to take advantage of favorable government incentives that are financially related.
2. Favorable government policies	The company seeks to take advantage of a more favorable government policy.
3. Increased access to energy infrastructure	The company seeks to have better access to energy infrastructure covering utilities such as electrical power.
4. Increased access to transportation infrastructure	The company seeks to have better access to transportation infrastructure such as roads and transport services.
5. Increased access to production infrastructure	The company seeks to have better access to production infrastructure such as factory space.
6. Increased availability of production capacity	The company seeks to utilize the existing production capacity more efficiently.
7. Increased availability of production technology	The company seeks to have better access to specific manufacturing technologies.
8. Increased availability of digital technology	The company seeks to have better access to digital technologies that are increasingly being integrated into manufacturing.
9. Increased delivery dependability	The company seeks to improve delivery dependability.
10. Increased knowledge protection	The company seeks to improve protection for its intellectual property and know-how.
11. Increased 'made-in' effect	The company seeks to improve its brand image through the 'made-in' effect.
12. Increased process quality	The company seeks to improve process quality in the manufacturing process.

13. Increased product flexibility	The company seeks to improve product flexibility through customization.
14. Increased product mix flexibility	The company seeks to improve product mix flexibility through increased responsiveness to changes in volume and variety.
15. Increased product quality	The company seeks to improve product quality.
16. Increased servitisation	The company seeks to improve services that are related to its products.
17. Increased supplier dependability	The company seeks to improve supplier dependability.
18. Increased supply chain control	The company seeks to have better control of the upstream supply chain.
19. Increased supplier flexibility	The company seeks to improve supplier flexibility through flexible supplier contracts.
20. Increased supply chain resilience	The company seeks to improve supply chain resilience, which is the ability to recover quickly from external disruptions.
21. Increased supply chain sustainability	The company seeks to improve the sustainability of the supply chain associated with stricter environmental regulations.
22. Increased labor flexibility	The company seeks to enforce more flexible labor contracts and flexibility in hiring and firing.
23. Increased access to labor resources	The company seeks to improve access to highly skilled labor resources.
24. Increased proximity to industrial cluster	The company seeks to increase spatial proximity to an industrial cluster.
25. Increased proximity to R&D	The company seeks to increase spatial proximity to its R&D function.
26. Increased proximity to suppliers	The company seeks to increase spatial proximity to its suppliers.
27. Reduced total cost	The company seeks to reduce the total costs of its business.
28. Reduced manufacturing cost	The company seeks to reduce the total manufacturing costs, which includes raw material, labor and energy components.
29. Reduced raw material cost	The company seeks to reduce its raw material cost component of manufacturing cost.
30. Reduced labor cost	The company seeks to reduce the labor cost component of the manufacturing cost.
31. Reduced energy cost	The company seeks to reduce the energy cost component of the manufacturing cost.
32. Reduced transportation cost	The company seeks to reduce its transportation costs.
33. Reduced overhead cost	The company seeks to reduce the overhead costs which have been overlooked during the offshoring process.
34. Reduced coordination cost	The company seeks to reduce its coordination costs in long supply chains.
35. Reduced transaction cost	The company seeks to reduce its transaction costs through efficient communication.
36. Reduced monitoring cost	The company seeks to reduce the monitoring costs.
37. Improved exchange rate	The company seeks to take advantage of a better exchange rate.
38. Reduced delivery lead-time	The company seeks to reduce delivery lead-time as a result of shorter distances and efficient transportation infrastructure.
39. Reduced time-to-market	The company seeks to reduce the time-to-market during new product development.
40. Reduced supply chain disruption	The company seeks to reduce the negative effect of unexpected disruptive events in its global supply chain.
41. Reduced cultural distance	The company seeks to reduce cultural distance and miscommunication.

3.3. Connection between reshoring drivers and operations capabilities

The connection between the identified reshoring drivers and operations capabilities is shown in Table 4. It can be observed that most of the reshoring drivers are related to small set of operations capabilities, which are mostly belonging to the same dimension or to dimensions which are related to each others.

Table 4. Connection between operations capabilities and reshoring drivers

Driver no.	Cost efficiency	Resource efficiency	Process efficiency	Product quality	Service quality	Process quality	Delivery dependability	Brand quality	Supplier dependability	Delivery time	Time to market	Product flexibility	Product line flexibility	Volume flexibility	Production mix flexibility	Labor flexibility	Delivery flexibility	Supplier flexibility	Product innovation	Service innovation	Process innovation	Technology innovation	Market innovation	Supply chain innovation	Product sustainability	Process sustainability	Supply chain sustainability
1	●																										
2	●	●																									
3		●	●			●															●	●				●	
4							●		●	●	●						●										
5		●	●	●		●						●	●	●	●						●	●				●	
6	●	●	●			●							●	●	●	●	●									●	
7		●				●													●	●	●	●		●			
8					●	●				●	●								●	●	●	●		●			
9							●		●																		
10																			●	●	●	●	●	●			
11				●	●	●		●																			
12					●	●		●																			
13												●	●	●	●		●										
14												●	●		●												
15				●	●	●		●																			
16					●														●	●				●			
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22	●	●										●	●	●	●	●											
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24									●			●	●	●	●			●	●	●	●	●	●	●			●
25				●	●	●						●							●	●	●	●	●	●	●	●	●
26		●	●			●	●		●									●									

27	●	●															
28	●	●															
29	●	●															
30	●	●															
31	●	●															
32	●																
33	●	●															
34	●																
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37	●																
38										●	●						●
39										●	●						
40							●		●	●							
41				●	●	●	●		●								

One example is given by the reshoring driver related to ‘increased proximity to R&D’, when a company get closer to R&D can improve not only the quality of the product and process, but also the innovation capabilities and sustainability capabilities depending on the priorities that the company wants to have. Another example instead is given by ‘increased supply chain control’ which can in turn improve capabilities related to quality, flexibility, innovation and sustainability. Companies that wants to reach a better control over the supply chain can improve their flexibility both in delivery and development but also improve supplier dependability and supply chain innovation and sustainability.

4. Conclusion

Based on the operations strategy implemented, manufacturing companies develop different operations capabilities. Reshoring decisions can impact and affect the development of operations capabilities, as they influence the structure of the company in terms of knowledge and resources. Moreover, the manufacturing companies develop operations capabilities in a cumulative way [14]. This is also emphasized in this study as reshoring drivers can match multiple operations capabilities belonging to one or more dimensions. Moreover, when companies need to move their production back to their home country, it is fundamental to evaluate and reorganize the capabilities needed to improve their competitiveness. Manufacturing companies need to better respond to these changes by developing critical operations capabilities.

The paper has identified the connection between operations capabilities and reshoring drivers. The contribution of the paper is both to research and practice. It advances the literature on both operations capabilities and reshoring research streams while identifying the specific operations capabilities that manufacturing companies should pursue in order to drive reshoring. The connection between these two research streams, that have different theoretical foundations, was investigated through a transdisciplinary approach [9].

This research paper can be considered as a starting point for building a framework for operations capabilities and reshoring drivers through a literature review. Hence, future research can strengthen the links and develop the framework further by applying it to an empirical setting, either through in-depth case studies to develop the matching more closely, or through a larger survey.

References

[1] M. Ketokivi, V. Turkulainen, T. Seppälä, P. Rouvinen, and J. Ali-Yrkkö, Why locate manufacturing in a high-cost country? A case study of 35 production location decisions, *Journal of Operations Management,* 2017, Vol. 49, pp. 20-30.

[2] V. Vanchan, R. Mulhall, and J. Bryson, Repatriation or reshoring of manufacturing to the US and UK: dynamics and global production networks or from here to there and back again, *Growth and Change,* 2018, Vol. 49, no. 1, pp. 97-121.

[3] D. Eriksson, P. Hilletofth, L. Ellram, and C. Sansone, To offshore or reshore: The battle of data points, *Supply Chain Management Review,* 2018, Vol. 22, No. 3, pp. 42-46.

[4] J. S. Arlbjørn and O. S. Mikkelsen, Backshoring manufacturing: Notes on an important but under-researched theme, *Journal of Purchasing and Supply Management,* 2014, Vol. 20, No. 1, pp. 60-62.

[5] M. E. Porter, *Competitive strategy: Techniques for analyzing industries and competitors*, The Free Press, New York, 1980.

[6] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, W. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 753-762.

[7] L. Bals, J. F. Kirchoff, and K. Foerstl, Exploring the reshoring and insourcing decision making process: toward an agenda for future research, *Operations Management Research,* 2016, Vol. 9, No. 3-4, pp. 102-116.

[8] J. V. Gray, G. Esenduran, M. J. Rungtusanatham, and K. Skowronski, Why in the world did they reshore? Examining small to medium-sized manufacturer decisions, *Journal of Operations Management,* 2017, Vol. 49, pp. 37-51.

[9] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, and W. J. Verhagen, Transdisciplinary systems engineering: implications, challenges and research agenda, *International Journal of Agile Systems and Management,* 2019, Vol. 12, No. 1, pp. 58-89.

[10] G. Dangayach and S. Deshmukh, Implementation of manufacturing strategy: a multisector study of the Indian manufacturing industry, *International Journal of Services and Operations Management,* 2008, Vol. 4, No. 1, pp. 1-33.

[11] J. G. Miller and A. V. Roth, A taxonomy of manufacturing strategies, *Management Science,* 1994, Vol. 40, No. 3, pp. 285-304.

[12] P. Barbieri, F. Ciabuschi, L. Fratocchi, and M. Vignoli, What do we know about manufacturing reshoring?, *Journal of Global Operations and Strategic Sourcing,* 2018, Vol. 11, No. 1, pp. 79-122.

[13] M. Sequeira, P. Hilletofth, and D. Eriksson, Criteria considered in a manufacturing reshoring decision: a multiple case study, *Advances in Transdisciplinary Engineering*, 2020, Vol. 13, pp. 610-621.

[14] A. Größler and A. Grübner, An empirical model of the relationships between manufacturing capabilities, *International Journal of Operations & Production Management,* 2006, Vol. 26, No. 5, pp. 458-485.

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Systems Dynamics and Empirical Studies of Innovation in the Automotive Industry

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Abstract. After a brief period of entrepreneurship and competition, the automotive industry settled into a tiered structure aligned with the assembly decomposition of the vehicle. In recent years, changes to automobiles, mobility, and energy are rapidly transforming the industry with potential to disrupt the classic roles of OEMs and Tier-1 suppliers. Several new large actors from outside the industry are now competing. This research leverages two methods to investigate how innovation diffusion impacts the position of Tier-1 suppliers. A system dynamic modeling approach and an empirical study were conducted for subsystems in this industry since 1990. The research progress and limitations from these methods separately, then in combination, are discussed with insights for further work and transdisciplinary studies in engineering.

Keywords. Automotive innovation, Tier-1 supplier, transdisciplinary studies of engineering

Introduction

This paper shares two studies of different methods towards a common question: Can innovation by Tier 1 automotive suppliers significantly change their position and performance given the traditional layered industry? An initial study leveraged existing theory to build a system dynamics model of innovation dynamics in the automotive industry. A second study applied an empirical approach, surveying industry experts and collecting product data. The interplay across the two methods helped the researchers to expand insights and refactor several times, in a back and forth exchange that strengthened both results.

Transdisciplinarity, a term originally coined in the 1970s as a concept in science research with an emphasis in sustainability, has been more recently considered in engineering of complex systems. [1]–[3] Engineering is faced with great challenges requiring innovation beyond the integration of existing disciplinary capabilities.[4] For the automotive industry, approaches to product development – suitable for newer complex, connected systems – require adaptation across technical and organizational decisions. For new product development, what uncertainty and change can be handled feasibly and desirably within limits of capability, resources, and time? How will new technologies compare to what other can and will do? Given a choice to innovate in a certain area, will the investment pay off? Thus, these engineering choices must leverage multiple disciplines within and outside engineering in combination.

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The early decades of the automotive industry were a period of diverse players and entrepreneurship, soon displaced by an enduring structure of dominant Original Equipment Manufacturers (OEMs) served by a multi-tiered supplier hierarchy.[5] The OEM sits at a top (level zero) layer and suppliers are arranged in tiers aligned by product decomposition. A Tier-1 (level one) company supplies subsystems to the OEM, Tier 2 companies supply Tier-1, and so on. In this classic model, the supplier is “owned’ by the OEM, either as vertically integrated division or captured by reliance for market insights and revenues. In this environment the Tier-1 supplier may find it difficult to divert attention from the command of the OEM nor otherwise to compete. In recent decades, challenges to this dominant structure have come and gone, or been absorbed.

1. Innovation and the Auto Industry

Competition from Japanese makers in the 1980s (enabled by loosely coupled vertical integration and lean capabilities) was followed by offshoring and modularity trends of the late 1990s. Indeed, some suppliers have been able to overcome previous limitations, becoming suppliers across multiple OEMs. Still, the predominant industry structure has not changed. The OEMs retain their dominant positions and the role of the Tier 1 suppliers has remained relatively unchanged. Jacobides et.al. studied the movements towards outsourcing and modularity (O+M) in the 1990s, which had the possibility to change the OEM role and industry structure [5]. In their study they argue that even as the Tier-1 suppliers (“mega suppliers”) increased their capabilities, the OEM continued to invest even more in R&D, to “know more than they make” [6]. They concluded that these initiatives, though widespread, were mostly reversed as OEMs recognized their role as integrator and the need to control suppliers. The authors go on to extrapolate recent potentially disruptive technologies such as electrification, batteries, and autonomy, asserting that the suppliers will not change the dominant industry architecture of the last century. They also argue that new entrants, such as Tesla, adhere to the classic pattern. The research objective of this paper was triggered by this assertion.

1.1. Open Innovation and Supplier Position

Through open innovation, ideas originate from (1) inside the company’s research process, and (2) outside the company and transferred inside. Some ideas also move out of the company, either early on, after opportunity identification and product planning, or later during the product development phases [7]. While many ideas in early phase do not see the light of day, the process of open innovation enables diversity of ideas generated both internally and external to the company. Lazzarotti et al.[8] studied European suppliers along with an OEM, noting that rarely do intellectual property (IP) and ideas flow to competition nor players in other industries. A mix of openness to collaborate (inbound innovation) is observed between the OEM, its suppliers, and others (e.g. competitors, cross-industry players, universities, customers, and research centers). A supplier’s view of open innovation is explored by Brown et al.[9], emphasizing need for organizational and cultural shifts. In addition to collecting ideas through internal and external channels, Delphi, though an internal service, involved suppliers in product innovation, technical issues, inter divisional co-operation, and business case validation.

Chesborough [10] discusses the latent economic value of a technology or invention until it is commercialized, referring to a business model as “the architecture of revenue.”

He highlights that "a mediocre technology pursued with a great business model may be more valuable than a great technology in a mediocre business model." New business models related to car sharing ecosystems, insurance, and mobility industries are expected in the coming years [11]. Tesla is an example of both technology and business models breaking conventions of the automotive industry. [12]

Parker and Van Alstyne imagine a firm as manager of a micro-economy, shaping an ecosystem with an emphasis on how innovation is open, closed and for how long. [13] Given specialized supplier capability, how long should intellectual property (IP) rights be protected in their micro-economy? Amongst trade-offs, they recognize the need for the supplier to retain rights, maintain price and gain advantage from their invention. At the same time, they describe potential benefit of the commons -- knowledge moving beyond the particular inventor and having an impact across suppliers.

2. A Systems Dynamics Study

This research began by looking at the auto industry as a system of stakeholders exhibiting value flow amongst them. Focused on Tier-1 and the OEM, a hypothesis explored competition between the Tier-1 supplier and the OEM and its effect on the dilution of innovation. A tension exists internal to the OEM, between internal vs. external innovation. While internal innovation may be time consuming, costly, and maintains control over the market, outsourced innovation is less expensive, can be expedited through competition between suppliers, yet might result in little to no innovation lead for the OEM.

An initial model built to test the original research hypothesis is shown in Figure 1. Starting in the upper left with the IP Driven (R1) loop, all else being equal, research generates patents after some delay. Increasing research will lead to more patents, more patents lead to greater product innovation which then increases innovation lead. Innovation lead is defined here as the advantage gained by converting internally developed technology into products from which the OEM alone benefits.

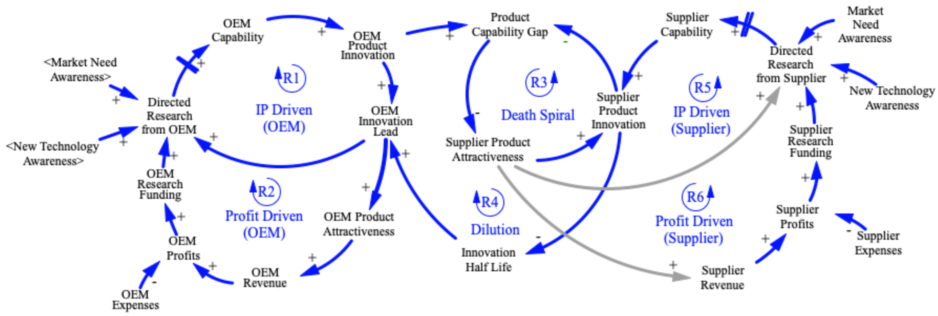

Figure 1: Causal loop diagram depicting OEM vs. Tier-1 supplier innovation model.

A second OEM causal loop is shown on the bottom left: Profit Driven (R2). Characterized by product attractiveness, revenue, profits, and research funding, the loop shows the profit incentive for funding of research. As Innovation Lead increases, Product Attractiveness also increases if the OEM uniquely offers the innovation in the market. Higher attractiveness leads to greater Sales and more Revenue. For given OEM expenses, higher revenue increases profits, which further increases research funding. Higher funding leads to an increase in projects that address market needs.

Shown on the right side of Figure 1, innovation by the supplier is modeled with four reinforcing loops. The Dilution loop (R4) captures a product system's useful commercial life. As *Supplier Product Innovation* increases, the *Innovation Half Life*, the time it takes for a product feature to reduce to half its original value, decreases. In other words, *Innovation Half Life* captures a premium product devolving into a base product -- a standard on cars from all manufacturers. OEMs attempt to increase half-life by maximizing lead over competition as long as possible. Meanwhile, the supplier's objective is to sell its innovation to many OEMs, displacing previous innovations and reducing half-life. Decrease in *Innovation Half Life* decreases *Innovation Lead* for the OEM. A lower lead drives decrease in *Research Studies*, and thus fewer patents. Fewer patents will result in lower product innovation, which in turn leads to lower *Product Capability Gap*. A higher capability gap is better for the OEM. Back in loop R4, as the gap decreases, *Supplier Product Attractiveness* increases, and higher attractiveness of supplier product leads to greater *Supplier Product Innovation*.

A second reinforcing loop, the Death Spiral (R3), drives loss of supplier product innovation. As *Product Capability Gap* increases, *Supplier Product Attractiveness* reduces, decreasing *Supplier Product Innovation* in that particular product segment. Lower *Supplier Product Innovation* in turn increases *Product Capability Gap*, resulting in loss of value for the supplier. Similar to the OEM, a supplier is influenced by an IP loop (R5). In R5, high *Supplier Product Attractiveness* drives increase of *Supplier Research* for the given funding, market needs and technology awareness. More effort by the supplier will increase patents, after some delay. High product innovation at the supplier side will result in smaller Product Capability Gap, which then leads to greater Supplier Product Attractiveness.

A Profit Driven loop (R6) captures the financial side of innovation on the supplier side. As *Supplier Product Innovation* increases, *Supplier Sales* increase. Higher sales then result in greater revenue for the suppliers. For given expenses, higher revenue results in greater supplier profits, thus increasing funding of new capability in the relevant segment. Greater research effort after some delay leads to more patents and *Supplier Product Innovation*. This increase in innovation then decreases the *Product Capability Gap*. An exogenous variable, *Market Need Awareness*, captures the supplier's insight into the market from working with multiple OEMs, suppliers, and technology trends. *New Technology Awareness* captures the level of awareness of technology not native to the automotive industry. These variables also influence OEMs research efforts.

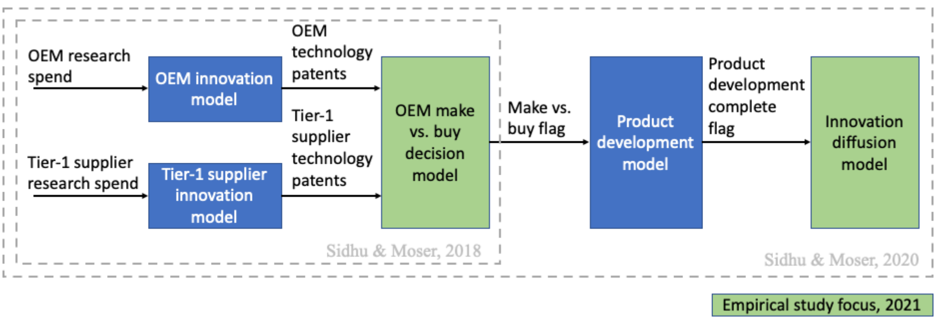

Figure 2: Overview of model-based study into automotive innovation adoption and diffusion.

Figure 2 shows the two stages of the model-based study. The innermost dashed box on the left represents the initially proposed causal loop model. Limitations of the initial model triggered an expansion and the need for the empirical study. Even early on, as the empirical study was being framed, the exercise revealed insights in two areas: the aftermath of a “buy” decision by the OEM for one product feature, and the diffusion of this product feature into car models offered by major North American (NA) manufacturers. The impact of the empirical study on the expanded model is represented by the green boxes in **Figure 2**, and discussed further in section 4.

3. An Empirical Study

In response to the first stage of the model-based approach, a separate empirical study was started focusing on two innovation dynamics: the competition between OEMs and Tier-1 suppliers (Red Queen Dynamics), and diffusion of technical innovation. North American automotive supplier relationships are tense, with aggressive projections, low profit margins, various regulatory standards, and dependence on the OEM. Tier-1 suppliers invest in various capabilities; talent acquisition, IP development and protection, innovative products, and marketing. Tier 1 suppliers seek to improve position and achieve an increased profit margin, less dependence on a single OEM, and products offerings across multiple OEMs.

The empirical approach selects a motor vehicle subsystem and draws insights from the “who supplies whom” interactions and their relationship to development of capability. The authors began with functional decomposition of a typical light-weight vehicle and identified 17 subsystems with innovation cycles over the last three decades (1990 to 2019). As is shown in **Figure 3**, the subsystems include powertrain, chassis, interior & comfort, infotainment & telematics, and advanced driver assistance systems.

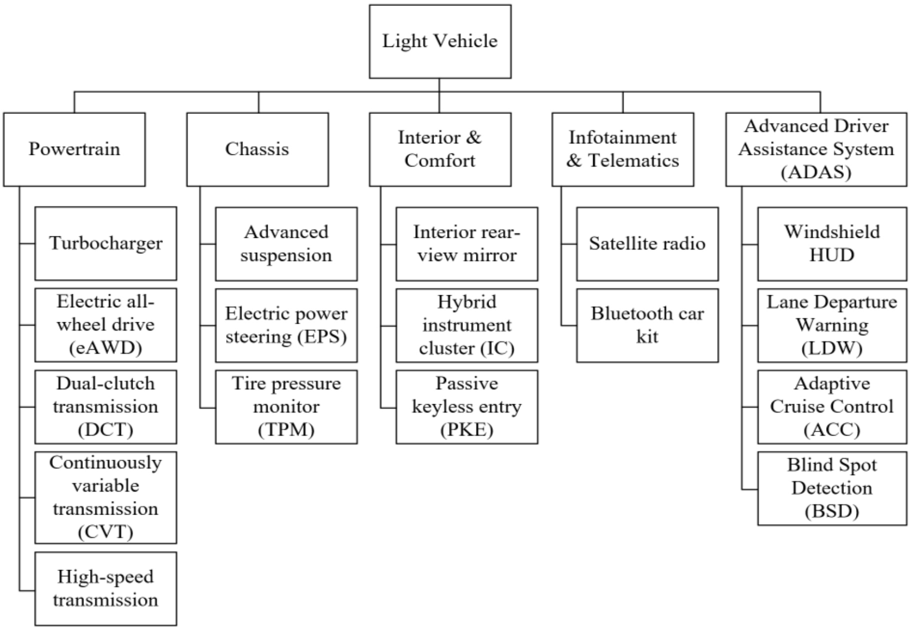

Figure 3: Light Vehicle product system decomposition used for evaluation and selection of product subsystems for the empirical study.

To prioritize and down-select candidate subsystems, a survey was conducted with mid-career product development professionals in the automotive industry, followed by several interviews. The survey evaluated the 17 Tier-1 subsystems based on four factors: pace of market adoption, breadth of technology diffusion, level of technical defensibility, and value to the total system performance and degree of potential achieved. The survey identified the passive keyless entry (PKE) as a top candidate for this study. PKE offers convenience of hands-free entry to a vehicle and ignition start, with the key fob remaining in the customer's pocket. The technology was first developed by Siemens VDO and introduced to the market by Mercedes-Benz before 2000 and reached an installation rate of around 20% in 2018. Based on light vehicles in the North American market, the study's period is aligned with the technology's first entry to market until a full innovation cycle is suggested by market diffusion. The study was designed for and intended for multiple Tier-1 subsystems with PKE as an initial subsystem. (Additional subsystem evaluations are in process). The automotive models of two major North American OEMs - General Motors (GM) and Ford Motor Company, are included, representing 30-40% of the US light-vehicle market, with 99 current and discontinued models from brands including Ford, Lincoln and Mercury from Ford, and Cadillac, Buick, Chevrolet, and GMC from GM.

Data of OEMs and Tier-1 suppliers were collected from publicly available data sources, including financial statements, vehicle owner's manuals, vehicle sales databases, product catalogs from various parts vendors, and the FCC database[14]. Data starts from model year 2004, when GM first introduced PKE in the Cadillac XLR, to 2020, the most recent complete model year. The number of models and sales data for a few light-truck models (i.e. F-series from Ford and Silverado from GM) are aggregated to align with OEMs sales release. **Figure 4** and **Figure 5** show PKE availability and estimated vehicle shipments between 2004 and 2020.

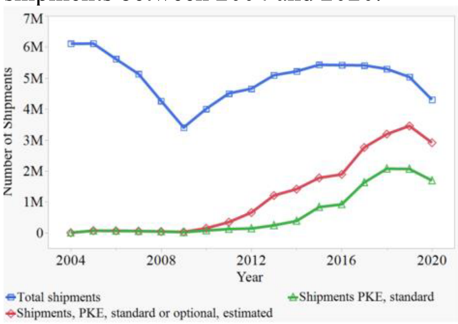

Figure 4: PKE Adoption by Model: Number of N.A. models (Ford and GM) compared to models with optional or standard PKE

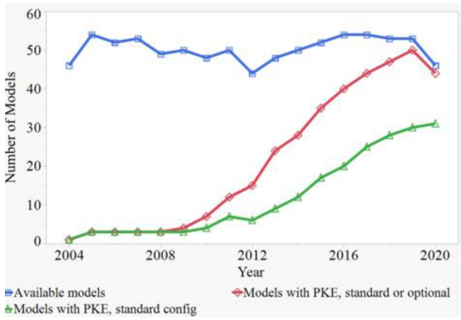

Figure 5: PKE Adoption by Vehicles Shipped: Shipments of vehicles (US) Ford and GM, compared to vehicles with PKE.

Diffusion of PKE follows the adoption s-curve: an initial period of slow growth between 2004-2009, followed by a fast adoption period between 2010-2018, and culminated with a plateau around 2020-2021. By the end of model year 2020, 95% of models manufactured by GM and Ford offered PKE either as standard or optional configuration, with an estimated 67% new vehicles equipped with PKE.

Figure 6 shows a comparison between Ford and GM. Ford introduced PKE to its customers in 2009, 4 years later than GM. However, the diffusion of PKE in Ford models is faster than GM. For example, 90% of models from Ford offered PKE at least as an option in model year 2015 while GM offered only 55%. **Figure 7** show a Sankey chart to illustrate the evolution of the number of OEM vehicle models supplied by Tier-1 suppliers in model years between 2004 to 2020. Siemens VDO (later acquired by Continental AG in 2007) was the first developer of PKE subsystems and therefore benefited as first mover. Siemens VDO/Continental supplied most vehicle models with PKE technology in the early adoption stage between 2004-2010, with competition from Hella and Strattec. A new competitor - Denso, emerged in GM's PKE supply chain in 2014 and became the dominant supplier of GM's PKE subsystem within 3 years. By the end of model year 2019, Continental was no longer on GM's PKE supplier list but remained as the sole supplier of PKE for Ford. By this point, Denso supplied 30 of 32 GM models offering PKE. Other Tier-1 suppliers remaining include Hella, which supplied PKE for GM's Corvette, a performance convertible, and Strattec supplying GM's Impala, a full-size car model discontinued in the model year 2020.

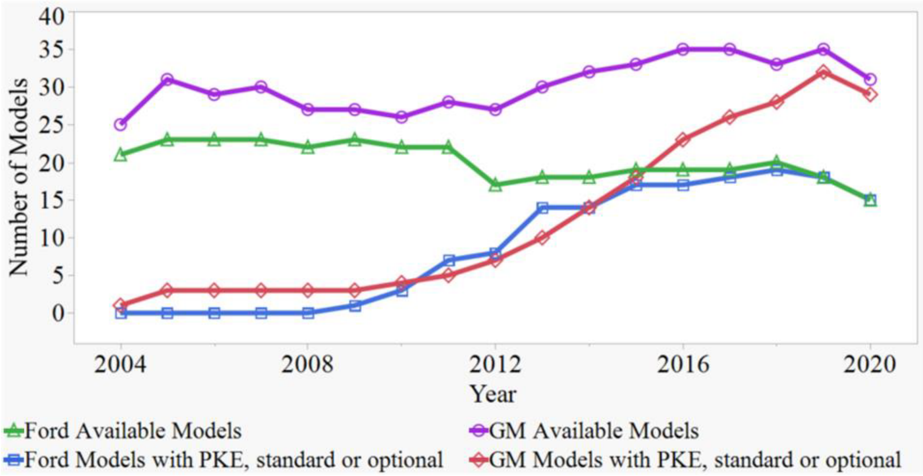

Figure 6: Adoption of PKE across Ford and GM, 2004 - 2020.

What is behind Denso's rise in GM's PKE supply chain? Denso has a good relationship with GM, awarded GM's top supplier awards for quality for many years, thus it is not surprising to see Denso emerge as a GM PKE supplier. Though Siemens VDO was the inventor of PKE, Denso was also a forerunner in keyless access systems. The company introduced RF technology to RKE systems as early as 1984 and owned similar market share of PKE systems as compared with Siemens VDO in 2006. 28% of Denso is owned by Toyota, supplying RKE and PKE systems to Lexus before 2006.

Why does Ford keep staying with Continental? Ford has collaborated with Siemens VDO/ Continental throughout the PKE diffusion curve. In a 2006 analyst's report, Ford did not consider convenience from PKE as a core user experience, outsourcing PKE to a Tier-1 supplier. This initial decision may have shaped Ford's product vision and supply chain management, leading to Continental as the only supplier to Ford's PKE systems.

4. Discussion

The two studies, still underway, seek to determine if and how an outsized investment in innovation by a Tier 1 supplier might change the position of suppliers compared to the historical pattern. In contrast to a typical model-building and validation exercise, in which the empirical study follows simply as calibration and validation, the two studies were framed, refined, and validated to some degree by the other. At the time of this conference paper draft, only a single subsystem has been evaluated. Market position outcomes data are still needed. However, the researchers summarize here the ongoing interplay between the two studies.

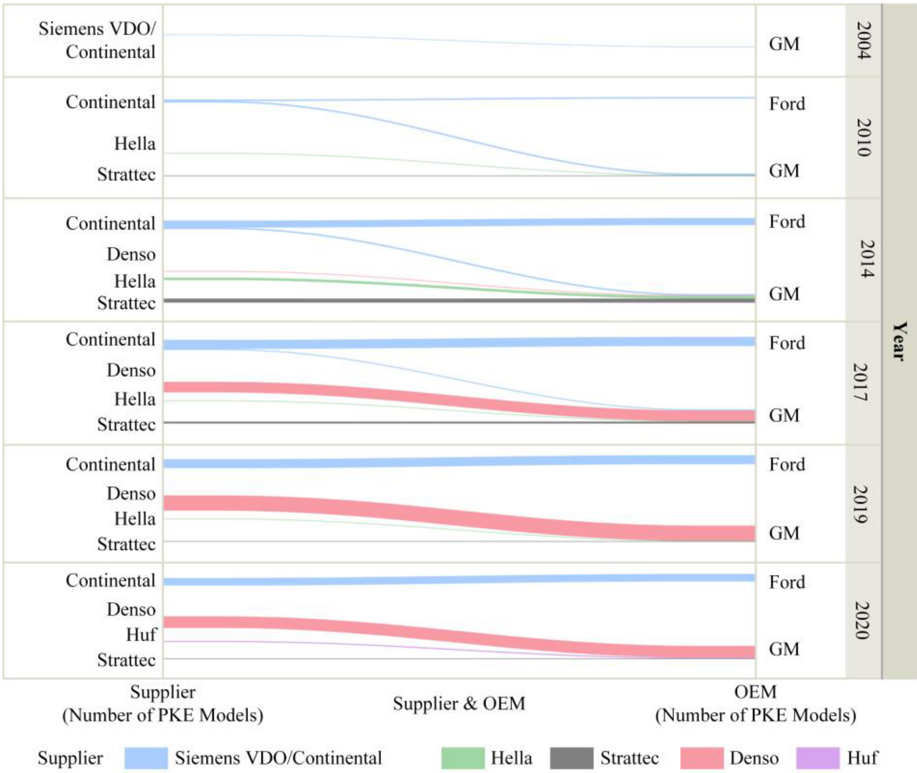

Figure 7: Adoption and Diffusion from Tier 1 Supplier to OEM for PKE, 2004 -2020

Dynamics missing in the initial SD model were stimulated by the empirical study, such as a weak reinforcing loop due to aftermarket products. The empirical study showed suppliers offering PKE kits to retrofit old models. An updated model in response to this insight includes shipments from aftermarket boosting the "market need awareness" and "new technology awareness" as input to supplier loops. The empirical study also revealed multiple OEM relationships for Tier-1 suppliers. In contrast, an early SD model was overly focused on one-to-one relationships. In response, (see Figure 2), the evolution of the SD model emphasized broader one to many diffusions. Further, make-buy decisions were modeled in a static way, and the empirical study exposed these decisions more clearly. In the case of PKE, the rise of Denso to dominate shows a Tier-1 player dynamically capturing the market.

The original SD model also assumed a stage-wise new product development with uniform "time equals zero" signaling the start of new capability investment. However, in the Siemens PKE case, product development had already happened and early diffusion was a leverage rather than development of capability. Likewise, the SD model assumes a product development process consistent across actors in the market. However, process capability, including accelerated model-based, start-up, agile, and platform approaches might explain a different dynamic. In the empirical study, interpretation of the duration from early prototypes to market entry could be explained better with this context.

In the second model, even with added system dynamics (SD) language to capture make vs. buy, technology integration, and innovation diffusion, several limitations remain. While data is available for total research spend and patents filed, these lack sufficient granularity to calibrate the SD model. The model would benefit from data on technology specific research spend, patents filed, product development, and product diffusion. Research funding to patent filing latency likely differ across OEMs and suppliers. These delays will not be clear unless technology specific data is available. Patent value and fit rather than assuming all patents have the same value. Rework cycle, project controls, and ripple and knock-on effects on product development could be considered to improve robustness of the model. Advertising effectiveness, contact rate, and adoption fraction will not be the same for all innovation diffusion. However, using the available diffusion data, these parameters can be identified.

The empirical study brought tangibility and real-world time scale, as seen through the innovation, introduction, and diffusion of a new technology across a real set of car models and multiple OEMs. Early on for the empirical study, the researchers endeavored to reduce influence of assumptions and insights of the system dynamic model, and instead considered how to capture and synthesize the actions, introduction, and diffusion unbiased by prior assumptions. In the framing of the empirical study, the structured decomposition of the product system and selection of target subsystems revealed certain types of subsystems that don't fit neatly into the framing of the problem in the SD model. In particular, subsystem products that are demanded and visibly directly by end users, for example software and communications platforms such as SiriusXM, Apple CarPlay, and Android Auto. The selection of subsystem in the empirical model triggered us to include TRL into the empirical study, which in turn is promising to consider in the SD model, as certain subsystem may not be yet in a state of sufficient maturity for viable adoption and diffusion. This limitation was seen again in powertrain subsystem examples, with certain hybrid or electric platforms early in their innovation cycle.

Several market entries are explained by capability acquisition, a phenomenon not clear in the SD model. The empirical study showed patterns of entry and diffusion at two different OEMs, GM and Ford, affirming a consistency across all models and a few exceptions due to acquisition. In another case, some Tier-1 suppliers act in partnership and strategic alliances, thus make-buy may also exist across the Tier 1 suppliers.

This back and forth has increased the research team's findings of limitation and possible extensions, otherwise easily skipped. A model paints a limited picture (all models as wrong, some are useful). The empirical study not only drove expansion and refinement of the model, but to also have more respect for its limits, inspiring the researchers to develop new, separate models.

References

[1] S. L. Ahire and T. Ravichandran, An innovation diffusion model of TQM implementation, *IEEE transactions on engineering management*, 2001, Vol. 48, No. 4, pp. 445–464.

[2] M. Atalay, N. Anafarta, and F. Sarvan, The relationship between innovation and firm performance: An empirical evidence from Turkish automotive supplier industry, *Procedia social and behavioral sciences*, 2013, vol. 75, pp. 226–235.

[3] M. Bensaou, Interorganizational cooperation: the role of information technology an empirical comparison of US and Japanese supplier relations, *Information Systems Research*, 1997, Vol. 8, No. 2, pp. 107–124.

[4] A. Brem and G. Schuster, Open Innovation and the Integration of Suppliers–Literature Review and Discussion on Supplier Innovation, in A. Brem and J. Tidd (eds.) *Perspectives on supplier innovation: Theories, concepts and empirical insights on open innovation and the integration of suppliers*, Imperial College Press, London, 2012, Vol. 18, pp. 67-94.

[5] S. C. Ellis, J. W. Henke Jr, and T. J. Kull, The effect of buyer behaviors on preferred customer status and access to supplier technological innovation: An empirical study of supplier perceptions, *Industrial marketing management*, 2012, Vol. 41, No. 8, pp. 1259–1269.

[6] B. H. Hall and B. Khan, *Adoption of new technology*, National bureau of economic research, 2003.

[7] A. Hanelt, S. Firk, B. Hildebrandt, and L. M. Kolbe, Digital M&A, digital innovation, and firm performance: an empirical investigation, *European Journal of Information Systems*, 2020, pp. 1–24.

[8] J. W. Henke Jr and C. Zhang, Increasing supplier-driven innovation, *IT Management Select*, 2010, Vol. 16, pp. 41–46.

[9] R. "Bryan" Jean, D. Kim, and R. R. Sinkovics, Drivers and performance outcomes of supplier innovation generation in customer–supplier relationships: The role of power-dependence, *Decision Sciences*, 2012, Vol. 43, No. 6, pp. 1003–1038.

[10] R. "Bryan" Jean, R. R. Sinkovics, and T. P. Hiebaum, The Effects of Supplier Involvement and Knowledge Protection on Product Innovation in Customer–Supplier Relationships: A Study of Global Automotive Suppliers in China, *Journal of Product Innovation Management*, 2014, Vol. 31, No. 1, pp. 98–113.

[11] T.E. Johnsen, Supplier involvement in new product development and innovation: Taking stock and looking to the future, *Journal of Purchasing and Supply Management*, 2009, Vol. 15, No. 3, pp. 187–197.

[12] J.-P. Kramer, E. Marinelli, S. Iammarino, and J. R. Diez, Intangible assets as drivers of innovation: Empirical evidence on multinational enterprises in German and UK regional systems of innovation, *Technovation*, 2011, Vol. 31, No. 9, pp. 447–458.

[13] J. P. MacDuffie and S. Helper, Creating lean suppliers: diffusing lean production through the supply chain, *California management review*, 1997, Vol. 39, No. 4, pp. 118–151.

[14] J. A. Machuca, C. H. O. Jiménez, and P. Garrido-Vega, Do technology and manufacturing strategy links enhance operational performance? Empirical research in the auto supplier sector, *International Journal of Production Economics*, 2011, Vol. 133, No. 2, pp. 541–550.

[15] A. Manello and G. Calabrese, The influence of reputation on supplier selection: An empirical study of the European automotive industry, *Journal of Purchasing and Supply Management*, 2019, Vol. 25, No. 1, pp. 69–77.

[16] A. Petroni and B. Panciroli, Innovation as a determinant of suppliers' roles and performances: an empirical study in the food machinery industry, *European Journal of Purchasing & Supply Management*, 2002, Vol. 8, No. 3, pp. 135–149.

[17] G. Premkumar, K. Ramamurthy, and S. Nilakanta, Implementation of electronic data interchange: an innovation diffusion perspective, *Journal of Management Information Systems*, 1994, Vol. 11, No. 2, pp. 157–186.

[18] N. J. Pulles, J. Veldman, and H. Schiele, Identifying innovative suppliers in business networks: An empirical study, *Industrial Marketing Management*, 2014, Vol. 43, No. 3, pp. 409–418.

[19] F. Rodríguez, R. Muncrief, O. Delgado, and C. Baldino, Market penetration of fuel-efficiency technologies for heavy-duty vehicles in the European Union, the United States, and China, *The International Council of Clean Transportation*, 2017, https://theicct.org/publications/market-penetration-fuel-efficiency-technologies-heavy-duty-vehicles-european-union, Accessed July 1, 2021.

[20] H. Saranga, R. George, J. Beine, and U. Arnold, Resource configurations, product development capability, and competitive advantage: An empirical analysis of their evolution, *Journal of Business Research*, 2018, Vol. 85, pp. 32–50.

[21] A. Schulze, J. Paul MacDuffie, and F.A. Täube, Introduction: knowledge generation and innovation diffusion in the global automotive industry—change and stability during turbulent times, *Industrial and corporate change*, 2015, Vol. 24, No. 3, pp. 603–611.

[22] C. Thomas, B. D. James, and F. D. Lomax Jr, Market penetration scenarios for fuel cell vehicles, *International Journal of Hydrogen Energy*, 1998, Vol. 23, No. 10, pp. 949–966.

[23] F. Wynstra, F. Von Corswant, and M. Wetzels, In chains? An empirical study of antecedents of supplier product development activity in the automotive industry, *Journal of Product Innovation Management*, 2010, Vol. 27, No. 5, pp. 625–639.

[24] T. Yan, S. Yang, and K. Dooley, A theory of supplier network-based innovation value, *Journal of Purchasing and Supply Management*, 2017, Vol. 23, No. 3, pp. 153–162.

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Cause-Effect Modelling of the Risk Analysis in Objects Development: An Application to Civil Structures

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Abstract. Cause-effect modelling, product-based analysis, and linguistic-based knowledge representation are concepts widely used in different engineering branches and offer ample ways for transdisciplinary engineering developments. An engineering solution consists of a tangible or intangible object able to satisfy specific requirements. The development of engineering projects faces many unknown, unpreventable, or uncontrollable phenomena. Risk analysis becomes an important item for project management. The identification of risks in the development of a solution is in general discretional, using particular models adapted to each specific project. On the contrary, we aim to a general and comprehensive risks analysis model, which is a non-common approach, based on products or results, for the identification of functionalities and defect causes of an object in a generic way. This article presents, in a product-based orientation, the definition of generic functionalities and generic causes categories of damage of an object. These main causes categories head the cause-effect model and constitute the set of adopted risk categories, which integrate the risk analysis model applicable to the development of tangible or intangible engineering solutions. The ex-post risks analysis of the collapse of a pre-stressed stayed bridge tower illustrates the use of the proposed risk analysis model.

Keywords. Object Functionalities, Cause-Effect Model, Risks Analysis, Knowledge Linguistic Model, Transdisciplinary Engineering, Civil Structures Risks

Introduction

In the development of engineering projects, as in general in human, social or natural activities there are many unknown, unpreventable, or uncontrollable phenomena, which bring incertitude to the previewed results. In this sense, risk analysis becomes an important item for the project management, aiming at successful project development, as it supported on the Project Experience Risk Information Library (PERIL) database, in [1], [2]. Risks in construction projects are treated in [3]. Risk analysis modelling in product innovation chain is the subject in [4]. Risk is the probability of having an adverse consequence, from the occurrence of an event. Many levels of risk may be considered in the activities and processes of a project, enclosed in the vulnerability concept, which constitutes a measure of propensity to have an adverse consequence. Risk and vulnerability are concepts defined initially in environmental sciences, among others in [5] and [6], but they are compulsory in engineering projects, in order to consider internal and external events affecting the activities and processes. Engineering has contributed to the development of risk models and their application in projects in different fields, as is described in [2], [4]. Risk models and methods of engineering support risk analysis in projects of diverse disciplines applying specific methods of theses, in a Cross-Disciplinary environment.

A goal of our research team searches to extend the concepts of Requirements Engineering to other knowledge fields using also in this propose the methods of those knowledge fields, applying in this way, concepts of Transdisciplinary Engineering. These engineering concepts are treated, among others, in [7]. Research in this field is considered in sources [8][9]. In source [10] the focus is on sustainability in transdisciplinary engineering projects involving society and the social the natural environment. [11] Incorporates the trans disciplinarity in engineering megaprojects of urban development. Diverse forms of disciplinarity in engineering interventions and the extension of Transdisciplinary Engineering to processes of social sciences are introduced in [12]. Deeping in this concept we define, according to Context and Domain concepts introduced in sourcce [13], basic elements of a linguistic approach that involves the expression of action, activity, process and mega process in the frame of a linguistic template considering a verb and seven parameters related to semantic functions of the verb. This model is based on case grammar proposed by Fillmore in [14], and complemented by Foronda in [15], [16]. A verb may express in causative or descriptive way an action, activity, processes, or a level of mega process, in source [13]. Based on these elements, we are working on the development of a process grammar applicable in computational linguistics.

The identification of risks in the development of a solution is in general discretional and undefined, without an exhaustive way to understand and follow this search. Diversity of aspects related to an object difficult to find generic, defined, and exhaustive product-based approaches for risk analysis. All objects, means, methods and circumstances included in the development processes of a solution may be expressed by agents' interventions (actions and interactions) represented by the referred template integrated by a verb and seven parameters. Taking profit of this semantic richesse, we examine the verb and its semantic function in the agents' interventions template for creating a framework of generic functionalities and a framework of generic causes of object damage. This last framework constitutes a set of risks categories, which guides a strict identification of risks classified according to these categories.

The materialization of a risk becomes a problem. Events appearing in the interior of a process may bring adverse consequences and derivative problems affecting substantial elements of processes in the development of engineering projects. Events emerge as the origin of an effect on an object and a source of causes of this effect, which may be discovered in the proposed set of generic causes. Considering causes as problems, specific causes of these are identified, which are, in turn, treated as problems, for which more detailed causes may be found, and so on. Ishikawa condensed this type of reasoning in the denominated Cause-Effect Diagram, as it appears in [17], [18], [19].

The Cause-Effect Diagram is a good means in order to analyse the possible cause of fails of a product or a service. Our solution offers a frame of sixteen main causes, obtained from the generic functionalities of an object. The construction of the framework of generic functionalities takes into account the possible roles assumed by an object during his life and all aspects described in the linguistic template integrated by a verb and seven parameters or semantic functions of the verb. Main and specific causes were then validated with concepts represented in a Goals and Characteristics Model, a powerful domain model used for the development of a product line of civil engineering structures, which is treated in source [20]. The proposed framework of causes guided the collapse analysis of a support tower of a suspended bridge, in its construction period.

This article includes in Section 1, after Introduction, elements for the definition of the framework of main causes. Cause-Effect Model for risks analysis is the subject of Section 2. Section 3 contains the application of risks analysis for the collapse of a support tower of a bridge. Section 4 describes the Conclusion and Future Work. The last Section presents the References.

1. Elements for the Definition of the Main Causes Framework

Problems related to an object acting as an agent appear in its interventions or in interventions of other agents using this object in some way. An agent is responsible for actions or interactions. An agent's intervention is an action of an autonomous agent or an interaction with other agents. We represent an agent intervention, through a template, in Figure 1, integrated by a verb and seven parameters indicating semantic functions of the verb. The template incorporates a verb, a main agent, an interacting agent, an object, a verb indicating causative or descriptive facts on the object, Situation 1 and situation 2 denoting changes occurred in the object, caused by that expressed by the verb. The means and method used by the main agent complete the seven parameters. So expressed agent's intervention constitutes a knowledge unit, useful for expressing inputs, results, and objects evolutions, considering evolution, transformations, operations, evaluations and decisions.

MAIN AGENT	VERB	OBJECT	SITUATION 1	SITUATION 2	MEANS	METHOD	INTERACTING AGENT

Figure 1. Agent´s Intervention Template.

An agent's intervention enriches the knowledge incorporated in objects there included, expressed in capacities and functionalities of these objects. The knowledge-based object development considers the knowledge acquired by its intervening agents, the knowledge associated with materials, means, methods, uses, technical, technological and scientific resources, and internal and external conditions affecting its development. Useful related aspects treated in the literature are described below in this paragraph. The Knowledge-based problem solving, in physical product development is presented in [21]. Perceptual knowledge related to physical object is considered in source [22]. Application of Knowledge Based Risk Management in Buildings is the subject in source [23]. Risk analysis based on Conceptual Object-Based is found in source [24]. Source [25][26] explains the transference of explicit and tacit knowledge.

In our research, we explore another way, based on the identification and treatment of knowledge associated to functionalities of an object. Agent's interventions involve an object in its different roles occurring in all moments and circumstances in the life of this object. The life of an object is a permanent incorporation of knowledge expressed in its functionalities and capacities. This paper introduces, in an object-based approach, the Generic Categories of Object's Functionalities, Figure 2, column 1, raised from the possible roles played by the object in its life, inspired by semantic functions in the before proposed linguistic template. Other article presents an approach discovering at first the Knowledge-Based Object's Capacities centered on processes of object´s lifecycle phases.

Failures or problems in the functioning of an object correspond to problems in the realization of its functionalities. In this way, we use the sixteen discovered generic categories of an object's functionalities, listed in Figure 2, column 1, for identifying the generic causes of an object's problem. We take these generic causes as risk categories, as appear in Figure 2, column 2. The high-level causes will be the main causes in the cause-effect model in the next section.

Object's Generic Functionalities	Generic Causes of an Object' Problem (Risk Categories)
What a tangible or intangible object does with the knowledge that it requires, takes, rejects, or receives, determining or affecting its nature, functioning or evolution.	C1-Insufficiency in what a tangible or intangible object does with the knowledge that it requires, takes, rejects, or receives, determining or affecting its nature, functioning or evolution.
What an object can do with it knows and according to its nature (essential characteristics or proprieties, structure, shape, components) and its environment.	C2-Deficiency in what an object can do with it knows and according to its nature (essential characteristics or proprieties, structure, shape, components) and its environment.
What an object does with that it knows and enhances.	C3-Inadequacy in what an object does with that it knows and enhances.
What an object does with that it knows and proposes (its function).	C4-Incapacity in what an object does with that it knows and proposes (its function).
What an object does with that it knows and diversifies (as a means. method, input, resource, component, or other uses).	C5-Insufficiency in what an object does with that it knows and diversifies (as a means. method, input, resource, component, or other uses).
What an object does with that it knows and reaches to learn and adopts.	C6-Deficiency in what an object does with that it knows and reaches to learn and adopts.
What an object does with that it knows, when revised, verified, validated, correct, and rectified.	C7-Inadequacy in what an object does with that it knows, when revised, verified, validated, correct, and rectified.
What a tangible or intangible, produced or derivate object does with that it knows, keeps, enables, and offers according to its nature, functioning, or evolution.	C8-Incapacity in what a tangible or intangible, produced or derivate object does with that it knows, keeps, enables, and offers according to its nature, functioning, or evolution.
What an object does with that it knows, configurates, shows and differentiates (as a means. method, input, resource, component, or other uses).	C9-Insufficiency in what an object does with that it knows, configurates, shows and differentiates (as a means. method, input, resource, component, or other uses).
What an object does with that it knows and reaches to recognizes and delimits.	C10-Deficiency in what an object does with that it knows and reaches to recognizes and delimits.
What an object does with that it knows, when reconfigured, recuperated, isolated and particularized.	C11-Inadequacy in what an object does with that it knows, when reconfigured, recuperated, isolated and particularized.
What a tangible or intangible, produced or derivate object does with that it knows, influences, determines and stablishes according to its nature, functioning, or evolution.	C12-Incapacity in what a tangible or intangible, produced or derivate object does with that it knows, influences, determines and stablishes according to its nature, functioning, or evolution.
What an object does with that it knows, identifies, affronts and discovers (as a means. method, input, resource, component, or other uses).	C13-Insufficiency what an object does with that it knows, identifies, affronts and discovers (as a means. method, input, resource, component, or other uses).
What an object does with that it knows and reaches to aggregate, substitute, eliminate, repair adapt, strength, review, conserve, adjust, provide, support, assay, modify, correct, update and receive.	C14-Deficiency in what an object does with that it knows and reaches to aggregate, substitute, eliminate, repair adapt, strength, review, conserve, adjust, provide, support, assay, modify, correct, update and receive.
What an object, intervening as mean, object, method or agent does together with other agents on other objects, with that it knows, integrates, isolates, interferes, activates, stops, and stimulates.	C15-Inadequacy in what an object, intervening as mean, object, method or agent does together with other agents on other objects, with that it knows, integrates, isolates, interferes, activates, stops, and stimulates.
What a tangible or intangible, produced or derivate object does with that it knows, conserves, retakes, adopts, ensures and protects as technical conditions and uses according to its nature, uses, risks and challenges.	C16-Incapacity in what a tangible or intangible, produced or derivate object does with that it knows, conserves, retakes, adopts, ensures and protects as technical conditions and uses according to its nature, uses, risks and challenges.

Figure 2. Generic Functionalities, Capacities and Problem Generic Causes of an Object.

2. Construction of Cause-Effect Model for Risks Analysis

An engineering solution may be a product or service, expressed by tangible or intangible objects. The existence of an object or a solution may be seen as a space of permanent assimilation of knowledge and experiences when the object is disposed to be intervened or it is effectively intervened as an object in its role as means, resource, or method in some process and when it is able to intervene or it intervenes as an agent in this or in other processes. An agent's intervention is an independent action or an interaction with other agents.

The causes of problems associated with an object appear when it exercises its functions. We proposed in Section 1, Figure 2, a framework of generic functionalities that an object may do. Functionalities are discovered from object' roles considered in the agent's intervention template, depicted in Figure 2 Levels of knowledge incorporated by the object support the object's capacities. Limitation of generic functionalities constitute a set of generic causes of damages on an object. Generic causes constitute risk categories, which we use as top causes in the cause-effect diagram, in Figure 3. The central effect of damaged object determined by generic causes is enunciated as "Loss of the essence and functions of an object", as it is described in the cause-effect model in Figure 3. The causes C1 to C16 show as head causes of the main effect in Figure 3 are listed in Figure 2 column 2. In turn, causes as limitations of each functionality have particular causes corresponding to essential elements involved in it.

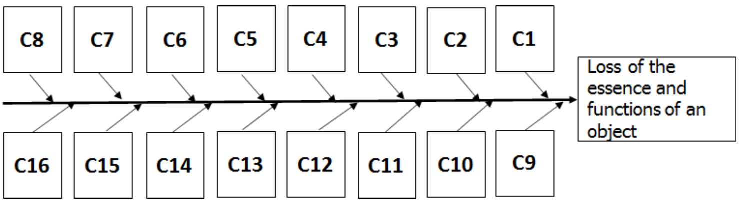

Figure 3. Cause-Effect Diagram.

Due to the extension of the whole set of causes, we show in the next paragraph, as an example, only the disaggregation of the first main cause, among 16 main causes, depicted in Figure 3.

C1- Insufficiency in what a tangible or intangible object does with the knowledge that it requires, takes, rejects, or receives, determining or affecting its nature, functioning or evolution.

- Deficiencies in previously built works
- Deficiencies in geology and soils
- Deficiencies in hydrological studies
- Inconsistency or incompleteness of technical standards used
- Inconvenient access conditions for people, equipment, materials
- Spaces and infrastructure inadequate for the construction of the works and for the operations on the site
- Adverse environmental conditions
- Deficiencies in the identification of the agents interested in the realization of the bridge and the actions and interactions that they must carry out in the processes of the phases of the bridge life cycle.
- Deficiencies in obtaining knowledge from studies, research and other sources, which must incorporate and use the bridge (as a solution). This knowledge is

treated in the actions and interactions of the interested agents so that individually and collectively they satisfy their objectives in relation to the construction and use of the bridge.

- Deficiencies regarding the suitability, capacity, and experience of those who must intervene in the execution of the works
- Failures in the scheduling of activities
- Unreliable Suppliers and Supply Scheduling
- Non-availability of machinery, equipment and adequate technical resources
- Non-availability of adequate human resources
- Poor construction methods
- Deficiencies in the management model of the work on the site (planning, organization, direction, execution, review and control)
- Deficiencies in the construction plans
- Deficiencies in the supervision of construction
- Insufficiency of advice in Construction

Main and subordinate causes affect the bridge and its support towers as one of its constituent elements. Some causes may focus on a tower as our particular study object. In the next Section, we consider in the risk analysis an extract of nine categories of causes involved in the tower collapse of a bridge and an extract of their subordinated causes.

3. Risks Analysis for the Collapse of a Support Tower of a Suspended Bridge

The causes of an effect manifested in an object (a solution), in its construction period, appear in the interventions (actions, interactions) carried out on the conceptual and/or physical elements of this solution and in its interventions (actions and interactions) or of one of its constituents with other agents, including natural agents, in a predictable or unpredictable way. The main damage causes and their disaggregated causes constitute the proposed risk analysis model, which drives ex-post risks analysis for understanding the collapse cause of a tower of a pre-stressed stayed bridge, in the construction stage. In this stage, in addition to the previous interventions, appear the interventions (actions and interactions) of the object (solution) with multiple agents in different contexts, and the use of that object (solution), as a means, resource or as an input in the previous and ulterior processes.

Causes-Effect Analysis in the Collapse of a Stayed Bridge Tower (a solution constituent), in the period of construction of the bridge, starts with the identification of the main effect (problem): the collapse of a stayed bridge tower.

The tower directly or through its constituent elements and the relationships between them performs functionalities within the framework of generic functionalities introduced in Figure 2. Said functionalities reveal categories of causes for the problems that may arise in the tower during its construction and during the construction period of the other complementary objects of the bridge as a whole solution.

The framework of causes, introduced in Section 2, considers nine general causes and within each one, more specific causes are stated, and for each one of these, detailed causes appear. In some categories, this disaggregation of causes reaches only the second level in our example. The disaggregation of causes runs in general until the level that the available knowledge allows. The nine categories of causes correspond to the tower in its construction period. The other seven causes belong to the ulterior lifecycle phases after the construction phase.

The present Section shows only 9 generic causes, (C1, C2, C3, C4, C5, C6, C7, C8, and C15), among 16 depicted in Figure 3, and their subcategories, needed to explaining, in an ex-post analysis, the collapse of the Chirajara bridge's tower, in Colombia, during the construction period. The first 8 main causes belong to the construction period, while the C15 corresponds to interaction with other agents, when the tower works during the whole bridge construction period. The depuration of those selected causes, using results of studies of interested parts and in situ observation, gave the nine specific causes highlighted bellow in bold italic type. The risk analysis model, originally conceived for anticipating solution for eventual future problems, supports the analysis and understanding the risks materialization in problems, and finally the explanation of causes of the tower collapse.

3.1 Extract of Causes considered in tower collapse.

C1-Insufficiency in what a tangible or intangible object does with the knowledge that it requires, takes, rejects, or receives, determining or affecting its nature, functioning or evolution.
-Deficiencies in previously built works
-Deficiencies in geology and soils
-Deficiencies in hydrological studies
-Inconsistency or incompleteness of technical standards used
-Deficiencies regarding the suitability, capacity, and experience of those who must intervene in the execution of the works
-Poor construction methods
-Deficiencies in the management model of the work on the site (planning, organization, direction, execution, review and control)
-Deficiencies in the supervision of construction
-Insufficiency of advice in Construction
C2-Deficiency in what an object can do with it knows and according to its nature (essential characteristics or properties , structure, shape, components) and its environment.
-Deficiencies in the conceptual structural model
C3-Inadequacy in what an object does with that it knows and enhances.
-Effect of the earthquake in the construction period
-Changes in geology, soils and hydrology after their studies, before and during the construction period
-Electric shock, winds and temperature changes in the construction period
-Manipulation of the built tower.
C4-Incapacity in what an object does with that it knows and proposes (its function).
-Deficiencies in the geometric properties (dimensions) of the tower and its components
-Deficiencies in materials
-Deficiencies in design methods
C5-Insufficiency in what an object does with that it knows and diversifies (as a means. method, input, resource, component, or other uses).
-Use of the tower or its components as support during construction
-Changes in the logical model of the structure caused in the construction
-Submit the tower or its components to unforeseen loads in terms of intensity or location during the construction period of the tower or of the bridge
C6-Deficiency in what an object does with that it knows and reaches to learn and adopts.

-Changes in the mechanical properties of materials.
-Changes in the quantity and proportion of materials
-Changes in the internal structure of the tower. Changes in its components and in its organization.
C7-Inadequacy in what an object does with that it knows, when revised, verified, validated, correct, and rectified.

Causes that demand radical interventions:
-Insufficiency (Lack) of one or more elements of the tower.
-Loss of validity of one or more elements of the tower.
-Intromission or obstruction of one or more elements in the operation of the tower as a whole.
Causes that demand moderate interventions:
-Damage, deficiency, deterioration of one or more elements of the tower.
-Incapacity of one or more elements of the tower to fulfil some functions, assimilate changes in a context or behave within it.
-Saturation or limit requirement of the capacities of one or more elements of the tower.
The two types of causes detailed above in turn constitute problems that call for radical or moderate interventions (solutions).
C8-Incapacity in what a tangible or intangible, produced or derived object does with that it knows, keeps, enables, and offers according to its nature, functioning, or evolution.
-insufficiency of a constituent of the constructed tower
-Deficiency in objects, which behaviour affects the tower, during or after the construction time.
-Incorporation of cracks, alterations of the sections, modifications in the quality of the materials, and changes in the arrangement and treatment of the constituent elements, affecting the behaviour of the tower during its construction and in the construction period of other works of the project
C15-Inadequacy in what an object, intervening as mean, object, method or agent does together with other agents on other objects, with that it knows, integrates, isolates, interferes, activates, stops, and stimulates.
The object, in interactions with other objects, can act as a whole or as some of its parts.
Causes that demand radical interventions:
-Dispersion or divergence of constituent elements of the tower
-Disturbance or loss of connection of a constituent element of the tower due to the presence or actions of other elements or other external objects
Causes that demand moderate interventions:
-Suspension or extinction of functions of one or more constituent elements of the tower in relation to other elements
-Activity, movement or unwanted behaviour of one or more constituent elements of the tower affecting other elements
- Decrease or depletion of the ability of one or more constituent elements of the tower for acting in its relationship with other elements.

3.2 Collapse Cause Analysis

Last resume of causes contains only the possible causes more directly involved in collapse of a Chirajara bridge's tower, in Colombia. The depuration of those selected causes, using the results of studies of involved parts and in situ observation, gave the nine causes highlighted in grey colour. For the analysis of the selected causes and then depurate causes, the designers used worldwide recognized linear and nonlinear structural analysis methods, and the critical analysis of six studies contracted by interested parties in the bridge project development, as he exposes it in source [27]. Furthermore, designers considered independent structural analysis carried out by other designer, contracted by the bridge constructor, in source [28], and the evaluation of the tower behaviour realized by the prestigious consultant Cervenka, referred in soures [29], [30]. The study of causes considered in subsection 3.1, according to the referred critical analysis of six studies mentioned in the last paragraph, verified the certitude of the bridge design and highlighted the obligated occurrence of external extreme forces surpassing the preventable limits. The search of these forces considered the events perceived by workers at the moment of the tower failure, any earthquake registered at this moment, the way as the tower collapsed, the state of the structure and soil, before and after the collapse, the state of surrounding areas, particular cut surfaces of the tower constituents, and the settlement of 5 cm of the tower foundation. Cerveka simulated these conditions and probed the high magnitude of forces required for causing the collapse. The sudden settlement appears as a generator of an external force, determinant of the tower collapse. The results of studies executed by designers, consultants, and other firms guided an arbitration tribunal, convoked by the constructor and the concessionaire of the work, to exempt the design and the designer of responsibilities in the tower collapse.

4. Conclusion and Future Work

The product-based analysis allows discovering the generic capacities and functionalities of an object in terms of roles that it can assume. These generic abilities aid to overcome the high abstraction grade and subjectivity of a product-based model compared with a process-based one. Linguistic template based on grammar cases considers the roles of objects and supports the knowledge modelling. The incorporation of knowledge in an object (a solution) using linguistic structures supports the extension of engineering to any knowledge field in transdisciplinary approaches. Ongoing work aims at establishing a process grammar for supporting the computational linguistic in any knowledge field. Actions, activities, processes. mega processes and higher structures cantered on the verb, considered in our research, open other ways for the language research, useful in computational linguistic. In the development of tangible and intangible solutions, the product-based risk analysis model offers ample way for understanding the essence, qualities, and behaviour of objects. Cause-effect modelling shows the behaviour of objects during their life. Cause-effect constitutes an expressive option for determining risk categories and orienting the risk analysis of solution.

References

[1] C. Kendrick, Overcoming project risk: lessons from the PERIL database. *PMI® Global Congress 2003*, North America, Baltimore, Project Management Institute. Newtown Square, 2003.

[2] T. Kendrick, *Identifying and Managing Project Risk*, 2d Edition. Amacom, New York, 2009.

[3] P.X.W. Zou, G. Zhang, and J. Wang, Understanding the key risks in construction projects in China, *International Journal of Project Management*, 2007, Vol. 25, pp. 601-614.

[4] G. Urrego-Giraldo, G.L. Giraldo G. Process Modeling for Supporting Risk Analysis in Product Innovation Chain, *20th ISPE International Conference on Concurrent Engineering*, Melbourne, 2013, IOS Press Amsterdam, pp 469-480.

[5] WCED. *Our Common Future: The World Commission on Environment and Development*. Bruntland Report, Oxford University Press, New York, 1987.

[6] R. Chambers, Vulnerability, Coping and Policy, *IDS Bulletin, Institute of Development Studies, University of Sussex, Brighton (England)*, April 1989, Vol. 20, No. 2. pp. 1-7.

[7] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandic and W. Verhagen, Transdisciplinary systems engineering Implications, challenges and research agenda, *International Journal of Agile Systems and Management*, 2019, Vol.12, No.1, pp. 58 - 89.

[8] G. Hirsch Hadorn, S. Biber-Klemm, W. Grossenbacher-Mansuy, H. Hoffmann-Riem, D. Joye, Ch. Pohl, U. Wiesmann, E. Zemp. The Emergence of Transdisciplinary as a Form of Research. In Handbook of Transdisciplinary Research. Ed. Springer Verlag, Bern, pgs. 19-42. 2008.

[9] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, W. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, Vol. 7, 2018, pp. 753-762.

[10] G. Hirsch Hadorn, D. Bradley, C. Pohl, St. Rist, and U. Wiesmann. Implications of Transdisciplinarity for Sustainability Research, *Ecological Economics*, 2006, Vol. 60, Issue 1, pp. 119-128.

[11] G. del Cerro Santamaría, Towards Transdisciplinary Urbanism: Megaprojects, Power and the Urban Imagination. *Transdisciplinary Journal of Engineering & Science*, 2018, Vol. 9, pp. 23-36.

[12] G. Urrego-Giraldo, G.L. Giraldo G., Engineering of Social Complex Realities, *Advances in Transdisciplinary Engineering*, Vol. 10, pp. 625-634.

[13] G. Urrego-Giraldo, *ABC-Besoins: Une approche d'ingénierie de besoins fonctionnels et non-fonctionnels centrée sur les Agents, les Buts, et les Contextes*. Ph.D. Thesis, Universidad Paris 1, Pantéon Sorbona, 2005.

[14] C. Fillmore, The case for case, The Ohio State University, 1967, http://files.eric.ed.gov/fulltext/ED019631.pdf, Accessed: July, 3 2021.

[15] J.C. Foronda, *Construcción de un modelo lingüístico para la representación del conocimiento contenido en textos escrito en lenguaje natural*. Tesis de Maestría. Universidad de Antioquia, Medellín, Colombia, 2013.

[16] J.C. Foronda, G. Urrego, G. Giraldo, Identification of Knowledge Units Contained in Spanish Texts. In: G. Quiroz Herrera and P. Patino Garcia (eds.), *LSP in Colombia: Advances and challenges*, Peter Lang, Berlin, 2014, pp. 85-102.

[17] K. Ishikawa, *Introduction to Quality Control*, Springer, Dordrecht, 1990.

[18] M. Coccia, The Fishbone diagram to identify, systematize and analyze the sources of general-purpose technologies. *Journal of Social and Administrative Sciences*, 2017, Vol. 4, Issue 4, pp. 291-303.

[19] K. Ishii and B. Lee, Reverse fishbone diagram: a tool in aid of design for product retirement, *Proceedings ASME design engineering technical conferences and computers in engineering conference, 96-DETC/DFM-1272*, 1996.

[20] G. Urrego-Giraldo, G.L. Giraldo G. and Olga-Eugenia Urrego, Introduction of a Goals and Characteristics Model for Implementing the Product Line Concepts: An Application in Civil Engineering, *Advances in Transdisciplinary Engineering*, Vol. 4, pp. 778-787.

[21] P. Burggräf, J. Wagner, Tim Weißer, Knowledge-based problem solving in physical product development. A methodological review, *Expert Systems with Applications*, 2020. Vol. 5, 100025.

[22] R.G. Meyers, Perceptual Knowledge and Physical Objects. In: *The Likelihood of Knowledge*. Philosophical Studies Series, Vol 38, Springer, Dordrecht, 1988, pp. 106-133.

[23] Y. Zou, S.W. Jones, and A. Kiviniemi, BIM and Knowledge Based Risk Management System: A Conceptual Model. *Conference: CITA BIM Gathering 2015*, November 12th -13th 2015, pp. 63-68.

[24] A.R. Short, *Design of Autonomous Systems for Survivability through Conceptual Object-Based Risk Analysis*, Colorado School of Mines. Thesis for the degree of Master of Science, 2011.

[25] C. Dhanaraj, M.A. Lyles, H.K. Steensma and L. Tihanyi, Managing tacit and explicit knowledge transfer in IJVs: the role of relational embeddedness and the impact on performance, *Journal of International Business Studies*, 2004, Vol. 35(5), pp. 428-442.

[26] N. Wognum, M. Wever, J. Stjepandić, Managing risks in knowledge exchange: Trade-offs and interdependencies, *Advances in Transdisciplinary Engineering*, 2016, Vol. 4, pp. 15-24.

[27] H. Urrego, How Powerful are the Models? *Risk Intelligence of Infrastructures. IABSE Conference*, Seoul, Korea, November 2020, S7-5.

[28] ICC. *Structural Review Technical Report under construction conditions Chirajara Bridge* (Spanish). July 16 2018. Medellín Colombia.

[29] N.N., *Investigation of Chirajara Bridge Collapse Task 1: Pushdown analysis*, Cervenka Consulting. 2018.

[30] N.N., *Investigation of Chirajara Bridge Collapse Task 3: Dynamic analysis*, Cervenka Consulting. 26-10-2018.

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Lifecycle's Processes-Based Categories for the Risk Analysis in the Development of Engineering Solutions: An Application to Civil Structures Development

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Abstract. Process concept gathers agents' action and interaction on objects and their associated knowledge, belonging to one of several domains, supported on Transdisciplinary Engineering concepts. An engineering solution is a tangible or intangible object able to satisfy the solution requirements. A solution incorporates knowledge and develops capacities and functionalities in processes of its lifecycle phases. The risk analysis in engineering solutions development is, in general, treated with particular risks frameworks selected or adapted to each project development. Damage risks of an object (solution) correspond to troubles in processes of its life cycle. Our research introduces a framework of generic capacities and another of functionalities of a solution and it uses generic functionalities as risk categories for classifying risks of damages of a solution. The use of knowledge expressed as object's capacities involving the recognized purposes of each lifecycle's phase, and object's functionalities derivate from object's capacities, constitute a contribution of this paper. In this process-based approach, the disaggregation of risk categories in specific risks aspects coincides with the disaggregation of risks categories in a product-based approach using a cause-effect model for the definition of risk categories. This mutual confirmation of both approaches enables their enhancement and use in any engineering field. The proposed risk analysis model supports the ex-post risk analysis of a collapsed tower of a pre-stressed stayed bridge in the field of civil structures development.

Keywords. Transdisciplinary Engineering, Risk Analysis, Civil Structures Risks

Introduction

A problem perceived by agents interested in a domain constitutes a demand of agents' interventions on material or immaterial objects of this and other domains. In the field Requirements Engineering, fundamental concepts of Domain Engineering are proposed [1], an introduction to Domain Analysis is the subject in [2], and a metamodel of domain is explained in [3]. An agent is responsible of an individual action or an interaction with other agents. An agent's intervention is an action of an autonomous agent or an activity or a process or mega-process involving the interactions of several agents. Thus, a domain is a field of knowledge and work, composed by interrelated tangible and intangible objects, where agents intervene in order to satisfy their goals. Context concept, as environment affecting a solution along its lifecycle, may have diverse representations, treated among others by [4], adds interactions capacities to solutions, in [5] and aids to construction and use of families of solutions, in [6]. This context concept supports in [7], [8] mobile and ubiquitous solutions incorporating context-awareness facilities. Other concept of context based on interested agents, characterized as agent's intervention context, is the central aspect in the requirements engineering approach presented in [9]. Agents intervene on domains' objects or knowledge related to these objects. Agents' interventions constitute contexts, where domains' knowledge acquire meaning and value. An Agents Interventions Context considers a set of agents, their interventions, circumstances that determine these interventions, the used means and methods, context's objectives and agents' goals and decisions. Context and domain concepts constitute a knowledge partition, in [9], [10]. The process concept delimits context and domain knowledge in [9].

In terms of context and domain, a process is a set of action and interactions of agents, which work on tangible and/or intangible objects belonging to one or several domains, progressing from initial or delayed supplies or contributions, using proper means, methods, and resource; and aiming at the obtaining of results, which satisfy individual and/or collective agents' objectives. In this sense, a process is an operative context, that is, a context applied on one or several domains looking for specific results. It is the application of a context on one or several domains in order to create value.

The development of a solution in engineering fields is a sequence of processes from the recognition of a problem and the first idea of a solution, to its elaboration, use, evolution, evaluation and end of its life. Project concept, in [11] guides the achievement of solution. The probability of an undesirable effect, coming from different causes, constitutes a risk. Risks in the development of an engineering solution are associated with its sequence of processes. Risk analysis in processes of a product innovation chain is introduced in [12]. Experiences of risks analysis in process of the Civil Engineering projects development are condensed in [13], [14], [15].

Risk analysis has had ample deployment in engineering projects, as it is condensed in the PERIL database, English acronymous for Project Experience Risk Information Library, in [16]. These projects use, in general, particular frameworks, representatives for each project, with approaches ranging in the Cross-engineering concept. We pursue now integrating methods of requirement engineering with methods of other knowledge disciplines in projects of these ones, reaching the field of Transdisciplinary Engineering, which concepts are considered in [17], [18]. The Transdisciplinarity as a research form is developed in [19]. This research is extended to sustainability in [20]. Transdisciplinarity in urban megaprojects is treated in [20]. The diversity of projects aiming to solutions in any activity field suggest generalizing a model of phases for project development in any knowledge area. Each phase represents a big process with particular results. Thus, a project development constitutes a set of big processes with a specific product of each one. Each specific product represents the capacities acquired by the solution in a particular phase. The solution, as a result of a project, incorporates all capacities acquired in each development phase. Acquired capacities, in each phase, are associated with the knowledge assimilated by the solution in this phase, in a similar way as human beings develop capacities in each development phase during their life. Going from living beings to engineering products, the lifecycle concept makes sense as a sequence of phases for incorporating and experiencing new knowledge. Based on capacities acquired, a solution can answer questions related to its real and potential functionalities. Models based in these questions in each phase of the life cycle extends the concept of project and its development methods beyond the knowledge disciplines limits. Engineering as knowledge for creating and applying methods and developing processes may cover all fields of knowledge and science.

The analysis of risks in the development of civil structures is a big concern for all involved agents. Many probable causes of fails, coming from a diversity of natural, human, and technological agents, may appear in the development processes of a engineering civil structural solution. The development of a civil structural element consists in a set of processes classified in phases framed in the following categories: pre-construction, construction, post construction, and functioning or use. These categories are high-level processes containing disaggregated processes associated with each phase.

We propose, in our process-based risks analysis model approach, a framework of object's capacities and functionalities associated with each recognized phase in the mentioned categories, for the identification of risks. This framework, based on processes, guides the identification of risks in the phases of life cycle of solutions in any knowledge field. Here, we apply this framework in pre-construction and post-construction phases in the lifecycle of a support tower of a pre-stressed suspended bridge, in Colombia. This experience allows us to compare the risk analysis effectuated with a framework of causes applied in a cause-effect model, which is a product-based approach. This comparison constitutes a mutual validation of processes-based and causes-based frameworks used for the risks analysis and offers specific and pertinent concepts to the use of risk models covering the identification, classification, and treatment of risks in civil structures solutions.

After the Introduction, this article presents in Section 1 the concepts of lifecycle and its processes, used in the identification of Risk Categories, and explains the construction of the Process-Based Risk Categories Model. The application of the Process-Based Risks Categories Model in the risk analysis of a support tower of a suspended prestressed bridge belongs to Section 2. Conclusion and future work constitute Section 3. Bibliography appears in the last Section.

1. Risk Analysis Model for the Engineering Project Lifecycle

The existence and behaviour of a tangible or intangible object representing an Engineering solution may be followed throughout its presence in processes along its life. These processes are gathered in phases of the Object-lifecycle supporting a process-based knowledge and functionalities acquisition. Failures of and object are experienced in excising it functionalities. Object's generic functionalities constructed along its lifecycle phases are expressive risk categories useful for the risk analysis of an Engineering solution.

1.1 Lifecycle Processes Used in the Identification of Risks Categories

The concept of lifecycle characterizes in an expressive way the development of living and inanimate objects, considering meaningful phases between their birth and death. An engineering solution is a tangible or intangible object able to satisfy the solution requirements. The sequence of processes that constitutes the existence of an object defines the lifecycle's phases. These represent big processes with specific and consolidated results, and conform stages referred to macro processes, which involve new agents, methods, means and circumstances.

Lifecycle Phases	Knowledge-Based Object Capacities	Object's Generic Functionalities (Risk categories)
Stage 1: Pre-construction		
Definition	What **it must** potentially do	What a tangible or intangible object does with the knowledge that it requires, takes, rejects, or receives, determining or affecting its nature, functioning or evolution.
Analysis: Requirements Study	What **it expects** potentially do	What an object can do with it knows and according to its nature (essential characteristics or proprieties, structure, shape, components) and its environment.
Analysis: Logical Model	What **it could** potentially do	What an object does with that it knows and enhances.
Design	What **it will** potentially do	What an object does with that it knows and proposes (its function).
Stage 2: Construction		
Planning	What **it must** do when concretized or implemented	What an object does with that it knows and diversifies (as a means. method, input, resource, component, or other uses).
Construction	What **it expects** to do when concretized or implemented	What an object does with that it knows and reaches to learn and adopts.
Testing	What **it could** do when concretized or implemented	What an object does with that it knows, when revised, verified, validated, correct, and rectified.
Operation	What **it will** do when concretized or implemented	What a tangible or intangible, produced or derivate object does with that it knows, keeps, enables, and offers according to its nature, functioning, or evolution.
Stage 3: Post-construction		
Programming and preparing the distribution	What **it must** do when put into practice or delivered	What an object does with that it knows, configurates, shows and differentiates (as a means. method, input, resource, component, or other uses).
Distribution	What **it expects** do when put into practice or delivered	What an object does with that it knows and reaches to recognizes and delimits.
Post-production Service	What **it could** do when put into practice or delivered	What an object does with that it knows, when reconfigured, recuperated, isolated and particularized.
Impact evaluation	What **it will** do when put into practice or delivered	What a tangible or intangible, produced or derivate object does with that it knows, influences, determines and stablishes according to its nature, functioning, or evolution.
Stage 4: Functionning or use		
Change identification	What **it must** do when functioning, used, and changed	What an object does with that it knows, identifies, affronts and discovers (as a means. method, input, resource, component, or other uses).
Application of Evolution Categories	What **it expects** to do when functioning, used, and changed	What an object does with that it knows and reaches to aggregate, substitute, eliminate, repair adapt, strength, review, conserve, adjust, provide, support, assay, modify, correct, update and receive.
Interaction with other agents	What **it could** do when functioning, used, and changed	What an object, intervening as mean, object, method or agent does together with other agents on other objects, with that it knows, integrates, isolates, interferes, activates, stops, and stimulates.
Mantainning of integrity, correction, consistency, and technical conditions	What **it will** do when functioning, used, and changed	What a tangible or intangible, produced or derivate object does with that it knows, conserves, retakes, adopts, ensures and protects as technical conditions and uses according to its nature, uses, risks and challenges.
Solution's uses as a means, method, ressource, component, input, and other uses		

Figure 1. Capacities, Processes of Solution and Risk categories.

The lifecycle, Figure 1, contains, in line 1, 6, 11, and 16, four stages (macroprocesses): Pre-construction, Construction, Post-construction, and Functioning or Use. Thinking in one whole process for the development project of a solution, the four stages constitute, in the same order, in column 5 of Figure 1, the four steps of a process: Input, Evolution, Evaluation and Decision, and Output.

Each stage, Figure 1, lines 1, 6, 11, and 16, in turn, contains four lifecycle's phases, Figure 1, column 1, according to the four steps of the respective macro-process in Figure 1, column 2, associated to this stage: Input, Evolution, Evaluation and Decision, and Output. In each one of the sixteen phases listed in column 2, the solution incorporates knowledge, expressed then, in capacities acquired and offered by the solution in this particular phase. These capacities denominated Knowledge-Based Object's Capacities appear in Figure 1, column 3.

1.2 Construction of the Process-Based Risks Categories Model

Object's functionalities are practical uses of object's capacities in order to satisfy requirements or goals of agents involved in processes of the object's lifecycle. Object's problems, which are risks materialization, occur in the exercise of object's functionalities. Object's generic functionalities derivate from object's generic capacities, listed in Figure 1, column 4, constitutes the risk categories of the proposed risk analysis model.

Requirements Engineering searches to find solutions, which resolve a problem satisfying defined requirements. As matter of knowledge and sensitivity solutions are tangible or intangible objects, whose existence, development, use, and roles are important in all fields of knowledge. In Engineering, by example, the amplitude of concepts such as object, process and method allow the apparition of Interdisciplinary, Multidisciplinary, Transdisciplinary and Supra-disciplinary Engineering and the intervention of these expressions of Engineering in all fields of the science. Supra-disciplinary looks for solutions assuming processes of human, and social sciences, cooperating in the creation, development, and application of methods of these sciences.

The next Section illustrates the application of the risk analysis model, using risk categories with their specific risk aspects, to the collapse analysis of a suspended bridge tower.

While in [15], authors introduced the Knowledge-Based Generic Functionalities of an object. Here, we establish the relationship between lifecycle's phases and Knowledge-Based Capacities and their derivate generic functionalities. In both approaches acquired knowledge expressed object's capacities is the same and the corresponding knowledge-based functionalities coincide too. The risk categories headed by objects' functionalities or limitations to the exercise of these functionalities involve the same risks subcategories.

2. Risks Analysis of a support tower of a suspended prestressed bridge

We apply the framework of risk categories for the ex-post analysis of the collapse of a stayed bridge tower, in the construction period of the Chirajara bridge superstructure, in Colombia. This bridge of 450 meters long was suspended by cables crossing over two towers with a central span of 300 meters. When events occur, the risk of damage to an object derives from problems. In the case referred to in this research, a support tower collapsed and we with designers together use the risk model for establishing and explaining events, risk concepts, and how problems materializing risks happened. The tower was constructed, and was being used in the elaboration process of the bridge superstructure. Only the processes of pre-construction and construction stages intervened in the tower, from the definition phase to the operation phase of its lifecycle. Under these circumstances, the analysis of the tower collapse considers the following elements extracted from Figure 1, column 4: the eight first risks categories, and the category 15th, named "Interaction with other Objects", corresponding to the third process of the stage 4, denominated "Functioning and Use". In fact, the bridge was in the construction stage and the tower was not ready, neither submitted to processes of the stage 3, nor other processes of stage 4, except the third process.

The next paragraphs present the involved risk categories and their subordinated specific risk concepts. A preliminary analysis allowed us together with designers and constructors to take the possible risk subcategories affecting the tower, according to its development state. Then, our research group, designers and constructor selected, based on specialized technical studies, the risks concepts more directly influencing the tower behaviour at the time of its collapse. These concepts are highlighted in bold italic type. R1, R2, R3, R4, R5, R6, R7, R8, and R15 are the involved risk categories, disaggregated in their specific risk subcategories until the second level.

R1 What a tangible or intangible object does with the knowledge that it requires, takes, rejects, or receives, determining or affecting its nature, functioning or evolution.

a) Deficiencies in previously built works. b) Deficiencies in geology and soils. c) Deficiencies in hydrological studies. d) Inconsistency or incompleteness of technical standards used. e) Inconvenient access conditions for people, equipment, materials. f) Spaces and infrastructure inadequate for the construction of the works and for the operations on the site. g) Adverse environmental conditions. h) Deficiencies in the identification of the agents interested in the realization of the bridge and the actions and interactions that they must carry out in the processes of the phases of the bridge life cycle. i) Deficiencies in obtaining knowledge from studies, research and other sources, which must incorporate and use the bridge (as a solution). This knowledge is treated in the actions and interactions of the interested agents so that individually and collectively they satisfy their objectives in relation to the construction and use of the bridge. j) Deficiencies regarding the suitability, capacity, and experience of those who must intervene in the execution of the works. k) Failures in the scheduling of activities. l) Unreliable Suppliers and Supply Scheduling. m) Non-availability of machinery, equipment and adequate technical resources n) Non-availability of adequate human resources. o) Poor construction methods. p) Deficiencies in the management model of the work on the site (planning, organization, direction, execution, review and control). q) Deficiencies in the construction plans. ***r) Deficiencies in the supervision of construction***. s) Insufficiency of advice in Construction.

These first causes affect the bridge and the tower as one of its constituent elements.
The following categories focus on the tower as the object of study that interests us.
R2 What an object can do with it knows and according to its nature (essential characteristics or proprieties, structure, shape, components) and its environment.

a) Insufficiencies in the definition of the requirements that the work must satisfy in terms of its operation and quality. b) Deficiencies in the operationalization of the requirements. c) Deficiencies in the logical structural model. c1) Structure (constituent elements and their relationships) not adequate. c2) Inappropriate form.

c3) Inadequate allocation of forces. c4) Inadequate consideration of the application of forces. c5) Inadequate structural analysis method.

R3 What an object does with that it knows and enhances.

a) Effect of the earthquake in the construction period. ***b) Changes in geology, soils and hydrology after their studies, before and during the construction period***. c) Electric shock, winds and temperature changes in the construction period. d) Manipulation of the built tower.

R4 What an object does with that it knows and proposes (its function).

a) Deficiencies in sections. a1) Insufficient dimensions. a2) Insufficiency of the steel area. a3) Insufficient cable area. a4) Insufficiency of the concrete area. a5) Coating deficiencies (compression reinforcement depth). a6) Deficiencies in surface treatments. b) Deficiencies in materials. b1) Insufficient quantity or proportions of materials (concrete, steel rods, steel cable, precast elements, plastic elements and other materials). b2) Deficiencies in the mechanical properties of materials (Ductility, flexibility, adherence, compressive strength, modulus of elasticity, yield point, yield strength). b3) Deficiencies in the behaviour of materials (elastic, plastic). b4) Deficiencies in treatments and their management. c) Deficiencies in design methods.

R5 What an object does with that it knows and diversifies (as a means. method, input, resource, component, or other uses).

a) Use of the tower or its components as support during construction. b) Changes in the logical model of the structure caused in the construction. ***c) Submit the tower or its components to unforeseen loads in terms of intensity or location during the construction period of the tower or of the bridge.***

R6 What an object does with that it knows and reaches to learn and adopts.

a) Changes in the mechanical properties of materials. b) Changes in the quantity and proportion of materials. c) Changes in the internal structure of the tower. d) Changes in its components and in its organization.

R7 Inadequacy in what an object does with that it knows, when revised, verified, validated, corrected, and rectified.

The deficiencies on different elements can appear simultaneously giving rise to a coincidence and chain of deficiencies in multiple elements of the tower.

Reasons that demand radical interventions:

a) Insufficiency (Lack) of one or more elements of the tower. ***b) Loss of validity of one or more elements of the tower***. c) Intrusion or obstruction of one or more elements in the operation of the tower as a whole.

Reasons that demand moderate interventions:

a) Damage, deficiency, deterioration of one or more elements of the tower. ***b) Incapacity of one or more elements of the tower to fulfil some functions, assimilate changes in a context or behave within it***. c) Saturation or limit requirement of the capacities of one or more elements of the tower. d) Deterioration, mismatch, lag of one various elements of the tower as a whole that limit its operation and capabilities. e) Existence, expansion or inappropriate behaviour of one or more elements of the tower. f) Wrong or abnormal behaviour of one or more elements of the tower. g) Loss of significance or validity of one or more elements of the tower. h) Loss of capacity, resources, or efficiency of one of several elements of the tower to achieve the results.

The two types of reasons detailed above, in turn, constitute problems that call for radical or moderate interventions (solutions), such as:

Radical interventions: aggregation, substitution, elimination

Moderate interventions: repair, adaptation, strengthening, maintenance (review, conservation, adjustment, provision, support, attention), modification, correction, update, recovery

The above reasons are deficiencies that have in turn a possible set of reasons, such as:

a) Changes in the location of other works of the project. b) Changes in the design of the set of works of the project. c) Changes in geology, in the soil in hydrology after its construction. d) Changes in pre-existing works. e) Changes in the earthquake regime after their construction. f) Changes in environmental conditions. g) Changes in the spaces and infrastructure to carry out the other works of the project. h) Changes or alterations of the construction processes of the other works of the project. i) Changes in the means and methods used for the other works of the project. j) Accidental or malicious actions on the processes, materials, the tower and its constituent elements.

R8 What a tangible or intangible, produced or derivate object does with that it knows, keeps, enables, and offers according to its nature, functioning, or evolution.

a) Insufficiency of a constituent of the constructed tower. ***b) Deficiency in objects, which behaviour affects the tower, during or after the construction time.*** c***)*** Deficiencies in the consideration of stresses and elastic deformation. d) Accumulated tension losses in cables. e) Deficiencies in the consideration of the yield point and the breaking moment. f) Deficiencies in the consideration of behaviour of cracked sections. g) Deficiencies in the consideration of the maximum moment and the ultimate resistance. h) Deficiencies in the consideration of the collapse of the structure and memento-curvature. i) Incorporation of cracks, alterations of the sections, modifications in the quality of the materials, and changes in the arrangement and treatment of the constituent elements, affecting the behaviour of the tower during its construction and in the construction period of other works of the project.

R15 Inadequacy in what an object, intervening as mean, object, method or agent does together with other agents on other objects, with that it knows, integrates, isolates, interferes, activates, stops, and stimulates.

The deficiencies on different components can appear simultaneously giving rise to coincidences and concatenations of deficiencies in multiple elements of the tower.

In its interactions with other objects, the tower and its interacting agent affect other objects, tangible or intangible. These interactions use means and methods, and consider the situations or circumstances of the objects on which they act, as well as, those circumstances affecting the used means and methods.

In these interactions with other objects, the object can act as a whole or some or some of its parts. In these cases, risk categories indicated possible object damages requiring radical or moderated interventions.

Causes that demand radical interventions:

a) Dispersion or divergence of constituent elements of the tower. b) ***Disturbance or loss of connection of a constituent element of the tower due to the presence or actions of other elements or other external objects.*** c) Presence or improper action of a constituent element of the tower in the place or trajectory of others

Causes that demand moderate interventions:

a) Suspension or extinction of functions of one or more constituent elements of the tower in relation to other elements b) Activity, movement or unwanted behaviour of one or more constituent elements of the tower affecting other elements c) Decrease or depletion of the ability to act of one or more constituent elements of the tower in its relationship with other elements.

The causes in turn constitute problems that demand radical or moderate interventions (solutions), such as:
Radical interventions: integration, isolation, interference.
Moderate interventions: activation, stopping, stimulation.

For the risk analysis, the bridge designer used recognized linear and nonlinear structural analysis and design methods, took in account 6 studies contracted by interested parts, an independent structural analysis carried out by a different designer, requested by the bridge constructor, and in situ observations and inspections, as well as, phenomena noticed by workers before the collapse. In fact, these ones perceived movements and sounds before the collapse, although any earthquake was registered. The mentioned technical contributions are condensed in [22], [23]. The critical analysis of the six demanded studies verified the certainty of the bridge design and revealed the existence of extreme forces surpassing the magnitude of predictable limits. The search of these forces considered the settlement of five centimetres of the tower foundation after the tower collapse, constated in situ phenomena there perceived before the collapse, the way as the tower felt down, the state, position and cut surfaces of tower constituents, and the final state of work site and surrounding areas. The evaluation of the tower behaviour and the simulated push down, realized by the world-wide known consultant Cervenka, in [24] [25], confirm the high magnitude of forces required for causing the tower collapse. The sudden settlement of the tower foundation appears as originator of external forces and determinant of the tower collapse. The referred studies, phenomena and detailed analysis presented by the designer and constructors supported the exoneration of the design and designer of responsibilities in the tower collapse, decided by an Arbitration Tribunal convoked by the Constructor and the work Concessionaire.

3. Conclusion and Future Work

The development of a solution in any engineering field involves a set of processes. A solution is a tangible or intangible object developed along its lifecycle. The concept of lifecycle allows to organize processes in lifecycle phases grouped in four stages: Pre-construction, Construction, Post-construction, and Functioning or Use.

Unwished effects on an object constitutes limitations to its capacities and functionalities, coming from troubles in processes of its lifecycle. Risks are classifiable into Generic Functionalities of a solution achieved in processes of its lifecycle phases.

The here proposed process-based risks categories cantered on generic functionalities coincide the product-based risks categories oriented by cause-effect proposed in [21].

The correspondence between generic functionalities of a solution and generic causes of the solution damage unifies the detailed disaggregation of risks aspects in both approaches, cause-effect and process based, applied to an ex-post risks analysis of a stayed bridge tower.

Ex-post risk analysis of the collapsed tower allowed discard the design responsibility and drove the study of soil and geological conditions causing sudden settlement of the tower foundation. The mutual confirmation of useability of product-based cause-effect and process-based functionalities approaches strengthen the capacities of both approaches and support their development and applicability in many engineering fields

Reference

[1] J. Neighbors, *Software Construction Using Components*, Ph.D. Thesis, Department of Information and Computer Science, University of California, Irvine, 1981.

[2] R. Prieto-Diaz, Domain Analysis: an introduction, *ACM SIGSoft Software Engineering Notes*, 1990, Vol. 15, No. 2, pp. 47-54

[3] P. Ramadour and C. Couvet. Modélisation de domaine pour l'ingénierie des SI para réutilisation. *12éme journées francophones d'ingénierie des connaissances*, 2001.

[4] T. Strang, and C.L. Popien. A Context Modeling Survey. *UbiComp 1st International Workshop on Advanced Context Modelling, Reasoning and Management*, 2004, pp. 31-41

[5] A.K. Dey. Understanding and using context. *Personal and Ubiquitous Computing, Special issue on Situated Interaction and Ubiquitous Computing*, 2001, Vol. 5, No. 1, pp. 4-7.

[6] N. Ubayashi, S. Nakajima and M. Hirayama. Context-dependent product line practice for constructing reliable embedded systems. *14th international conference on Software product lines: going beyond*, 2010, pp. 1-15.

[7] A.K. Dey and G:D Abowd. Towards a Better Understanding of Context and Context-Awareness. *Workshop on the What, Who, Where, When, and How of Context-Awareness*, 2000.

[8] W.N. Schilit, *A System Architecture for Context-Aware Mobile Computing*, PhD thesis, Columbia University, 1995.

[9] G. Urrego-Giraldo, *ABC-Besoins: Une approche d'ingénierie de besoins fonctionnels et non-fonctionnels centrée sur les Agents, les Buts, et les Contextes*, Ph.D. Thesis, Universidad Paris 1, Pantéon Sorbona, 2005.

[10] G. Urrego-Giraldo, G.L. Giraldo G., Differentiated Contribution of Context and Domain Knowledge to Products Lines Development, *Advances in Transdisciplinary Engineering*, Vol. 1, 2014, pp. 239-248.

[11] N.N., Pmbok Guide. Project Management Body of Knowledge. 5th Ed. ANSI/PMI, Philadelphia, 2013.

[12] G. Urrego-Giraldo, G.L. Giraldo G. Process Modeling for Supporting Risk Analysis in Product Innovation Chain. *20th ISPE International Conference on Concurrent Engineering*, Melbourne, 2013, IOS Press Amsterdam, pp 469-480.

[13] P.X.W. Zou, G. Zhang, and J. Wang, Understanding the key risks in construction projects in China, *International Journal of Project Management*, 2007, Vol. 25, pp. 601-614.

[14] K.-F. Chien, Z.-H. Wu, and S.-C. Huang, Identifying and assessing critical risk factors for BIM projects: Empirical study, *Automation in Construction*, 2014, Vol. 45, pp. 1-15.

[15] L.E. Velàsquez, O.L. Urrego, and G. Urrego-Giraldo. Lifecycle's Processes-Based Categories for the Risk Analysis in the Development of Engineering Solutions: An Application to Civil Structures Development, *Advances in Transdisciplinary Engineering*, 2021, Vol. 17, in press.

[16] T. Kendrick, *Identifying and Managing Project Risk*, 2d Edition. Amacom, New York, 2009.

[17] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandic and W. Verhagen. Transdisciplinary systems engineering Implications, challenges and research agenda. *International Journal of Agile Systems and Management*, 2019, Vol.12, No.1, pp. 58 - 89.

[18] G. Urrego-Giraldo, G.L. Giraldo G., Engineering of Social Complex Realities, *Advances in Transdisciplinary Engineering*, Vol. 10, pp. 625-634.

[19] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, W. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, Vol. 7, 2018, pp. 753-762.

[20] G. Hirsch Hadorn, D. Bradley, C. Pohl, St. Rist, and U. Wiesmann. Implications of Transdisciplinarity for Sustainability Research, *Ecological Economics*, 2006, Vol. 60, Issue 1, pp. 119-128.

[21] G. del Cerro Santamaría, Towards Transdisciplinary Urbanism: Megaprojects, Power and the Urban Imagination. *Transdisciplinary Journal of Engineering & Science*, 2018, Vol. 9, pp. 23-36.

[22] H. Urrego, How Powerful are the Models? *Risk Intelligence of Infrastructures. IABSE Conference*, Seoul, Korea, November 2020, S7-5.

[23] ICC. *Structural Review Technical Report under construction conditions Chirajara Bridge* (Spanish). July 16 2018. Medellín Colombia.

[24] N.N., *Investigation of Chirajara Bridge Collapse Task 1: Pushdown analysis*, Cervenka Consulting. 2018.

[25] N.N., *Investigation of Chirajara Bridge Collapse Task 3: Dynamic analysis*, Cervenka Consulting. 26-10-2018.

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Towards an Integrated MCDM and BSC Method to Support the Digital Transformation Strategy in Railway Companies

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Abstract. Digital transformation is now widely discussed and applied in different enterprises and under various organizational aspects. Traditional industries recognize the need to innovate and digitalize their business processes and models. Among these industries, the railway sector presents a vast space for digital transformation. The railway has several operational, regulatory, regional and technological specificities that must be taken into account in the digitalization processes. Given the multiple aspects involved and the transdisciplinarity, the digital transformation strategy and roadmap of companies must be defined in a way that fits it to the corporate strategy, allowing digital transformation program to be implemented effectively, prioritizing internal sectors with the greatest strategic impact, generating greater productivity, business models improvement, security and, above all, competitiveness for the sector. This research aims to propose a model for the definition of the digital transformation strategy in the railway companies using the Balanced Scorecard (BSC) as a tool for strategic organizational analysis and multi-criteria decision-making (MCDM) to define the drivers for digital transformation in the railway. Finally, to demonstrate the proposal, a case study will be carried out at a Brazilian railway company.

Keywords. Digital transformation, railway, organizational strategy, transdisciplinarity, BSC, MCDM

Introduction

Traditional organizations must adapt and embrace change. The digital transformation will not only help to grow but also generate new and better business models creating value for all stakeholders [1]. The success of the digital transformation process requires the organization to develop a series of capabilities that vary according to the business context and the specific needs of each organization. Therefore, the organizational strategy must be adapted to digital reality, by integrating new technologies into the business model [2].

According to [3], strategic orientation is the main determinant and influencing factor for digital transformation. Digital transformation is not a linear process and there are

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different possibilities for the course of actions [4]. Organizations lack strategic clarity, they tend to fail in this round. The organization needs to know what it wants to achieve through the digital transformation process so that it can strategically plan its actions [1] and all efforts must be directed towards the fulfillment of this strategy [3]. Technology has evolved from an active back office to an essential element in building corporate strategy. Therefore, technology and business strategies must be aligned in equal terms, with the output of a digital business strategy [4][5].

Given the importance and urgency of digital transformation in companies, decision-makers seek to develop strategies that make this process feasible [4]. However, a clear strategic vision is one of the main gaps and challenges faced by traditional enterprises in the face of digital transformation [1]. [4] indicate that at the beginning of the transformation process, companies tend to experiment or react to external changes. Only in a second moment do they carry out adequate systematic planning.

There is a gap in the literature related to methods that help to create a digital transformation strategy integrated with the organizational strategy, based on analytical techniques [6], mainly for service industries. [7] shows a domain of representativeness of studies related to digital transformation in manufacturing, mainly with the expansion of industry 4.0 concepts. Traditional sectors of the economy are also looking for new challenges and opportunities related to digital transformation. Railway companies fall into this type of sector and digitalization is a key point for improving the operational efficiency of rail transport and represent a significant challenge in terms of the theoretical and practical development of solutions for operating conditions and operating specificities of the rail market [8]. In [8], the authors also point out that in the construction of the configuration of influencing factors in the process of digitalization the business models of railway companies, one of the relevant aspects is that the companies strategies presuppose the digitalization of key areas in the coming years and conclude the study indicating the need to expand research related to digital transformation in the railroad to clarify various topics related to the subject, given the inherent complexity of the sector and the dynamics of developing solutions for the digital economy.

A low level of correlation, in the opinion of the consulted specialists, between the digital transformation of the business models of the railway companies and the integration of operational processes is shown [9]. This result does not initially prove the importance of digitalization and its impact on improving the operational activity of the railway companies studied. The authors comment that this result may be surprising in the context of railway operations, which work similarly to an integrated and dependent technical ecosystem of operational sectors (planning, maneuvering, traction, maintenance), but emphasize that the result is possibly due to the low level of technological progress by railway operators and indicate that, in the future, with the implementation of technology and evolution about digital transformation, the level of correlation between digital transformation and operational integration must be improved.

There is a lack related to digital transformation in the railway industry, as well as approaches with tools and methods for creating digital transformation strategies in line with organizational strategies. This article seeks, based on the appropriation of multi-criteria strategy and decision-making methods and tools, applied to the creation of a strategy for digital transformation, to propose a method to indicate, among technological elements, those with the greatest strategic impact for organizations, to contribute elements that allow greater clarity to decision-makers in the definition of digital transformation roadmaps. Also, to assess applicability, a case study in the railway industry is proposed, specifically in a freight railway, to contribute to the evolution of the modal towards digital transformation.

This article is structured as follows: Section 1 presents a brief review of the literature on digital transformation in the railroad, BSC, and MCDM. Section 2 presents the proposed method integrating BSC and MCDM. In section 3 the application of the method in a case study in a brazilian freight railway industry. Section 4 discusses the applicability of the method and the results obtained. Finally, in section 5 the conclusion of the study.

1. Literature review

1.1. Railway digital transformation

A brief review of the literature, digital transformation can be defined in general terms as an organizational change, on several levels, which includes the exploitation of digital technologies to improve existing processes and the exploration of digital innovation that can enhance business models [1][4].

A robust and reliable rail system is important to provide high social and economic value [10]. It is a complex market from a legal, regulatory point of view and concerning the division of responsibilities between individual entities, which may vary regionally. The main problem faced by the sector, in many countries, is being competitive to other modes (eg.: road and air) [9]. Greater mobility, productivity, and environmental gains are reflected in the increased use of the railway modal. Therefore, better rail reliability, effectiveness, and efficiency in operational processes are essential. To overcome these challenges, the railway industry needs to develop strategies that allow a transformation of the existing configurations to a digitalized system [10].

Digitalization in the railway industry is a key factor providing opportunities for growth of social aspects that influence the quality of services and operational safety, as well as improving business efficiency and providing a greater competitive and strategic advantage for the modal given the positioning of the sector in the economy digital. The use of technology allows the transformation of resources into economic results and activation of the market and new customers [8].

In this context, [8] point out that service challenges are an important approach, in line with the concepts of service management 4.0. Digital transformation in the railway plays a fundamental role in improving the integration of operational processes, reducing complexity, enhancing efficiency, and reducing costs. Therefore, it represents a significant challenge, as its dynamics must respect important regulatory aspects that involve the railway business model. In this way, digitalization involves the development of organizational, operational, and technical, theoretical, and practical solutions, in a systemic and multidimensional way. The digital transformation in the freight railroad has a broadly multidisciplinary and challenging aspect. This can be seen, for example, in the European Rail industry Freight Agenda (ERIFA), in which 27 technologies were identified in 5 different pillars of improvement: energy efficiency, productivity and capacity, reliability, noise reduction, and the total cost of ownership [8][13][14].

1.2. Balanced Scored Card (BSC)

An organizational strategy shows how the company intends to create value for its customers, stakeholders, shareholders [12]. Among the existing strategic management models, the BSC is one of the most widely found [13]. The BSC translates the organizations mission and strategy into a systematic framework for strategic measurement and management, holistically complementing the financial performance measurements with measurements of the company's future performance factors plus the assessment of how the organization creates value for customers and how to improve internal capabilities and investments needed to improve long-term performance and competitiveness [14].

Source [12] presents a descriptive framework for strategies for creating value, linked in a chain of cause and effect, containing the following important elements:

- Financial performance: the maximum definition of organizational success. The strategy describes how the company intends to create sustainable financial growth;
- Customer value proposition: the central element of the strategy. Success with customers is the main factor for financial performance;
- Internal processes: create and deliver value to the customer, the good performance of the internal processes indicates progress towards success with the customer;
- Learning and growth: describe how people, technology, and organizational culture combine to support the strategy.

1.3. Multi Criteria Decision Making (MCDM)

A multicriteria decision problem consists of a situation in which there are at least two alternatives for choosing, to meet multiple (possibly conflicting) objectives, complex alternatives, important uncertainties, and significant consequences. These objectives are associated with variables that represent it and allow the evaluation of alternatives [15], [16].

MCDM is a process that seeks the best alternative among a series of alternatives considered adequate. MCDM methods are techniques to support decision-making given a finite number of alternatives, as well as a finite set of alternatives, as well as a set of objectives and criteria for evaluating the alternatives and their classification based on the level of satisfaction of the objectives [17]. One of the principles of multicriteria approaches is to help decision-makers to organize and synthesize this information in a way that they feel comfortable and confident about decision making [18].

The Analytic Hierarchy Process (AHP) method is one of the multi criteria decision making method which it has an additive aggregation method for modeling the decision maker's preferences. Proposed by Saaty, uses a peer-to-peer comparative procedure between alternatives of a given criterion using a nine-level semantic scale [15]. According to [19] the organization of objectives, attributes, problems in a hierarchical way provides an overview of complex relationships inherent in decision making and supports the decision-maker by assessing the problem at levels of the same order of magnitude from a comparison more homogeneous. For this purchase, the fundamental Saaty scale is used, which consists of a comparative judgment range that varies from "equal" to "extreme" (neutral, moderate preference, strong preference, very strong preference) corresponding to the numerical scale (1, 3, 5, 7, 9) respectively.

[20] describes a way to decompose decision making as a definition of the problem and desired knowledge, structuring the decision hierarchy with the decision objective at

the top, then in a broad perspective, passing through the intermediate levels to the lowest levels.

2. MCDM and BSC integrated method to support the Digital Transformation

The alignment and strategic mapping reflects the need for a prioritized portfolio and aligned with the company's strategy. This alignment can be done through a strategic mapping complemented by a value attribution model. To assemble the portfolio of innovative projects and programs guided by strategic mapping, it is important to define the related lines of action and validate whether these lines are in line with the company's strategy. Having defined the strategic objectives and lines of action, a value assignment model can be used in which weights are assigned to each strategic objective and scores for each project grouped in the lines of action [21].

Multicriteria methods to bring simplicity and transparency to the calculation of tradeoffs between evaluation criteria present in a BSC. The development of integrated use of multicriteria and BSC decision-making tools can be a key factor to provide success in the implementation and use of BSC by organizations [22].

The proposed method aims to support decision-making about digital transformation strategies, by pointing out performance drivers based on the organization's strategy (layer A), in which the BSC demonstrates enterprise vision in its organizational aspects in different perspectives and the technological map relates technological trends that can be applied in the rail freight sector. Layer B shows the application of the MCDM tool (AHP), which is divided into two stages and considers the strategic and technological elements of layer A as criteria. Finally, layer C shows the drivers for defining the digital transformation roadmap, or that is, the strategic and technological elements, obtained from the AHP, with greater relevance indicating themes in which the enterprise must allocate greater efforts of evolution.

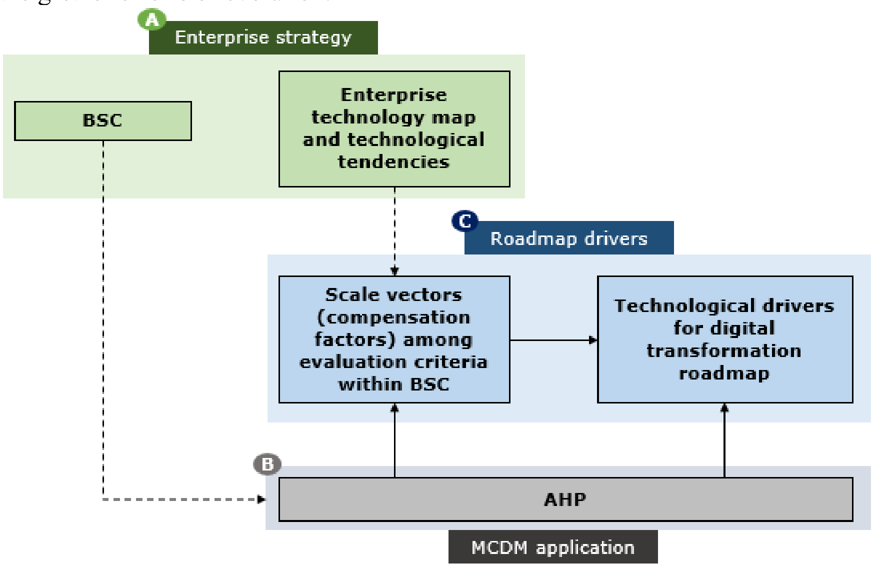

Figure 1. MCDM and BSC integrated method to support the Digital Transformation.

2.1. AHP analysis

In this way, the AHP is shown as an adequate tool for assessing the impacts of each dimension on the company's strategy and of the technological elements in the strategic dimensions as the perceptions related to the impact of the BSC dimensions on the strategy are intangible for comparison and do not follow a specific standard, as recommended by [20], [23].

In this AHP analysis, the criteria considered are the BSC's dimensions. In the suggested description of [12]: Financial, customers, processes, and learning. These dimensions are not limiting, the addition of dimensions can be considered according to the needs of the company [14].

The alternatives are the technological elements, which can be obtained from mapping technological trends (eg.: foresight), sector-specific studies, business diagnostics, technological mapping, benchmarks with other companies and industries.

The application of the method allows the decision-maker to fragment a wide universe of possibilities, bringing greater clarity to how each of the alternatives (digital technologies) can collaborate with the company in obtaining the expected results, thus contributing to the construction of a digital transformation strategy adhering to the business strategy as a whole.

2.2. AHP method execution

The execution of the AHP method consists of 7 steps proposed by Saaty.

Step 1: Pairwise comparison between the dimensions, to generate the comparison matrix A, in which each a_{ij} element represents the relative preference, according to the Saaty scale [19], [24], [25], the criteria of row i concerning the criteria of column j.

$$A = \lfloor a_{ij} \rfloor \tag{1}$$

Step 2: Matrix is normalized, according to equation 2, dividing each element of the matrix by the sum of its column::

$$a_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \text{, where j = 1, 2, 3, ... , n} \tag{2}$$

Step 3: Eigenvector (relative importance or scale vector). It is an unconnected matrix of quantities, showing only the order of relative importance of the elements. For calculating the auto vector, Saaty exposes equation (3). This eigenvector shows the relative value of the elements, so the sum of its elements is always equal to 1:

$$W_i = \frac{\sum_{j=1}^{n} a_{ij}}{n} \text{, where i = 1, 2, 3, ..., n} \tag{3}$$

Step 4: Analysis of the consistency of the evaluation, indicates that for proper application, a matrix must present an uncertainty of less than 10%. For this calculation, the sum of the weighted values (W) is initially calculated using equation 4:

$$W = A * W_i \tag{4}$$

Then, using equation 5, the eigenvalue of the obtained matrix (λ_{max}), is calculated, which consists of the arithmetic mean of dividing the sum of the weighted values (W) by the eigenvector (Wi):

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{[W]}{W_i} \quad (5)$$

The consistency index is calculated by equation 6:

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \quad (6)$$

Finally, the consistency rate (CT) is given by equation (7), in a relationship between consistency index and random index (given by table 1):

$$CT = \frac{(CI)}{(RI)} * 100\% \quad (7)$$

Table 1. RI index

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

3. Case study

For the validation and extraction of perceptions related to the applicability and contribution of the proposed method, a brief case study was carried out in a Brazilian freight railway industry. In carrying out this study, the evaluations present in the methodology were carried out by an innovation manager at the company and occurred in two phases. The first with the objective of evaluating the dimensions of the BSC about the company's moment and pointing out which factors are the most relevant to the company's vision. The second phase, on the other hand, took place by assessing the impact of digital technologies, previously mapped by the company, having at the end a technological direction to assist in the definition of the digital transformation strategy and roadmap. Subsequent topics detail the execution and results of the case study.

3.1. BSC analysis by AHP

The BSC of the company under study consists of 6 general dimensions, which were pairwise compared, to analyze the relative impact on the strategy and submitted to the AHP. At the level of amendments, 16 technological approaches were compared to read the relative strategic impact for the company. Figure 2 shows the hierarchy used in the application of AHP.

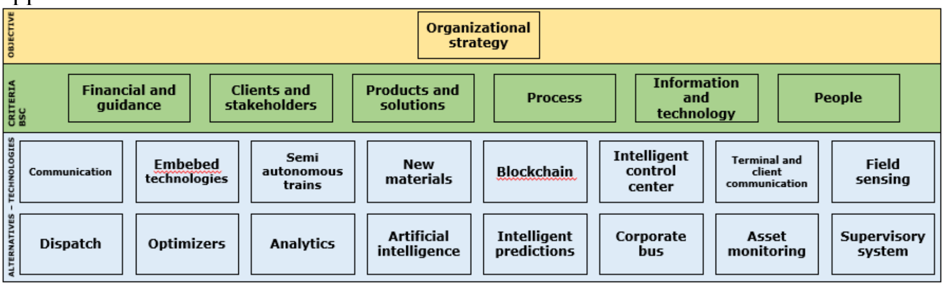

Figure 2. Enterprise BSC hierarchy dimensions.

For the operationalization of the AHP method, the *SuperDecision* software was used, obtaining, as a result, for the assessment of the relative mapping of the BCS dimensions, the scale vector shown in table 2.

Table 2. AHP scale vector for BSC dimensions.

Dimension	Value	Dimension	Value
Clients and Stakeholders	0,46145	Financial and guidance	0,07872
People	0,26174	Information and technology	0,04590
Process	0,12549	Products and solutions	0,02650

From this result, it can be inferred that clients and stakeholders are the strategic dimension with the greatest impact for the company, being this the first driver for the construction of the digital transformation strategy.

The evaluation of alternatives consists of pairwise comparing each technological element to the dimensions of the BSC that are at the top level. For the demonstration in this study, the step was carried out for the dimension with the greatest impact (clients and stakeholders), resulting in table 3.

Table 3. AHP scale vector for technologies in customer and stakeholders dimension.

Dimension	Value	Dimension	Value
Asset monitoring	0,18818	Analytics	0,03459
Terminal and client communication	0,17193	Communication	0,03408
Supervisory	0,08756	Intelligent predictions	0,03401
Blockchain	0,08351	Optimizers	0,03311
Intelligent control center	0,08192	Artificial intelligence	0,03187
Semi autonomous train	0,08113	New materials	0,01992
Field sensing	0,05523	Dispatch	0,01474
Embedded technologies	0,04103	Corporate bus	0,00897

This analysis shows that, for the strategic dimension of clients and stakeholders, from the perspective of the responding decision-maker, the technological factor with the greatest impact is asset monitoring.

4. Discussion

The construction of the proposed framework and its application in a case study allows us to observe that the proposal is positive to generate drivers and discussions related to the construction of a strategy and roadmap of digital transformation adhering to the company's strategy, providing greater clarity to decision-makers on the approaches of greater importance. impact and trend of positive results.

Asset monitoring makes it possible to optimize maintenance based on the identification of behaviors and variations in assets, which makes it possible to prevent accidents, unplanned delays, and business losses. Thus increasing overall efficiency and reducing operating costs [26]. Blockchain can bring credibility and transparency in faster, more effective and traceable commercial relations, reducing errors, costs and risk of fraud [27]. Another example is the semi-autonomous train that impacts fuel economy and emission of pollutants (10% reduction). Generating operational cost reduction and cleaner transportation for clients [28].

This analysis, when taken to a group of decision-makers, generates different personal views and discussions, since they are interpretations subject to subjectivity and that this is intrinsic to multicriteria methods. Therefore, it is important that there is a diversity of decision-makers participating in the analysis and that all results are considered, either through rounds of negotiation until a common agreement is reached, or through the use of mathematical equations that take into account different perceptions.

Although the proposal brings clarity to decision-makers to technological elements, for a holistic view of strategic impact, it is also important to observe and map the operational processes so that, from a diagnosis of digital matrices in each phase of the process, it is possible to improve the targeting of technologies that provide greater impact and adherence to the company's strategy. Finally, the application of AHP involving a high number of alternatives generates high-order comparison matrices which impact a large volume of comparisons pair by pair for decision-makers, this can take a lot of time and difficult organization of schedules and engagement of people. Alternatives like simplified version purpose by [29] or revision of the hierarchical structure segmenting the evaluative space can increase the attractiveness of the AHP method.

5. Conclusion

Digital transformation is an increasingly explicit and multidisciplinary need for organizations in general. Technological evolution in an exponential way requires quick decisions and the right strategies so that companies can achieve their goals and increase their competitiveness in the digital economy.

The strategy for digital transformation must have a relevant role and adhere to the corporate strategy, for these decision-makers must have clarity of where they want to go and how technology can drive this movement when defining their action plans. However, this is one of the biggest challenges faced by organizations, which can lead to inconsistent decisions and waste of resources.

Organizations and sectors of the traditionalist industry impose an even greater challenge on their managers, as they have a lower level of maturity in the digitalization of their operations and demand a rapid evolution in this sense to remain competitive. The railway industry, characterized as a traditionalist industry, is of great relevance for economic and social development and functions as an ecosystem of dependent operations in which digitalization is essential to expand operational capacity and improve its competitiveness.

The MCDM are an important tool to help the construction of a holistic vision and building strategies for digital transformation, even in the most traditionalist industries that have shorter maturity and greater complexity, as occurs in the railway industry.

The proposed framework, based on the sum of the BSC and the AHP, allows the deconstruction of strategic and technological elements and analysis "in parts", bringing to the decision-makers greater clarity and reasoning in their analysis, making the strategic directions for building a roadmap of actions digitalization programs that are adherent to the company's strategic objectives.

Future work may expand the application of the tool to validate the proposal, as well as use outranking mcdm tools to direct the roadmap of actions.

References

[1] C. Shahi and M. Sinha, Digital transformation: challenges faced by organizations and their potential

solutions, *Int. J. Innov. Sci.*, 2020, Vol. 13, No. 1, pp. 17–33, doi: 10.1108/IJIS-09-2020-0157.
[2] J. Reis, M. Amorim, N. Melao, and P. Matos, Digital Transformation : A Literature Review and Guidelines for Future Digital Transformation : A Literature Review and Guidelines for Future Research, *10th Eur. Conf. Inf. Syst. Manag. Acad. Conf. Publ. Ltd.*, 2016, Vol. 1, No. March, pp. 20–28, doi: 10.1007/978-3-319-77703-0.
[3] I. Pihir, K. Tomičić-Pupek, and M. Tomičić Furjan, Digital transformation playground, *J. Inf. Organ. Sci.*, 2019, Vol. 43, No. 1, pp. 33–48, doi: 10.31341/jios.43.1.3.
[4] S. Berghaus and A. Back, Stages in Digital Business Transformation: Results of an Empirical Maturity Study, *MCIS 2016 Proc.*, 2016, Vol. 22.
[5] S. Nadkarni and R. Prügl, Digital transformation: a review, synthesis and opportunities for future research, *Management Review Quarterly*, 2021, Vol. 71, pp. 233–341.
[6] M. Güler and G. Büyüközkan, Analysis of digital transformation strategies with an integrated fuzzy AHP-axiomatic design methodology, *IFAC-PapersOnLine*, 2019, Vol. 52, No. 13, pp. 1186–1191, doi: 10.1016/j.ifacol.2019.11.359.
[7] R. Teichert, Digital transformation maturity: A systematic review of literature, *Acta Univ. Agric. Silvic. Mendelianae Brun.*, 2019, Vol. 67, No. 6, pp. 1673–1687, doi: 10.11118/actaun201967061673.
[8] M. Jabłoński and A. Jabłoński, Social factors as a basic driver of the digitalization of the business models of railway companies, *Sustain.*, 2019, Vol. 11, No. 12, pp. 1–29, doi: 10.3390/su10023367.
[9] M. Jabłoński and A. Jabłoński, Social Perspectives in Digital Business Models of Railway Enterprises, *Energies,* 2020, 13(23), 6445.
[10] V. Jägare, R. Karim, P. Söderholm, P.-O. Larsson-Kråik, and U. Juntti, Change management in digitalised operation and maintenance of railway, *Int. Heavy Haul Assoc. STS 2019 Conf.* , 2019, pp. 904–911.
[11] N.N., *Digital Trends in the Rail Sector*, UNIFE-The European Rail Supply Industry Association, 2019, https://www.unife.org/wp-content/uploads/2021/02/Digital-trends-in-the-Rail-sector.pdf.
[12] R. S. Kaplan and D. P. Norton, *Strategy Maps*, Harvard Business School Press, Boston, 2004.
[13] F. Frezatti, D.D.S. Bido, A.P.C. Da Cruz, and M.J.D.C. Machado, O Papel Do Balanced Scorecard Na Gestão Da Inovação, *Rev. Adm. Empres.*, 2014, Vol. 54, No. 4, pp. 381–392, doi: 10.1590/s0034-759020140404.
[14] R. S. Kaplan and David Norton, *The Balanced Scorecard: Translating Strategy into Action*, Harvard Business School Press, Boston, 1996.
[15] A.T. de Almeida, *Processo de decisão nas organizações: construindo modelos de decisão multicritério*. Editora Atlas S.A., Sao Paulo, 2013.
[16] G. S. Parnell, T. A. Bresnick, S. N. Tani, and E. R. Johnson, *Handbook of decision analysis*, Wiley, Hoboken, 2013.
[17] C. M. Rodrigues, F. Deschamps, E. de F. R. Loures, J. M. A. P. Cestari, and I. H. de Freitas, Digital Transformation Project Portfolio Selection/Prioritization: Literature Review and Future Directions, *IJCIEOM 2019, LNMUINEN*, 2020, pp. 282–292.
[18] V. Belton And T. J. Stewart, *Multiple Criteria Decision Analysis An Integrated Approach*. 201AD.
[19] T.L. Saaty, How to make a decision: The Analytic Hierarchy Process, *Eur. J. Oper. Res.*, 1990, Vol. 48, pp. 9–26, doi: 10.1007/978-1-4614-3597-6_1.
[20] T.L. Saaty, Decision making with the analytic hierarchy process, *Int. J. Serv. Sci.*, 2008, Vol. 1, No. 1, pp. 83–98, doi: 10.1504/ijssci.2008.017590.
[21] A. Tauvy *et al.*, *Fomento à inovação: Da ideia ao recurso*. Inventta+bgi, 2016.
[22] F.A.F. Ferreira, Measuring trade-offs among criteria in a balanced scorecard framework: Possible contributions from the multiple criteria decision analysis research field, *J. Bus. Econ. Manag.*, 2013, Vol. 14, No. 3, pp. 433–447, doi: 10.3846/16111699.2011.631744.
[23] T.L. Saaty, To Make a Decision : The Analytic, *Interfaces (Providence)*, 1994, vol. 24, no. 6, pp. 19–43.
[24] T.L. Saaty, An Exposition of the AHP in Reply to the Paper ‘Remarks on the Analytic Hierarchy Process,” *Manage. Sci.* , 1990, Vol. 36, pp. 259–268.
[25] T.L. Saaty, How to Make a Decision: The Analytic Hierarchy Process, *J. Oper. Res.* , 1990, Vol. 48, pp. 9–26.
[26] A. Thaduri, D. Galar, and U. Kumar, Railway assets: A potential domain for big data analytics,” *Procedia Comput. Sci.*, vol. 53, no. 1, pp. 457–467, 2015, doi: 10.1016/j.procs.2015.07.323.
[27] N. Wognum, C. Bil, F. Elgh, M.Peruzzini, J. Stjepandić, W. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 753-762.
[28] J. Huang, Y. Deng, Q. Yang, and J. Sun, An Energy-Efficient Train Control Framework for Smart Railway Transportation, *IEEE Trans. Comput.*, 2016, Vol. 65, No. 5, pp. 1407–1417, doi: 10.1109/TC.2015.2500565.
[29] J.E. Leal, AHP-express: A simplified version of the analytical hierarchy process method, *MethodsX*, 2020, Vol. 7, 100748, doi: 10.1016/j.mex.2019.11.021.

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Multi-Stage Fuzzy-Logic Model for Evaluation of Reshoring Decisions

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Abstract. Reshoring decisions are complex due to multiple groups of criteria that have an impact on the decision involved. In order to support this manual decision-making process, more advanced tools need to be developed. The purpose of this paper is to explore a multi-stage fuzzy-logic model to support the reshoring decision-making process through a transdisciplinary approach. Three relevant stages pertaining to reshoring decisions were identified: production resources, production capabilities, and competitive priorities. For each stage, factor loading values were used to create fuzzy rules. The model provides a decision recommendation based on a set of input reshoring scenarios. The research contributes to the reshoring literature providing a multi-stage fuzzy-logic model that simultaneously handles different groups of criteria, and to practitioners by contemplating different key competencies within a company during the reshoring decision process.

Keywords. Reshoring, decision support, fuzzy logic, multi-stage, transdisciplinary

Introduction

Manufacturing companies have increasingly relocated their activities back to their home country, which is known as reshoring [1]. Reshoring decisions are less understood with respect to the decision-making process [2, 3]. Consequently, many authors have indicated that the research on reshoring decision support is of high priority [4]. One reason for the lack of research related to decision support is the complexity that is present in these decisions [5]. Another reason is the presence of too many groups of criteria that have an impact on the decision, challenging managers whether to consider all of the present criteria or only a reduced set consisting of the most important criteria [6]. Yet another possible reason for the lack of research in this area is that these decisions sometimes involve human preconceived notions, which need to be contemplated and avoided, if possible [7]. Consequently, dealing with such complex decisions involving an unmanageable number of criteria that are hard to quantify and measure, as well as a biased management team, requires advanced decision support tools that can handle these issues jointly.

Different kinds of decision support tools or models have been developed to either understand or support reshoring decisions. For instance, system dynamics models provide insights into the heuristics of the managers based on gaps between desired and achieved performance [5]. Other examples are landed-cost models that lead to cost-based reshoring decisions [8]. Both models focus on cost and quality criteria but lack

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perspectives on other criteria, for example, time, flexibility, innovation, and sustainability that make up a company's competitive priorities [3].

Fuzzy logic-based tools, that have been applied to a wide range of operations management problems, have been developed for reshoring decisions [9-11], however, these include only one group of criteria, limiting their use to only the initial stages of the reshoring decision-making process. It has been proposed that fuzzy logic-based tools should consider criteria beyond the competitive priorities of a company using a multi-stage architecture for reshoring decisions [11]. Furthermore, different key persons within the company are the managers who are involved during the reshoring decision-making process, focus on different groups of criteria based on the needs of different organizational functions [12].

Developing decision support for manufacturing reshoring requires a transdisciplinary approach. Reshoring is real life, practice-oriented, and society-relevant problem. The persons involved in reshoring decisions belong to different disciplines [12]. Developing decision support for such problems requires having an open mind to various disciplines and to cross the boundaries spanning the different disciplines, especially engineering and operations management [15, 16].

The purpose of this study is to develop a multi-stage fuzzy-logic model to evaluate different reshoring decision scenarios. The need for a multi-stage model is due to the different types of criteria that are considered simultaneously in a reshoring decision. A multi-stage model is suitable when handling the complexities of a large number of criteria [13, 14]. Furthermore, reshoring is a multi-dimensional decision with trade-offs that need to be balanced between various dimensions [1]. Finally, a fuzzy-logic version of a multi-stage model is appropriate in order to handle the uncertainties present in the criteria. To prove the value of the model and the correctness of the generated results, a set of reshoring alternatives, or scenarios, are applied to the model.

1. Literature review

This section reviews the literature on three areas that are relevant for this study: the reshoring decision-making process, the decision-making criteria, and fuzzy-logic decision support for reshoring.

1.1 Reshoring decision-making process

Several authors have proposed a generic decision-making process for reshoring. These can be classified into linear and cyclical decision-making processes. The linear reshoring decision-making process comprises five stages of feasibility and further three stages for implementation inspired by the insourcing process [17]. The cyclical reshoring decision-making process consists of several loops for feasibility and implementation. There is a lack of clear distinction between the feasibility and the implementation loops, which allows for the decision to be reversed even if the implementation has just started [6]. The cyclical decision-making process indicates the complexities present in the reshoring decision-making process that cannot be captured by the linear decision-making process.

1.2 Reshoring decision-making criteria

The decision criteria are those factors that are considered in the decision-making process [10]. The main criteria are cost, quality, lead times and flexibility [18, 19]. These criteria correspond to the competitive priorities of the company, as the main objective of any reshoring is to increase the overall competitiveness [3]. Of these criteria, cost and quality are considered most important for reshoring, while sustainability is often considered to be the least important criteria [20].

In order to achieve the desired competitive priorities, the capabilities and resources in the production need to be identified [3], which are considered subsequent criteria (or sub-criteria) to the competitive priorities. Some sub-criteria related to production capabilities, for example, improvements in product or process quality, reduced total costs [19] improved production flexibility [21], and volume flexibility [18] have been investigated and their importance has been communicated through either factor loading values or priority weights.

Sub-criteria pertaining to resources need to be considered in reshoring decisions [4], as resources are either spent or transformed to achieve the desired competitive priority [3]. For example, a resource such as highly skilled labor is required in the home country as the shop floor tasks become automated when reshoring [23]. Furthermore, reshoring projects consider heavy investments in automation technologies and robotics [24]. Reshoring decisions, in some cases, require physical proximity to R&D functions and industrial clusters for innovation [4]. With increasing emphasis on sustainability, there is a need for more sustainable manufacturing processes [25]. The set of reshoring decision criteria belong to competitive priorities, production capabilities, and production resources are shown in the table (Table 1).

Table 1. Criteria groups in reshoring decisions with their relative importance.

Group	Criteria	Relative importance	Source
Competitive priorities	Cost	0.38	[20]
	Quality	0.41	[20]
	Time	0.07	[20]
	Flexibility	0.07	[20]
	Innovation	0.07	[20]
	Sustainability	0	[20]
Production capabilities	Process efficiency [Cost]	0.7425	[19]
	Process quality [Quality]	0.832	[19]
	Volume flexibility [Flexibility]	0.55	[18]
	Production mix flexibility [Flexibility]	0.72	[21]
Production resources	Proximity to R&D	0.664	[26]
	Proximity to industrial cluster	0.02	[27]
	Availability of labor	0.791	[19]
	Availability of production infrastructure	0.626	[28]
	Availability of production technology	0.793	[19]
	Availability of digital technology	0.14	[21]
	Availability of production capacity	0.61	[18]

1.3. Fuzzy-logic decision support for reshoring decisions

The fuzzy-logic decision support is associated with several degrees of truth values that allow for the expression of linguistic statements like human reasoning [29]. The degrees of truth values are known as membership grades where each variable like *"bad"*, *"neutral"* or *"good"* is transformed to a truth value from zero to one. Fuzzy-logic decision support consists of four functional blocks, as shown in Figure 1. First, the fuzzification block transforms the input data into fuzzy values. Next, the knowledge block consists of the variable lists, membership functions, and rules. Next, the inference block consists of operations that fire one or more rules from the knowledge block and returns a fuzzy value. Finally, the defuzzification block converts the fuzzy value to an output that is understandable to the user.

Fuzzy-logic decision support has been explored for reshoring decisions [9-11]. To replicate the reasoning of the reshoring experts, three novel concepts were outlined. The first concept, relative labels, provides an intuitive and consistent way of reasoning for the decision-maker. For example, the variables, *negative* and *positive* are suggested to be consistent to different stakeholders rather than absolute variables *low* and *high* [9]. The second concept is the high-level rules, which consist of a reduced set of rules that are obvious and meaningful for the decision-maker. The high-level rules simplify the rule design process [9]. The third concept is the variable weights in the design of the fuzzy rules. The variable weights facilitate the automatic creation of the fuzzy rules [9], simplifying the design process. Therefore, the fuzzy-logic decision support for reshoring can be designed in two ways: (1) complete rules or (2) reduced set of high-level rules [9, 11].

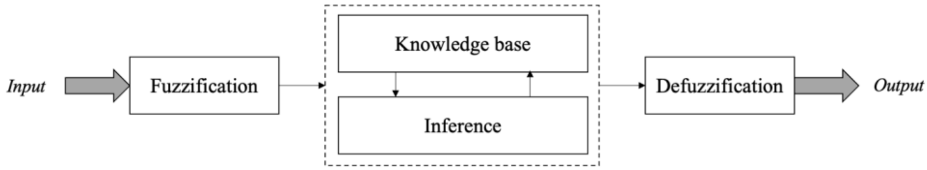

Figure 1. Fuzzy logic system.

2. Development of multi-stage fuzzy-logic model for reshoring decisions

A multi-stage fuzzy-logic model is developed based on weights of criteria found in previous research [18-21]. The first stage focus on production resources, the second on production capabilities, and the third one on competitive priorities. The stages are connected in a cascaded manner [13]. The development of each stage follows a stepwise procedure explained in continuation.

2.1 Define linguistic variables and linguistic labels for each stage

The linguistic variables are equivalent to the criteria found in the review (Table 1). The relative linguistic labels *negative* and *positive* were used for the inputs, both having a Gaussian distribution of membership functions. The range of all of the input variables was defined from [-10, 10], where -10 indicates the most negative impact on the variable when reshoring, while 10 indicates the most positive impact on the variable when reshoring. For the output, the linguistic labels *Exit* and *Further evaluate* were used, each having a triangular distribution of membership function.

2.2 Define variable weights for each stage

In the second step, variable weights are specified. The weights for the variables are retrieved from factor loading values from existing surveys in the reshoring literature [19, 21, 22, 26, 30] as shown in Table 1. The variable weights obtained from the surveys are then normalized. This is shown in Table 2.

Table 2. Normalized weights of criteria.

Criteria	Relative importance	Normalized weights
Cost	0.38	0.38
Quality	0.41	0.41
Time	0.07	0.07
Flexibility	0.07	0.07
Innovation	0.07	0.07
Sustainability	0	0
Process efficiency [Cost]	0.7425	0.261
Process quality [Quality]	0.832	0.292
Volume flexibility [Flexibility]	0.55	0.193
Production mix flexibility [Flexibility]	0.72	0.253
Proximity to R&D	0.664	0.182
Proximity to industrial cluster	0.02	0.005
Availability of labor	0.791	0.217
Availability of production infrastructure	0.626	0.171
Availability of production technology	0.793	0.217
Availability of digital technology	0.14	0.038
Availability of production capacity	0.61	0.167

2.3 Generate fuzzy rules for each stage

In the third step, the fuzzy rules are generated in an automatic manner applying the normalized variable weights [9, 11]. The variable weights were assigned to the antecedent part of each fuzzy rule, while the consequent part of each rule was computed in a weighted-sum manner. Therefore, a complete set of rules was generated. For the first stage (i.e., production resources) 128 rules were generated, for the second stage (i.e., production capabilities) 16 rules were generated and for the third stage (i.e., competitive priorities) 64 rules were generated, all in an automatic fashion.

2.4 Select model parameters for each stage

In the fourth step, appropriate parameters are specified for each stage of the fuzzy logic model. The parameters [AND=min; OR=max; Implication=min; Aggregation=max; Defuzzification=mom] was set for each stage based on the best setting reported for fuzzy logic-based reshoring models [11].

2.5 Combine each fuzzy-logic stage

In the fifth step, the stages were assembled using the Fuzzy Logic Toolbox and Simulink found in MATLAB R2018a. This forms the multi-stage fuzzy-logic architecture for reshoring decisions (Figure 2). The first stage '*Production resources'* comprises the seven variables that concern either proximity or availability of resources. The variables are combined through a multiplexor to allow a shared input into the fuzzy inference system. The second stage *'Production capabilities'* comprises the four variables connected to a multiplexor prior to the fuzzy inference system. As capabilities can be directly linked to achieved competitive priorities [3], each of the four variables also branches out towards the respective competitive priorities. Two of these variables (i.e., Volume flexibility, and Production mix flexibility) are combined using a mean operation before reaching the third stage. The third stage *'Competitive priorities'* comprises the six variables. Finally, the outputs are combined and visualized using the scope operation.

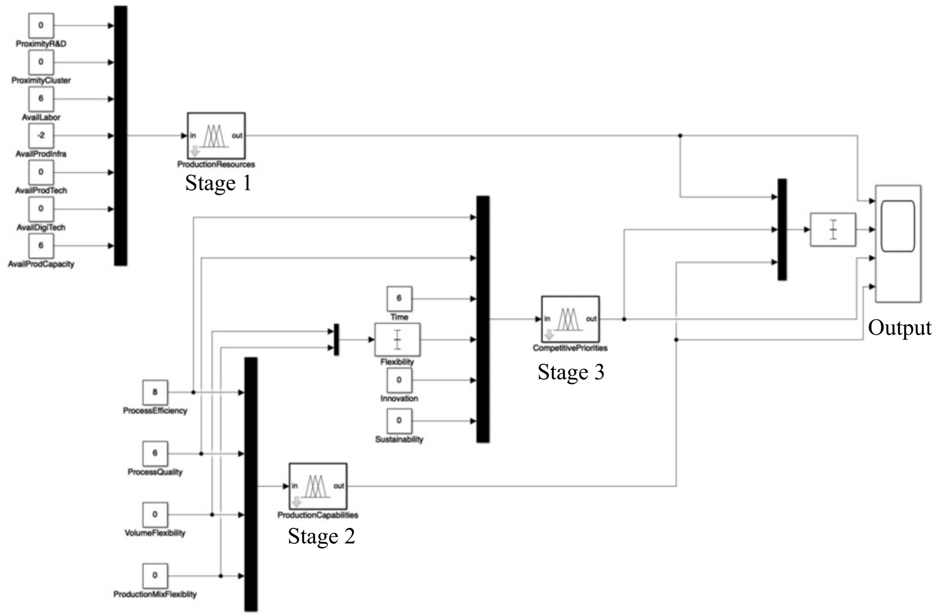

Figure 2. Multi-stage fuzzy-logic architecture for reshoring decisions.

2.6 Develop reshoring scenarios

In the sixth and final step, the multi-stage fuzzy-logic architecture was tested using ten different reshoring scenarios as input (Table 3). The first five scenarios were developed based on case study descriptions found in the reshoring literature [23, 31]. The coding of the five scenarios was done by first, extracting the case descriptions to a spreadsheet and then, mapping a value [-10,10] against the criteria, where -10 indicates a strong negative impact on a criterion while 10 indicates a strong positive impact. Scenarios 1, 2, and 3 were reshoring cases [23], whereas scenarios 4 and 5 were cases where firms did not reshore [31]. The variables that were not involved in the case description were marked with a zero. The last five scenarios were developed by the author to further test the model. Scenario 6 is a case when all values except 'Sustainability' and 'Availability of labor', are negative. This could be the case when the social pillar of sustainability is positively impacted at the expense of other reshoring criteria. Scenario 7 is a case when all the values except 'Availability of labor' and 'Volume flexibility' are positive. This could be the case when a company cannot cope with changing demands. Scenario 8 could be a case when the company is able to innovate by locating close to R&D and industrial clusters, but, at the expense of flexibility-related criteria, while scenario 9 being the opposite of 8. Finally, scenario 10 is when all the values except ‘Availability of labor’ and ‘Time’ are positive. This could be a case when the company cannot find competent labor and has long lead times. The complete list of scenarios is shown in Table 3.

Table 3. Set of scenarios for testing the multi-stage fuzzy-logic model.

Scenario	**Proximity to R&D**	**Proximity to industrial cluster**	**Availability of labor**	**Availability of production infrastructure**	**Availability of production technology**	**Availability of digital technology**	**Availability of production capacity**	**Process efficiency**	**Process quality**	**Volume flexibility**	**Production mix flexibility**	**Time**	**Innovation**	**Sustainability**
1	0	0	6	-2	0	0	6	8	6	0	0	6	0	0
2	6	0	0	0	0	0	6	0	0	6	0	8	0	0
3	4	0	4	4	6	0	0	0	4	8	4	0	0	0
4	0	0	-4	0	0	0	-4	4	-8	0	0	-4	0	0
5	0	0	-4	0	0	0	0	4	-4	0	0	-4	0	0
6	-4	-4	8	-6	-4	-4	-6	-8	-2	-6	-4	-4	-4	6
7	6	4	-2	6	4	8	2	4	10	-2	6	4	8	4
8	8	6	2	-4	4	6	-4	-6	4	-6	-2	-4	6	4
9	-2	-4	-2	4	-2	-2	2	-2	-2	4	6	4	-6	-4
10	4	2	-2	4	6	2	4	6	8	2	4	-4	4	6

3. Results

The results from the multi-stage fuzzy logic-based model when applying to the ten reshoring scenarios are shown in Table 4. The column ‘output value’ shows the output from the model in the range [-10,10], while the column ‘decision recommendation’ suggests whether a reshoring decision should be further evaluated or not (i.e., to exit the decision-making process). The decision recommendation from the first five scenarios can be compared to the actual result described in the case studies. It was found that four out of the five recommendations were consistent with the actual outcome. A conflict in recommendation was found in one of the scenarios (scenario 2) in which the output resulted in 0.00, thereby recommending exiting the decision-making process while the outcome being described in the case study that the company had reshored. For scenarios 1 and 3, the model resulted in 3.53 and 3.22 respectively, which is a recommendation to further evaluate reshoring. On the other hand, for scenarios 4 and 5, the model recommends exiting the decision-making process. For scenarios 6-10, all the inputs were non-zeros values. For Scenario 6, the output from the model suggests a value of -6.26, which gives a decision to exit the reshoring decision-making process. On the other hand, for Scenario 7, the output suggests a value of 6.08, which gives a decision to further evaluate the reshoring decision-making process.

Table 4. Evaluation of reshoring scenarios.

Scenario	Output value	Decision recommendation	Outcome from case description
1	3.53	Further evaluate	Reshored
2	0.00	Exit[a]	Reshored
3	3.22	Further evaluate	Reshored
4	0.00	Exit	Continued offshoring
5	0.00	Exit	Continued offshoring
6	-6.26	Exit	*n.a*
7	6.08	Further evaluate	*n.a*
8	-1.6	Exit	*n.a*
9	-5.5	Exit	*n.a*
10	6.25	Further evaluate	*n.a*

[a]Conflict in model output and outcome

4. Concluding discussion

There is a need to develop advanced tools to support the reshoring decision-making process [4, 26]. As an answer, a transdisciplinary approach was adopted to develop a decision support tool. A transdisciplinary approach that combines knowledge from the engineering and operations management domains.

The developed multi-stage fuzzy-logic model simultaneously considered three groups of reshoring criteria. The developed model is relevant to reshoring decisions as different competencies could be involved in the decision-making process. The first group consisted of production resources, the second stage consisted of production capabilities, while the third stage consisted of overall competitive priorities. While previous research only considered competitive priorities for initial screening tools, this research includes a perspective of capabilities and resources which are relevant in an extended decision-making process. The ability of a multi-stage architecture to consider various groups of criteria make the decision-making process holistic. Furthermore, the developed decision support tool also indicates the output from each of the three stages in a digital format. This allows the decision-maker to understand the status of each stage while taking a decision.

The developed model contributes to the reshoring domain by providing a decision support tool that can be used in the decision-making process. The model is capable of branching the domains of engineering and operations management to solve a practically relevant problem in a transdisciplinary approach. For future research, the developed multi-stage fuzzy-logic model needs to be further tested on even more decision scenarios. Additional decision scenarios from published case study research needs to be explored to further test the model and by using different measures of accuracy. Furthermore, the developed multi-stage fuzzy-logic model needs to be tuned to avoid conflicting results.

References

[1] J. V. Gray, K. Skowronski, G. Esenduran, and M. J. Rungtusanatham, The Reshoring Phenomenon: What Supply Chain Academics Ought to know and Should Do, (in English), *Journal of Supply Chain Management,* 2013, Vol. 49, no. 2, pp. 27-33.

[2] C. Sansone, P. Hilletofth, and D. Eriksson, Critical operations capabilities for competitive manufacturing: a systematic review, *Industrial Management & Data Systems,* 2017, Vol. 117, no. 5, pp. 801-837.

[3] C. Sansone, P. Hilletofth, and D. Eriksson, Evaluation of critical operations capabilities for competitive manufacturing in a high-cost environment, *Journal of Global Operations and Strategic Sourcing,* 2020, Vol. 13 No. 3, pp. 229-250.
[4] P. Barbieri, F. Ciabuschi, L. Fratocchi, and M. Vignoli, What do we know about manufacturing reshoring?, *Journal of Global Operations and Strategic Sourcing,* 2018, Vol. 11, No. 1, pp. 79-122.
[5] J. V. Gray, G. Esenduran, M. J. Rungtusanatham, and K. Skowronski, Why in the world did they reshore? Examining small to medium-sized manufacturer decisions, *Journal of Operations Management,* 2017, Vol. 49, pp. 37-51.
[6] A. Boffelli, G. Orzes, and S. Dotti, “How to reshore”: Some evidence from the apparel industry, *IEEE Engineering Management Review,* 2018, Vol. 46, No. 4, pp. 122-127.
[7] S. Grappi, S. Romani, and R. P. Bagozzi, Consumer stakeholder responses to reshoring strategies, (in English), *Journal of the Academy of Marketing Science,* 2015, Vol. 43, No. 4, pp. 453-471.
[8] M. Gylling, J. Heikkilä, K. Jussila, and M. Saarinen, Making decisions on offshore outsourcing and backshoring: A case study in the bicycle industry, *International Journal of Production Economics,* 2015, Vol. 162, pp. 92-100.
[9] P. Hilletofth, M. Sequeira, and A. Adlemo, Three novel fuzzy logic concepts applied to reshoring decision-making, *Expert Systems with Applications,* 2019, Vol. 126, pp. 133-143.
[10] M. Sequeira, *Developing decision-support tools for evaluation of manufacturing reshoring decisions*, Jönköping University, lic thesis, School of Engineering, 2020.
[11] P. Hilletofth, M. Sequeira, and W. Tate, Fuzzy-logic-based support tools for initial screening of manufacturing reshoring decisions, *Industrial Management & Data Systems,* 2021, Vol. 121 No. 5, pp. 965-992.
[12] A. Moretto, A. S. Patrucco, and C. M. Harland, The dynamics of reshoring decisions and the role of purchasing, *International Journal of Production Research,* 2019, pp. 1-16.
[13] F.-L. Chung and J.-C. Duan, On multistage fuzzy neural network modeling, *IEEE Transactions on fuzzy systems,* 2000, Vol. 8, No. 2, pp. 125-142.
[14] L. Wang and Z. Liu, Data-driven product design evaluation method based on multi-stage artificial neural network, *Applied Soft Computing,* 2021, Vol. 103, 107117.
[15] K. Govindan, H. Mina, and B. Alavi, A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19), *Transportation Research Part E: Logistics and Transportation Review,* 2020, Vol. 138, 101967.
[16] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, and W. J. Verhagen, Transdisciplinary systems engineering: implications, challenges and research agenda, *International Journal of Agile Systems and Management,* 2019, Vol. 12, no. 1, pp. 58-89.
[17] L. Bals, J. F. Kirchoff, and K. Foerstl, Exploring the reshoring and insourcing decision making process: toward an agenda for future research, *Operations Management Research,* 2016, Vol. 9, No. 3-4, pp. 102-116.
[18] B. Dachs, S. Kinkel, A. Jäger, and I. Palčič, Backshoring of production activities in European manufacturing, *Journal of Purchasing and Supply Management,* 2019, Vol. 25, No. 3, 100531.
[19] M. Johansson, J. Olhager, J. Heikkilä, and J. Stentoft, Offshoring versus backshoring: Empirically derived bundles of relocation drivers, and their relationship with benefits, *Journal of Purchasing and Supply Management,* 2019, Vol. 25, No. 3, 100509.
[20] M. Sequeira, P. Hilletofth, and A. Adlemo, AHP-based support tools for initial screening of manufacturing reshoring decisions, *Journal of Global Operations and Strategic Sourcing,* 2021, https://doi.org/10.1108/JGOSS-07-2020-0037.
[21] A. Ancarani, C. Di Mauro, and F. Mascali, Backshoring strategy and the adoption of Industry 4.0: Evidence from Europe, *Journal of World Business,* 2019, Vol. 54, No. 4, pp. 360-371.
[22] B. Dachs, S. Kinkel, and A. Jäger, Bringing it all back home? Backshoring of manufacturing activities and the adoption of Industry 4.0 technologies, *Journal of World Business,* 2019, Vol. 54, No. 6, 101017.
[23] G. Engström, K. Sollander, P. Hilletofth, and D. Eriksson, Reshoring drivers and barriers in the Swedish manufacturing industry, *Journal of Global Operations and Strategic Sourcing,* 2018, Vol. 11, No. 2, pp. 174-201.
[24] B. B. Nujen, D. E. Mwesiumo, H. Solli-Sæther, A. B. Slyngstad, and L. L. Halse, Backshoring readiness, *Journal of Global Operations and Strategic Sourcing,* 2019, Vol. 12 No. 1, pp. 172-195.
[25] L. Fratocchi and C. Di Stefano, Does sustainability matter for reshoring strategies? A literature review, *Journal of Global Operations and Strategic Sourcing,* 2019, Vol. 12 No. 3, pp. 449-476.
[26] J. Stentoft, O. S. Mikkelsen, and J. K. Jensen, Flexicurity and relocation of manufacturing, *Operations Management Research,* 2016, Vol. 9, No. 3-4, pp. 133-144.
[27] S. Kinkel, Trends in production relocation and backshoring activities: changing patterns in the course of the global economic crisis, *International Journal of Operations & Production Management,* 2012, Vol. 32, No. 6, pp. 696-720.

[28] L.-E. Gadde and P. Jonsson, Future changes in sourcing patterns: 2025 outlook for the Swedish textile industry, *Journal of Purchasing and Supply Management,* 2019, Vol. 25, No. 3, 100526.

[29] L. Zadeh, The concept of a linguistic variable and its application to approximate reasoning—I, *Information sciences,* 1975, Vol. 8, No. 3, pp. 199-249.

[30] L. M. Ellram, W. L. Tate, and K. J. Petersen, Offshoring and reshoring: an update on the manufacturing location decision, *Journal of Supply Chain Management,* 2013, Vol. 49, No. 2, pp. 14-22.

[31] C. Joubioux and E. Vanpoucke, Towards right-shoring: a framework for off-and re-shoring decision making, *Operations Management Research,* 2016, Vol. 9, No. 3-4, pp. 117-132.

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Adaptation Mechanisms and Service Quality Dimensions in Dynamic and Turbulent Environments: Empirical Results

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Abstract. Organizations internally seek to develop adaptation and resilience processes or adaptation mechanisms to cope with drastic changes in the environment in order to survive. The changes in the environment affect the perception of product and service quality by the consumer, which are related to customer satisfaction. The purpose of this work is to identify the service quality dimensions that are nested within organizations and the mechanisms to adapt its processes to the turbulent environment. Twenty-four multiple case studies in the construction sector were developed through semi-structured interviews with customers and managers. The results suggest that there are new service quality dimensions; from the customers perspective such as: requirements management and process optimization, emotional intelligence, ergonomic analysis, permanent training of masons, extra activity, monitoring and others. The adaptation mechanisms that organizations use to guarantee service quality are integral training, saved budget, paradigm change, management system, teamwork, and others.

Keywords. Adaptation Mechanisms, Construction Sector, Service Quality Dimensions, Transdisciplinary, Turbulent environments.

Introduction and literature review

The dynamic and turbulent changes that occur in organizations and their environments are nowadays frequent. Organizations seek internally to develop adaptation and resilience processes or adaptation mechanisms in the face of context variables that change noticeably, to survive and achieve sustainability [1]. Therefore, it is important that organizations develop their actions in the face of dynamic and turbulent changes from a holistic point of view with the objective to integrate efforts from every department or area within the organization.

The Construction Sector (CS) has a complex structure by its nature, and at the same time it must face even more drastic changes in the environment with uncertainty, ambiguity and volatile information [2]–[4]. The International Standard Industrial Classification and the Central Product Classification [5], consider that the CS has two parts: first, construction that covers the physical outputs of construction activities (e.g., buildings or civil engineering works); and second, construction services that cover

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services provided in constructing these objects [5]. Construction is also a process of delivering physical outputs to clients through a temporary production system that consists of elements shared with other projects [6]. Therefore, the CS can offer goods and services at the same time [7]. Both dimensions are generally present in all construction projects and are dynamically and non-linearly related, which justifies why the CS can be considered and treated as a complex system [8, 9].

Service quality (SQ) is related to the satisfaction of clients in the short term. The purpose of SQ in an organization is to evaluate the satisfaction of consumers through the analysis of the gap between the expectations and the perceptions of the consumers in a specific time after receiving a service [9]–[11]. It is dependent on technical quality and functional quality, with an important component related to corporate image [12]. Technical quality tries to interpret what are the expectations, the functional quality tries to find the way in which the organization interprets the characteristics and translates them to technical specifications of work, and the corporate image deals with the perceptions of the consumers about the organization of the service that depends on: technical and functional quality, price, external communications, physical location, appearance of the site, and the competence and behaviour of service firms' employees [13]. SQ is the consequence not only of the performance of service, but also of the interaction between customer and firms [14]. SQ is an important determinant of customer satisfaction which in turn influences customers' loyalty [15]. Thus, SQ can be described as a multidimensional and dynamic concept.

Table 1 summarizes the traditional SQ dimensions referred in the literature [8, 9] that may affect SQ in the CS.

Table 1. Service Quality traditional dimensions: important aspects.

SQ Dimension	Most important aspects
Reliability	Total quality of work output Reputation and experience Delivery times
Responsiveness	Professionals' skills Worker's behaviour Technological tools Incident's resolution Work disruptions
Assurance	Competence Credibility Confidentiality
Empathy	Access Courtesy Communication Understanding the customer Interaction with customers
Tangibles	Technological tools

The traditional SQ dimensions can be described as:

- *Reliability,* as the ability to perform the service in a careful and reliable manner in a general consistency of performance and dependability (total quality of work output, relation with the physical progressive product quality and quality control, reputation and experience, relation with the image and prestige won through quality works done in the past and "know-how" of interaction with customers, delivery times, integrity, honesty, and ethics management in their processes).
- *Responsiveness*, willingness to help clients and provide fast service. It is related with time which is important to customers in the CS (professionals' skills,

workers behaviour as the dynamic ability to understand the customers' requirements and proactive attitude, technology tools in relation to incorporate virtual simulation of a construction project, 3D simulation, virtual reality, incidents resolution, work disruptions).

- *Assurance*, knowledge, and attentions shown by employees and their abilities to generate credibility and confidence. It is related to credibility, confidentiality, wisdom, and competence.
- *Empathy*, personalized attention with kindness and courtesy. It is related to understanding the customers' expectations and objectives; communication and permanent feedback in the project development (access, courtesy, communication, understanding the customer, interaction with customers).
- *Tangible's elements*, aspect of physical facilities, equipment, machines, tools, means of safety, the location of the project, personnel, and communication materials (technological tools, interaction between organizations and customers through technological applications).

Traditional dimensions represent an important approach that aims to improve the quality of the organizations within the CS. SQ dimensions influence the decision-making process, the improvement of plans and the formulation and implementation of strategy. SQ dimensions help to improve the organization competitiveness and the adaptation to the market [12, 13]. However, new SQ dimensions can be identified in the literature. Table 2 summarizes new SQ dimensions referred in the literature [8] that may affect the SQ in the CS.

Table 2. Service Quality new dimensions: important aspects.

SQ new dimension	Most important aspects
Quality Aesthetic	Aesthetic (construction) Technical (construction)
Design	Flexibility Adaptability
Care in work execution	Social responsibility
Innovation	Sustainability Social responsibility

The new SQ dimensions referred in the literature can be described as:

- *Quality aesthetic*, it is related to aesthetic and technical workmanship in the project execution.
- *Design*, it is related with construction design, completion processes, technologies, organization, and assembly (flexibility and adaptability before, during and after execution of the project) and versatility with a conceptual strategic model of the construction.
- *Care in execution of work*, it is related with the preventive actions of the organizations to avoid accidents and incidents during the work process.
- *Innovation*, it is related to offering a construction services which imply technological solutions to social, environment and economic sustainability needs; organizations within the CS show to customers the responsibility to optimise resources through sustainable innovation processes (sustainability, social responsibility). Some service innovation processes.

Drastic changes around the world have led many organizations to reinvent their actions in the provision of products and services. Some of the organizations that have adapted to the changing environment have been able to stay in the market and generated competitive advantage, while others have closed their production and gone bankrupt. To analyse this situation, we use the term VUCA, which is the acronym standing for Volatility, Uncertainty, Complexity and Ambiguity. It represents the actual and normal situation of this century where the environment is in a state at the edge of chaos or in a certain deterministic state of the chaos around the world [4]. According to Darwin's Origin of Species, it is not the most intellectual of the species that survives; it is not the strongest that survives; but the species that survives is the one that is best able to adapt and adjust to the changing environment in which it finds itself. Adaptation Mechanisms (AM) are understood as plans or strategies that could help organizations develop their adaptable capacity, and to generate an internal change to improve quality requirements and to provide service and product quality [17]. The adaptation process is generated to improve dynamic capabilities of work team.

The adaptation process is influenced by many factors which have different natures and origins. These factors can intersect several knowledge domains due to their inherently different conceptual and empirical affiliations. In order to better understand the adaptation phenomena in a complex and turbulent context related to SQ, a multidisciplinary and interdisciplinary perspective may be needed. In this work, several disciplinary areas from engineering, and other fields, are applied to take account of the diversity of factors that affect the object under study, which are particularly visible and evident in the diversity of the service quality dimensions and adaptation mechanisms that are addressed in the study. The main disciplinary approach is related to quality management, but other areas are also integrated to provide a broader and more comprehensive understanding, such as the area of quality engineering, and other related to industrial engineering such as innovation management, but also organizational studies and systems and complexity theory, not to mention technical dimensions. In this particular paper we focus on only some of these areas, but the underpinning research involves all the mentioned fields.

The purpose of this work is to identify AM organizations of the CS use under turbulent environment to adapt SQ dimensions as a result on environmental changes. To do that some empirical results that represent two perspectives; customers, and managers, are presented and discussed.

1. Methodology

The methodology adopted was based on exploratory multiple-cases studies. Exploratory study because the authors wanted to discover how organizations of the CS develop AM in a dynamic and turbulent environment oriented to guarantee SQ. Also, a descriptive study was carried out to identify new SQ dimensions for the CS involving customers and managers. Multiple-case studies involved customers and managers. The snowball technique (is used commonly when it is difficult to identify members of the desired population) within the category of volunteer sampling in the non-probability sampling technique [18] was adopted to select 24 respondents (12 customers and 12 managers). The main participants are the managers of the organizations and the customers of the CS in Cuenca city, Ecuador.

The research method used in this work has seven phases.

1. Develop the instruments (questionnaires for managers and customers).

2. Spanish translation process.
3. Instrument validation process.
4. Interview's execution process.
5. Interview transcription process.
6. Systematization and analysis of information.
7. Analysed results writing.

The instruments were developed to identify dimensions associated with new SQ dimensions and to identify the AM that organizations use to guarantee SQ in a dynamic and turbulent environment. The semi-structured interview instrument had three sections: (i) general information of the interviewee, (ii) questions to understand the customer and manager experience in a project within the CS and their perception about SQ dimensions and AM, and (iii) questions to validate SQ dimensions.

After the Spanish translation process was made, a validation process with three customers and three managers within the CS was performed. Semi-structured interviews were based on developed questionnaires.

A detailed transcript of interviews was made to analyse the qualitative information from the customers and the managers, through qualitative analysis techniques. Every question was analysed with detail to obtain information in relation to the research objectives. Later, an English translation process was made. An integration of concepts was made and is presented in the Results section.

Many of the managers interviewed have participated in the public sector. Other present an important interaction with organizations within the CS in remodelling construction processes, housing construction, real state, departments, and others.

2. Results

In this section the results are presented based on customers and managers' perspectives.

2.1. Customers interviews results

Traditional and new SQ dimensions were considered relevant by customers of the CS. In this case, "care in execution of work" represented the most important dimension, followed by "responsiveness", "tangibles elements", "quality aesthetic" and "reliability". Customers identified additional SQ dimensions not referred in the literature, that seem to be relevant the CS.

The new SQ dimensions that emerged from the customers interviews were:

- *Requirements' management and processes' optimization* in the interaction between customers and organizations; it depends on whether it is in the public or private sector; however, it is necessary to reduce the activities which do not generate value and fulfil customer's requirements.
- *Emotional intelligence* in the construction manager to generate customers' satisfaction; skills to manage and solve problems.
- *Ergonomics analysis* in the design process of a construction work to adapt the installation to the people.
- *Permanent training* of the bricklayers to generate dynamic capabilities, experience, and professionalism.

- *Bonus item,* consists of giving an attractive attribute, functionality or upgrade to customers and generate more satisfaction through an unbudgeted offer.

2.2. *Managers interviews results*

The most important traditional and new SQ dimensions identified in the literature from the managers' perspective are: "reliability", "responsiveness", "empathy", "assurance", "design", "care in execution of work", and "tangibles elements".

The new SQ dimensions that emerged from the managers' interviews were:

- *Planning to reduce waste,* is a cultural process to incorporate within the organizations in the CS; also, to generate preventive processes to avoid resources' waste.
- *Project monitoring* is important to incorporate a monitoring process to understand every step in the project.
- *Deeper socialization of technical aspects*, it is important to inform customers about the construction process and technical aspects must be more explained.

Managers' perspective on the relevant internal stabilization strategies or AM to sustain the construction process were analysed. On the one hand, changes in construction are not recommended because they generate more costs (budget), delays in delivery and possible future problems if the changes are at the structural level. On the other hand, other cases indicate change could be made and it would generate customer satisfaction, despite increasing costs to be assumed by the customer.

The AM that help to generate an internal change within the organizations of the CS are induced based on managers' perceptions. The AM are:

- *Integral training*, is related with the employees need to know the new technology, trends, methodologies, and strategies to respond to an exigent market.
- *Saved budget*, consists of saving some money to respond to a complex environment and maintain financial liquidity.
- *Paradigm change*, is related with developing an internal process to change the actual paradigm and find other ways to work.
- *Management system improvement*, is oriented to organize the processes, documents, evidence and clarify the decision making process.
- *Teamwork empowerment*, is related with employee's empowerment.
- *Permanent feedback*, involving customers and collaborators through effective meetings.
- *Versatile construction project*, is the orientation to improve the adaptation of the construction with different technologies.
- *Innovation*, is key to generate new ideas, new approaches in critical situations with an integral solution.
- *Service approach*, to generate a service culture in the employees.
- *Formal approbation*, to guarantee through signed documents the adaptation of the work.

3. Discussion

3.1. Different perceptions on SQ dimensions from customers and managers

The traditional and new SQ dimensions described in the literature are confirmed among customers and managers. However, customers present new SQ dimensions and some of them are shared between customers and managers.

The new SQ dimensions identified from customers' and managers' perspectives are presented in Table 3. The SQ dimensions were establish through a deep analysis from open and close questions of the data collection instrument.

The customers' perspectives are different from the managers' perspectives. The managers' focus is on technical aspects while the customers refer soft and emotional aspects related with the construction project.

Table 3. SQ dimensions by customers and managers perspective.

From Customers perspective	From Managers perspective
Requirements' management and processes' optimization	Planning to reduce waste
Emotional intelligence	Project monitoring
Ergonomics analysis	Deeper socialization of technical aspects
Permanent training	
Bonus item	

The understanding of drivers of customers' satisfaction, through the analysis of SQ dimensions [19] could help organizations to adapt their structure and processes to manage through turbulent and dynamic environments [20]. Increase in customer satisfaction can lead to future purchase intention and ultimately to market share increase [19]. Therefore, a holistic, flexible, and adaptable attitude from managers and respective organisational processes, including the communication between customers and organizations, seem to be relevant to face changing customer's requirements and expectations, because SQ is influenced by environmental changes.

Managers emphasize on building constructions that are useful, that are friendly to the environment, that have a sustainability approach, that have a purpose and that the subsequent maintenance is the least frequent possible [21]. Results suggest that managers could plan to provide a bonus activity and frequent training of collaborators to generate greater customer satisfaction [22].

3.2. Adaptation mechanisms to guarantee a Service Quality

Table 4 and Table 5 show the articulation between the AM identified and the new SQ dimensions presented in the Results section. The relation was established through a deep analysis of the interviews and the systematization and analysis of information from customers and managers.

Requirements' management and processes' optimization seems to be the focus of all the AM, since this has a direct impact on cost and customer perception of SQ. Requirements management are necessary to deal with customer's VUCA requirements during project execution.

AM to deal with SQ dimensions relevant to customers are difficult to establish because "the customer is right", however he may not have knowledge about technical aspects to allow a clear and complete definition of requirements which may lead to customer unsatisfaction when the project is delivered. Thus, requirements' management and processes' optimization in the CS is a difficult task that may be subject of further research to focus on the adaptation of the business model for an organization considering the uncertainty, the dynamic requirements, and the complexity of the construction project. Results suggest that training, parading change, and innovation are AM referred by managers that impact all the SQ dimensions referred by customers.

Table 4. Adaptation Mechanisms and SQ dimension from customers' perspective.

	SQ Dimensions from Customers' perspective				
Adaptation Mechanisms	Requirements' management and processes' optimization	Emotional intelligence	Ergonomics analysis	Permanent training	Bonus item
Integral training	✓	✓	✓	✓	✓
Saved budget	✓				✓
Paradigm change	✓	✓	✓	✓	✓
Management system	✓		✓		✓
Teamwork	✓	✓		✓	
Permanent feedback	✓				✓
Versatile construction project	✓		✓		
Innovation	✓	✓	✓	✓	✓
Service approach	✓	✓		✓	✓
Formal approbation	✓		✓		✓

Table 5. Adaptation Mechanisms and SQ dimension from managers' perspective.

	SQ Dimensions from Managers' perspective		
Adaptation Mechanisms	Planning	Follow up	Deeper socialization of technical aspects
Integral training	✓	✓	✓
Saved budget	✓	✓	✓
Paradigm change	✓	✓	✓
Management system	✓	✓	
Teamwork		✓	
Permanent feedback	✓	✓	✓
Versatile construction project	✓		✓
Innovation		✓	
Service approach	✓		✓
Formal approbation	✓		

Managers consider the importance of AM because it helps to improve SQ dimensions. The AM that have influence on all the SQ dimensions according to managers perspective, are improving job skills and paradigm change. Innovation is a SQ dimension and an AM at the same time. This is due to the dual nature of the concept of innovation, which can be understood as a process but also as an outcome of the process. Changing the firm's internal process related to innovation management may be considered a mechanism that responds to the needs of the market in terms of the provision of new products or services that increase costumers' perception of quality.

Diverse and different criteria were analysed from the managers' perspective about the AM which help to improve SQ. Some factors, such as integrity in the execution of the work, a good requirements management, a developed work team, experience, adaptability, proactive action, project customization, all are key to resolve particular problems [23].

Customers identified strategies and/or AM through experiences with firms within the CS. The reaction of customers depends on their expectations. Managers, on the other hand established AM to have effective negotiation processes. Collecting both points of view was helpful to understand the motivations behind the responses. A more thorough comparison and analysis of the two perspective is out of the scope of this paper due, in part, to space limitations.

4. Conclusions

According to the interviews results, CS is a complex sector and satisfying customers' expectations represents a great challenge [24]. Each construction project has a variety of variables to considerer, such as: its nature (simple or complex), the intervention sector (public and/or private), and the customer (one person, many peoples and/or an institution) [25]. An eclectic research approach was followed through the application of a mix of concepts to better take into account the diversity of the nature of the factors that affect the phenomena.

From this exploratory study, new SQ dimensions were identified. They may suggest a new research path for a more thorough study. The SQ dimensions from customers' and managers' perspectives are different in the CS confirming previous research [11]. Managers express SQ dimensions related with technical aspects while customers highlight emotional aspects. Thus, there is an important gap between these two perspectives which can be a path for future research [11], [17].

The understanding of drivers of customer satisfaction, which may be related to new dimensions, is the key element of SQ [19], and SQ culture developed in organizations could help to adapt their structure and processes to respond to changing and turbulent environments [20]. It is important to consider customer satisfaction to increase the market of customers and the future behavioural intention [19] and the features of the dynamic environment and their influence in the SQ [19].

An opportunity for an in-depth study in relation to these empirical results is to develop an organizational resilience process oriented to face the dynamic and turbulent environments with AM to guarantee the SQ [1].

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References

[1] D. Coute *et al.*, *Emotional Intelligence: Resilience*, Harvard Bu. Harvard Business Review Press, Cambridge , 2017.

[2] A. Prakash and M. Phadtare, Service quality for architects: scale development and validation, *Eng. Constr. Archit. Manag.*, 2018, Vol. 25, No. 5, pp. 670–686.

[3] R. Y. Sunindijo, B. H. W. Hadikusumo, and T. Phangchunun, Modelling service quality in the construction industry, *Int. J. Bus. Perform. Manag.*, 2014, Vol. 15, No. 3, pp. 262–276.

[4] O. Mack, A. Khare, A. Kramer and T. Burgartz, *Managing in a VUCA World*. Springer International Switzerland, 2015.

[5] N.N., *Central Product Classification (CPC) Version 2.1*, vol. 4, no. March. United Nations, New York, 2015.

[6] S. Bertelsen and S. Emmitt, The Client as a Complex System, *13th Int. Gr. Lean Constr. Conf. Proc.*, no. JULY 2005, pp. 73–79, 2005.

[7] W. F. Maloney, Construction product/service and customer satisfaction, *J. Constr. Eng. Manag.*, 2002, Vol. 128, No. 6, pp. 522–529.

[8] M. F. Barragán-Landy, S. Sousa, and F. Romero, Service quality factors in the construction sector: A literature review, *{IOP} Conf. Ser. Mater. Sci. Eng.*, vol. 800, p. 12035, May 2020.

[9] V. Parasuraman, A. Zeithaml, and L. L. Berry, A Conceptual Model of Service Quality and Its Implications for Future Research, *J. Mark.*, 1985, vol. 49, no. 4, pp. 41–50.

[10] A. Parasuraman, V. a Zeithaml, and L. L. Berry, SERQUAL: A Multiple-Item scale for Measuring Consumer Perceptions of Service Quality, *J. Retail.*, 1988, Vol. 64, p. 28.

[11] A. Parasuraman, L. L. Berry, and V. A. Zeithaml, Refinement and reassessment of the SERVQUAL scale, *J. Retail.*, 1991, Vol. 67, No. 4, pp. 420-450.

[12] C. Grönroos, A Service Quality Model and its Marketing Implications, *Eur. J. Mark.*, 1984, Vol. 18, No. 4, pp. 36–44.

[13] N. Seth, S. G. Deshmukh, and P. Vrat, Service quality models: a review, *International Journal of Quality & Reliability Management*, 2005, Vol. 22, No. 9, pp. 913-949.

[14] D. Rew, J. Jung and W. Cha, Service productivity vs service quality: a zero-sum game?, *Int. J. Qual. Reliab. Manag.*, 2018, Vol. 35, No. 9, pp. 1835–1852.

[15] E. E. Izogo and I.-E. Ogba, Service quality, customer satisfaction and loyalty in automobile repair services sector, *Int. J. Qual. Reliab. Manag.*, 2015, Vol. 32, No. 3, pp. 250–269.

[16] S. Weigel and K. Hadwich, Success factors of service networks in the context of servitization – Development and verification of an impact model, *Ind. Mark. Manag.*, 2018, Vol. 74, pp. 254–275.

[17] P. Forsythe, Construction service quality and satisfaction for a targeted housing customer, *Eng. Constr. Archit. Manag.*, 2016, Vol. 23, No. 3, pp. 323–348.

[18] M. Saunders, P. Lewis, and A. Thornhill, *Research Methods for Business Students*, Seventh Ed. Pearson Education Limited, Edinburgh Gate, 2016.

[19] F. Y. Y. Ling and C. L. K. Chong, Design-and-build contractors' service quality in public projects in Singapore, *Build. Environ.*, 2005, Vol. 40, No. 6, pp. 815–823.

[20] S. Pekkola, M. Saunila, and H. Rantanen, Performance measurement system implementation in a turbulent operating environment, *Int. J. Product. Perform. Manag.*, 2016, Vol. 65, No. 7, pp. 947–958.

[21] D. Li, Y. Zhao, L. Zhang, X. Chen and C. Cao, Impact of quality management on green innovation, *J. Clean. Prod.*, 2018, Vol. 170, pp. 462–470.

[22] M. G. Holm and J. Bröchner, Office conversions: The effects of craftsman-user interaction, *Facilities*, 2000, Vol. 18, pp. 535–545.

[23] A. Czajkowska and M. Kadłubek, Management of Factors Affecting Quality of Processes in Construction Enterprises, *No1 POLISH J. Manag. Stud. Czajkowska A*, 2015, Vol. 11, pp. 28–38.

[24] E. C. M. Hui and X. Zheng, Measuring customer satisfaction of FM service in housing sector, *Facilities*, 2010, Vol. 28, No. 5/6, pp. 306–320.

[25] A. H. Al-Momani, Examining service quality within construction processes, *Technovation*, 2000, Vol. 20, No. 11, pp. 643–651.

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Product Platforms and Production – Current State and Future Research Directions Targeting Producibility and Production Preparation

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Abstract. New business opportunities are created when the advantage of changeable manufacturing systems expand beyond increased freedom in production location to increased freedom in product design. However, there are new challenges to overcome, including improved ability to design and adapt products when requirements from stakeholders quickly change and/or new technology rapidly evolves. Simultaneously, the producibility of each design must be ensured while keeping the lead-time of the whole process to the minimum. Changeable product platforms (both flexible and adaptable platforms) are gaining attention in both research and industry. However, the level of alignment and integration of product development and production is critical for the efficiency of the product realization process. In this study, we map the state of practice in five companies with an initial literature review. The companies had no formal platform strategy and faced challenges with variant management and development time, had manual processes for production preparation and reuse of technical solutions and knowledge happened through components and documents. The production preparation and reuse were dependent on the engineer's competence. Future work will concentrate on identifying how manufacturing inputs can be added as a design asset in a changeable product platform to enhance producibility and production preparation.

Keywords. Product Platform, Production, Producibility, Production Preparation, Transdisciplinary Approach

Introduction

The uncertainties and design freedom in the early phases of product development lead to challenges such as the gradual definition of product characteristics, uncertainties in product mix due to long lead time, high product complexity, product variations and a solution space that is not predefined [1, 2]. The uncertainties in factors such as product mix and volume necessitate increasing the responsiveness of the company to changing conditions in all operations including design and production [3]. Reusing past solutions and designs in new designs will help to reduce the uncertainties [4], lead-time and cost. The product platform concept has been identified to support this reuse of assets such as component design [5].

Support is required for improved ability to design and adapt products when requirements from stakeholders change quickly and/or new technology evolves rapidly. Simultaneously, the producibility of each design must be ensured while keeping the lead-time of the whole

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process to a minimum. Changeable product platforms is an emerging topic in research and industry. The level of alignment and integration of specific product platforms and production is critical for the efficiency of the product realization process. Production preparation through methods such as Design for Manufacture will develop a collective understanding of product design and manufacturing [6]. It is necessary to include producibility aspects in the early phases of development to support flexibility and remove costly modifications during later phases [7].

In this study, the state of practice in five companies is mapped with a frame of reference on methods and practices in platform-based development and production preparation. The case companies belonged to sectors such as lighting, outdoor power products, automotive and industrial house building. The current practice was analyzed from the data collected by interviews conducted with the case companies. The interviewee group was transdisciplinary with representatives from project management, new product development, design, production, purchasing, testing and quality departments. A total of fifty interviews were conducted from the five case companies. The purpose of the study is to understand the current state of practice for production preparation and identify future research directions for enhancing producibility and production preparation.

1. Frame of reference

Product platforms are identified as an enabler for achieving product variation and support customization [8]. Product platform definition varies from a collection of assets such as component designs which can be shared across products [9], a group of related products [10] to assets such as knowledge and relationships [5]. The benefits of platform utilization are dependent on when the customer is involved in the specification process [11]. The product specification process can be categorized into four types depending on when the customer is involved– engineer to order (ETO), modify to order (MTO), configure to order (CTO) and select variant (SV) [12]. There are fluctuations in requirements in ETOs during the early and late stages of the product development process due to continuous customer involvement [13] which results in uncertainties [14]. A platform-based development can help to achieve efficient reuse across variants while facing challenges such as an increase in the frequency of introduction of new products, change of existing parts, changes in government regulations and changes in processes [15]. Han et al. [16] propose the concept of Uncertainty-Oriented Product Platform (UOPP) to increase the adaptability of enterprises to uncertainties. UOPP includes platform models such as flexible product platform, adaptable product platform, market-driven product platform and sustainable product platform [16]. A flexible platform considers into account uncertainties and consists of flexible elements. A flexible element is an element that can accommodate changes to create product variants without large investments [17] . Flexibility is achieved by modifying the parameters of the flexible elements. The flexible platform can avoid costly redesigns and costs associated with manufacturing changes [18]. Adaptable product platforms meet the dynamically changing customer requirements using the degrees of freedom in the product and process design and generate solutions through the reuse of existing knowledge, process resources and existing product geometries [19]. We define a changeable product platform as the combination of both flexible and adaptable platform principles. One example of a changeable product platform approach is the design platform that supports the use of heterogeneous design assets [13]. The design assets can be the product, processes, knowledge (guidelines, lesson learned etc), constraints, people and relationships [20]. The design platform model proposed by

Andre et al. [21] considers inputs from disciplines such as design engineering, project management, quality engineering, purchasing, manufacturing engineering, cost engineering and requirement engineering as resources. This approach supports the use of transdisciplinary design resources in product development.

The production preparation process (3P) is part of lean thinking which is aimed at eliminating waste during product and process design [22]. This lean 3P methodology benefits from utilizing cross-functional teams to have product or process improvement, allows for rapid testing of ideas and embeds lean manufacturing concepts into the design itself. The ability to assess producibility in multiple design alternatives will enable design engineers to make design decisions that will prevent costly redesigns later in the development by ensuring that the product family fulfils the required manufacturing conditions [23]. Producibility considerations allow the design engineers to exploit the production facilities to provide better costs and quality [24]. Approaches such as design for manufacturing (DFM) and design for assembly (DFA) provides guidelines to the designers and utilizes manufacturing inputs to assess producibility during product design [23, 25]. But, DFM focuses on process capabilities of manufacturing and this information is often lacking during the early development phases [7]. DFM requires designers to have a good understanding of the manufacturing constraints [26]. Madrid et al. classifies producibility failures and presents methods for producibility assessment. The failures can be operational failures and quality failures. The producibility assessments can be carried out by function models, design structure matrixes, using models from computer-aided design, computer-aided engineering and computer integrated manufacturing. A Manufacturability Assessment System (MAS) can be used to reduce development time by virtually checking the manufacturability of the product [27]. Heikkinen et al [28] presented a rule-based manufacturability assessment system that is automated and enabling set-based concurrent engineering (SBCE).

SBCE begins by considering a range of solutions and gradually narrowing it down to a final solution [29]. The set of feasible solutions are defined by the design and manufacturing engineers together. There are three principles to SBCE- map the design space, integration by intersection and establish feasibility before commitment [29]. The principle of mapping the design space concentrates on defining the feasible regions based on past knowledge, engineering checklists etc. and communication between the functional groups. The principle of integration by intersection target solutions that are feasible, following minimum solution constraints to maintain flexibility and robust solutions. The principle of establishing feasibility before commitment focuses on the gradual elimination of solutions based on developing knowledge, staying within the committed sets and managing the uncertainty at integrating events. The efficiency of the SBCE process is that the elimination can be done more confidently than selection based on the available knowledge [30]. Levandowski et al. [2] give an approach using SBCE principles to support the development of a platform based on functions and design solutions without compromising the range of solutions possible. This approach uses a combination of scalable and modular platforms in the preparation face.

Design automation and digitalization helps to improve the efficiency of the product development process. Design automation can be defined as the computerized automation of tasks in the design process to support the implementation and reuse of information and knowledge in solutions, tools or systems [31]. It can support design synthesis, design analysis and plan for manufacture. Design automation is of two types-information handling and knowledge processing. Digitalization supports product development through the use of digitized information such as digital guidelines, data generated during the product lifecycle [32]. Both these help to reduce costs, lead times and meet customer requirements. Heikkinen et al. [28] present an automated method for producibility analysis and Andre et al. [21]

presents a digital platform manager to support the design of variants. These examples show the application of automation and digitalization to support product development. The advent of Industry 4.0 has opened new opportunities for digitalization and design automation. Industry 4.0 includes the concepts of smart factories, cyber-physical systems, adaptation to human needs etc [33]. It supports short development periods, individualization on demand, flexibility, decentralization and resource efficiency. Tao et al. [34] present how digital twin combined with big data can support product development. The system generates data that can support conceptual design, detailed design and virtual verification. The literature review indicates that usage of product platforms can support production preparation through the use of design assets. But the usage of product platforms is limited in the ETOs at present.

2. Current industrial practice

The study for current industrial practice was conducted to understand the challenges faced in the industries during product development, production preparation and the usage of product platforms to enhance producibility. A collaboration project was formed with five companies participating in a 3½-year research project. The five case companies under investigation represented a wide sample group with business areas of lighting, automotive, power products and construction. This selection allowed the study to identify challenges and draw conclusions that apply in general to the industries.

Table 1: Company description and interview details

Company (Business)	Specification process	No. of interview	Interviewee roles
C1 (Lighting)	ETO/MTO/ SV	10	Industrialization head, NPD manager, Design engineer, Production technician, Product and applications manager, Production manager, Project manager, Production Manager
C2 (Industrial house building)	ETO	10	Project manager, Project leader- construction site, Purchaser, Technical Manager, Development engineer (CAD process/methods), Development engineer (product platform), Design engineer, Production manager, Production technician, Production processor
C3 (Outdoor power products)	SV	9	Project manager, Project sourcing manager, Group manager Product Lab (R&D), Engineering manager (R&D), Lead engineer (R&D), Industrialization project manager, Production manager, Quality process manager, Production technician
C4 (Industrial house building)	ETO	10	Process owner, Product Manager, Project manager- construction site, Business area manager, Designer, Development engineer-CAD process, Development engineer-product platform, Production processor, Production manager, Production technician
C5 (Automotive)	ETO/SV	11	Project manager, Method developer, Group manager construction, Process owner/design manager, Manager Simulation, Production technical manager, Materials and process engineer, Production technician, Press shop and injection molding engineers

Table 1 gives an overview of the number of interviews and interviewee roles that formed the base for the current state mapping. Company 1 (C1) develops and manufactures lighting systems for the public environment, indoor lighting and outdoor lighting. Company 2 (C2) is a construction company that builds schools, daycares, offices etc. Company 3 (C3) is a global multi-brand company that develops, manufactures and sells forest, park and garden products for professional use such as chainsaws, cutting machines and robotic lawnmowers. Company 4 (C4) is a construction company that focuses on building houses. Company 5(C5) is a global manufacturer that develops, manufactures and sells products for sports and outdoor activities such as roof racks for cars, strollers, and bike trailers. A total of 50 semi-structured interviews were conducted with individuals representing product development, engineering design, production, purchasing and project management. The same set of questions was used for the interview. The interviews were then analysed by the authors and the results are presented in the sections below.

2.1. Challenges and current state of production preparation and technical solution reuse

Table 2: Challenges at case companies (Numbers represents the count of respondents who identified the challenge)

Theme	Challenges	C1	C2	C3	C4	C5	Total
Development	Development time	6	1	4	3	6	20
	Development costs	1	2			1	4
	Lifecycle perspective		1	1	1		3
	Supplier lead times/ Supplier changes	1			1		2
	Early decisions	2					2
	Reliability of Development time plan					1	1
Variant	Variant management	6	3	4	4	3	20
Requirements	Standards and regulations		1	1	6		8
	Handling changing requirements	2	2		1	1	6
	New Technology	1		1			2
Knowledge	Documentation					1	1
	Incorrect conclusions from early models					1	1
	Lack of concrete action plan for problem	1					1
	Human factors and competencies	1					1
	Lack of information leading to errors			1			1
Production	Production system				3		3
	Late involvement of production		1				1
	High cost for production changes				1		1
Planning	Multiple projects/Resource allocation	3				1	4
Automation	Automation of industrialisation process					1	1
Communication	Communication between design and production	1					1
Standardisation	Standardised way of working				1		1

The companies currently have no formal product platform strategy. They have identified it as a highly interesting field and some have tested but not found a way forward. The traditional way of platform development poses challenges as it requires high investment at the same time as the need to fulfil unique requirements, be able to quickly introduce new technology, adapt to new legalisation and sometimes optimise performance. Table 2 shows the challenges faced during product development. The numbers in table 2 represent the number of respondents who identified the particular challenge. There was a consensus among the companies regarding the challenges faced and development areas. Development time, variant management, changing standards and regulations and changing requirements were identified by all five companies as challenges they need to handle. Development time was a challenge as it created the need to prioritize between projects. Also, it created uncertainties due to changes in requirements and resources like people. Variant management was a challenge because of the large number of articles and the complexity it creates in manufacturing. Automation, communication, competence development, digitalization and information management were identified as the top development areas needed to handle these challenges.

Table 3 gives an overview of the asset reuse in the companies. It was necessary to understand the current level of reuse of technical solutions and knowledge as it forms the base for the development of the platform. They reuse standard components, component libraries in CAD or PLM systems, previous models and knowledge reuse through documents such as guidelines and lessons learned. The reuse of solutions and knowledge is dependent on the skills of the individual.

Table 3. Methods of asset reuse (Numbers represents the count of respondents who identified the challenge)

Category	Reused item	C1	C2	C3	C4	C5	Total
Documents	Guideline document (Procedures and methods)	3	1	9	2	3	18
	Lessons learned document	3	3	6		4	16
	Standard sheets		7				7
	Checklists (DFX,design reviews etc)	4				1	5
	Deviations/ disruption reports		2		2		4
	Project review		1				1
Human factor	Human competencies (experience, knowledge)	5	3	2	3	6	19
	Sharing knowledge through meetings	4	1	1	6	3	15
	Team to capture knowledge	1			2	5	8
Models	Start from previous CAD model		2	3	4	3	12
	Libraries in CAD/PLM	3	3	1		1	8
	CAD templates		2		3	1	6
	Calculation model	1	1	2	1	1	6
	Standard Dimensions		1		2		3
	Test models		1	1		1	3
	Simulation code					1	1
Components	Component/Solution reuse	8	2	3	7	8	28

Production preparation and integration between product development and production mainly happens through communication between design and production engineers. The integration process is embedded in the development process. There are meetings, checklists and workshops that enable production preparation and integration but the efficiency of this process is individual dependent. A need for production awareness among design engineers has been identified. The opportunity lies in automating this process and increasing the accessibility of information through digital tools. The interview summary for production preparation and integration is given in table 4.

Table 4. Production preparation and challenges faced

Company	Ways of production preparation and integration between product development and production
C1	Integration method is established in their development process. There is a cross-functional team with a production representative to give a producibility assessment. There are dialogues and brainstorming activities during the development phase. Designers have access to manufacturing methods. Checklists such as design reviews and construction walkthroughs and prototypes are used to ensure integration and producibility. Production software is used to load the products onto the production stations. Performance indicators are monitored throughout the process. The challenges faced are not having people with the right skills and production is not flexible. Opportunity lies in the automatic transfer of information, utilization of DFA and DFM, improving transparency and communication.
C2	The production department is involved early in the development process. There are meetings such as heads-up meeting, kick-off meetings and drawing reviews to ensure production preparation. The proven solutions are added to standard sheets. Problems arising during production are conveyed to the drawing departments through feedback where improvements are made. The efficiency of production preparation is person dependent. They face issues with customization and competence. Areas of improvement identified are standardization, collecting information from customers, digital BIM models and better communication between design and production. They also need to automate the preparation process and presently there are some automation for activities such as generating cutting lists from BIM software
C3	The new product development (NPD) process includes dialogues with production and suppliers. A manufacturing representative is present in the NPD process. They use knowledge from suppliers, cost engineers and commodity managers. Manufacturability is assessed through drawing reviews, 3P-workshops, PFMEA and DFA. They need digital tools to ease communication and bring production strategy into the design by creating awareness within R&D. There is a redesign loop at the later stages to correct any mistakes. Opportunity lies in integrated information, automation and competence improvement.
C4	Ensures manufacturability through the development process. There are interactions between designers and production engineers. They have 3D models and control files for production lines for the elements being manufactured. This data can be exported to the ERP system. A cross-functional team makes rough mockups and does test runs. They need a better platform for documenting and sharing information. Opportunity lies in digitalization, automation and standardization.
C5	Integration is controlled by the product development process and production preparation is ensured at the third gate of the process where they decide on procurement of equipment and allocation of resources. There is a production representative in the project and continuous dialogues take place between the designers and production engineers. The project group is cross-functional and has representatives from project management, design, production, quality and testing departments. Risk analysis, FMEA, DFM, DFA, checklists and prototypes are used. Training and workshops are conducted to increase alignment between the design and production departments. Simulations, better structure for design reviews, a design that supports automation and flexibility, early supplier involvement and training for new employees are the identified improvement areas.

3. Analysis and future research directions

The current state study showed that companies do not have a formal product platform strategy but it is identified as an interesting field. Development time, variant management and requirements management are the main challenges faced by all the case companies. Though the challenges faced are similar, the industrial house building companies are influenced more by external changes such as standards and regulations. Christensen et al. [1]

and Han et al. [16] identified the challenges as gradual determination of product characteristics, product variations, uncertainties in markets, customer requirements, technologies, policies, and regulations. These were in line with the challenges identified from the current state of practice and Han et al. [16] propose a platform approach to overcome these. Improvements in the areas of communication, automation, digitalization, information management, standardization, flexibility and adaptability of systems were needed to meet the challenges. The technical solution reuse happens through component libraries with standard components, documents such as standard sheets and design reviews, knowledge banks of guidelines and procedures, lessons learned documents and rules defined on drawings. Integrations between design and production happen mostly through communication, meetings, standard sheets, checklists, prototypes and there is a production representative in the development team in most cases. The challenges faced both in solution reuse and production preparation is that it happens through communication and is dependent on the individual's competence.

Producbillity consideration during the product development process is important to improve quality and reduce cost [35]. Design engineers should know the manufacturing capabilities of the company to achieve this [24]. The production preparation process and solution reuse in the case companies are dependent on the skills and knowledge of individuals which limits its efficiency. A platform strategy can improve the reuse of design and production information [36]. The literature review helped in identifying the different platforms strategies and concepts that can support in developing product platform means to enhance producibility in the industry. The uncertainty-oriented product platform (UOPP) [16] and the design platform (DP) [21] approaches with flexible elements [18] may help in managing changing requirements from customers, market and legal. The concept of Set-Based Concurrent Engineering (SBCE) supports reuse and knowledge development which helps to improve future development projects and production preparation as both design and production teams prepares the feasible set of solutions together [29]. Digitalization and design automation methods can be used to introduce manufacturing inputs into the design process. Stejpandić et al [37] and Levandowski et al. [38] showed how integration of computer-aided drawing (CAD), product data management (PDM), enterprise resource planning systems (ERP) and product configurators can support optimization and analysis of new products. These along with the automated producibility assessment technique [28] shows how digitalisation and design automation can be used for capturing and reusing product and process knowledge. The concept of digital twin can also be explored as it supports the conceptual design, detailed design, and virtual verification [34].

New knowledge in product platform development could enable the companies to increase their competitiveness by supporting the design and development of changeable product platform. Future research work will focus on understanding the challenges faced in the industry to ensure producibility and how the changeable product platform can support to overcome these challenges. The changeable product platform may be based on the combination of product platforms, SBCE, digitalisation and design automation. This will allow the proposed platform to be able to meet the changing requirements and new technology development. Integration with the production is pro-actively coordinated in such a platform by accomodating/controlling the critical production aspects using design/engineering assets, digitalisation and automation. This platform can also support means to guide towards and/or asses producibility. Means for improved understanding of the interfaces between product and production systems, current producibility failures and constraints across design and production are also needed. The current state of practice analysis has shown that there is a base for platform implementation with some solution reuse and manual production preparation. This gives an opportunity for implementing a changeable product platform concept to assess producibility and production preparation through the support of digitalisation and design automation tools.

4. Conclusions

The purpose of the paper was to identify the challenges, current state of practice concerning producibility and production preparation in the case companies. Also, to identify how critical production aspects can be accommodated/controlled by the design of the product platform for efficient manufacturing through a literature survey. The case companies did not have a formal platform strategy and had some manual production preparation methods. The solution reuse was mostly restricted to components/designs and knowledge reuse happens through meetings or documents. The literature study helped to identify concepts of product platforms such as flexible and adaptable platforms which along with SBCE, producibility, design assets, digitalization and design automation can be used to develop a platform concept that can support producibility enhancement. This can help the companies to be competitive through reduced development time and better adaptability towards changes.

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References

[1] B. Christensen and T. D. Brunoe, Product Configuration in the ETO and Capital Goods Industry: A Literature Review and Challenges, in S. Hankammer et al. (eds.) *Customization 4.0*, 2018, pp. 423-438.
[2] C. Levandowski, D. Raudberget and H. Johannesson, Set-Based Concurrent Engineering for Early Phases in Platform Development, *Advances in Transdisciplinary Engineering*, Vol. 1, 2014, pp. 564-576.
[3] S. M. Ferguson, A. T. Olewnik and P. Cormier, A review of mass customization across marketing, engineering and distribution domains toward development of a process framework, *Research in Engineering Design*, 2014, pp. 11-30.
[4] D. V. Khadilkar and L. A. Stauffner, An Experimental Evaluation of Design Information Reuse During Conceptual Design, *Journal of Engineering Design*, 1996, pp. 331-339.
[5] D. Robertson and K. Ulrich, Planning for Product Platforms, *Sloan Management review*, 1998, pp. 19-31.
[6] O. Battaïa, A. Dolgui, S. S. Heragu, S. M. Meerkov and M. K. Tiwari, Design for manufacturing and assembly/disassembly: joint design of products and production systems, *International Journal of Production Research*, 2018, Vol. 56, pp. 7181-7189.
[7] J. Madrid, J. Landahl, R. Söderberg, H. Johannesson and J. Lööf, Mitigating risk of producibility failures in platform concept development, *31st Congress of the International Council of the Aeronautical Sciences, ICAS 2018*, 2018, https://www.icas.org/ICAS_ARCHIVE/ICAS2018/data/papers/ICAS2018_0101_paper.pdf.
[8] L. Hvam, N. Mortensen and J. Riis, *Product Customization*, Springer-Verlag, Berlin Heidelberg, 2008.
[9] K. T. Ulrich and S. D. Eppinger, *Product Design and Development*, McGraw-Hill, Irwin, 2012.
[10] T. W. Simpson, Z. Siddique and R. J. Jiao, *Product platform and product family design: methods and applications*, Springer Science & Business Media, Berlin, 2006.
[11] M. Bonev, M. Wörösch and L. Hvam, Utilizing platforms in industrialized construction: A case study of a precast manufacturer, *Construction Innovation*, 2015, Vol. 15, No. 1, pp. 84-106.
[12] B. Hansen, *Development of industrial variant specification systems*, IKON Tekst & Tryk A/S, 2003.

[13] S. André, F. Elgh, J. Johansson and R. Stolt, The design platform–a coherent platform description of heterogeneous design assets for suppliers of highly customised systems, *Journal of Engineering Design*, 2017, pp. 599-626.
[14] K. Safsten, G. Johansson, N. Lakemond and T. Magnusson, Interface challenges and managerial issues in the industrial innovation process, *Journal of Manufacturing Technology Management*, 2014, pp. 218-239.
[15] M. T. Michaelis, H. Johannesson and H. A. Elmaraghy, Function and process modelling for integrated product and manufacturing system platforms, *Journal of Manufacturing Systems*, 2015, pp. 203-215.
[16] X. Han, R. Li, J. Wang, G. Ding and S. Qin, A systematic literature review of product platform design under uncertainty, Journal of Engineering Design, pp. 266-296, 2020.
[17] E. S. Suh, *Flexible Product Platform*, Ph. D. Thesis, Engineering Systems Division, Massachusetts Institute of Technology, 2005.
[18] E. S. Suh, O. L. de Weck and D. Chang, Flexible product platforms: framework and case study, *Research in Engineering Design*, 2007, pp. 67-89.
[19] G. Schuh, M. Lenders and J. Arnoscht, Focussing product innovation and fostering economies of scale based on adaptive product platforms, *CIRP Annals - Manufacturing Technology*, 2009, pp. 131-134.
[20] D. Raudberget, F. Elgh, R. Stolt, J. Johansson and M. Lennartsson, Developing agile platform assets – Exploring ways to reach beyond modularisation at five product development companies, *International Journal of Agile Systems and Management*, 2019, Vol. 12, No. 4, pp. 311-331.
[21] S. André and F. Elgh, Modeling of transdisciplinary engineering assets using the design platform approach for improved customization ability, *Advanced Engineering Informatics*, 2018, Vol. 38, No. July, pp. 227-290.
[22] S. Ramakrishnan and M. V. Testani, "An integrated lean 3P and modelling approach for service and product introduction, *Proceedings IIE Annual Conference, Norcross*, 2011, pp. 1-8.
[23] J. Landahl, C. Levandowski, H. Johannesson and O. Isaksson, Assessing producibility of product platforms using set-based concurrent engineering, *Advances in Transdisciplinary Engineering*, Vol. 3, 2016, pp. 35-44.
[24] S. Gedell, M. T. Michaelis and H. Johannesson, Integrated model for co-development of products and production systems - A systems theory approach, *Concurrent Engineering Research and Applications*, 2011, pp. 139-156.
[25] C. Poli, *Design for Manufacturing*, Butterworth-Heinemann, Boston, 2001.
[26] S. Yang and Y. F. Zhao, Additive manufacturing-enabled design theory and methodology: a critical review, *International Journal of Advanced Manufacturing Technology*, 2015, Vol. 80, No. 1-4, pp. 327-342.
[27] S. Shukor and D. A. Axinte, Manufacturability analysis system: Issues and future trends, *International Journal of Production Research*, 2009, pp. 1369-1390.
[28] T. Heikkinen, R. Stolt, F. Elgh and P. Andersson, Automated Producibility Assessment Enabling Set-Based Concurrent Engineering, *Advances in Transdisciplinary Engineering*, 2016, Vol. 3, pp. 947-956.
[29] D. K. Sobek, A. C. Ward and J. K. Liker, Toyota's Principles of Set-Based Concurrent Engineering, *Sloan Management review*, 1999, https://sloanreview.mit.edu/article/toyotas-principles-of-setbased-concurrent-engineering/, Accesed July, 1 2021.
[30] D. Raudberget, Practical Applications of Set-Based Concurrent Engineering in Industry, *Journal of Mechanical Engineering*, 2010, pp. 685-695.
[31] M. Cederfeldt and F. Elgh, Design automation in SMEs - Current state, potential, need and requirements, *CED 05, the 15th International Conference on Engineering Design*, 2005.
[32] S. Hallstedt, O. Isaksson and A. Öhrwall Rönnbäck, The Need for New Product Development Capabilities from Digitalization, Sustainability, and Servitization Trends, *Sustainability*, 2020, Vol. 12, No. 23, 10222.
[33] H. Lasi, P. Fettke and H. Kemper, Industry 4.0, *Business & Information Systems Engineering*, 2014, Vol. 6, No. 4, pp. 239-242, https://aisel.aisnet.org/bise/vol6/iss4/5, Accesed July, 1 2021.
[34] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang and F. Sui, Digital twin-driven product design, manufacturing and service with big data, *International Journal of Advanced Manufacturing Technology*, 2018, Vol. 94, pp. 3563–3576.
[35] J. Madrid, *Design for Producibility in Fabricated Aerospace Components Department of Industrial and Materials Science*, Ph.D. Thesis, Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, 2020.
[36] J. Landahl, *Platform Design for Producibility*, Ph.D. Thesis, Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, 2018.
[37] J. Stjepandić, E. Ostrosi, A. J. Fougères and M. Kurth, Modularity and supporting tools and methods, in J. Stjepandić et al. (eds.) *Concurrent Engineering in the 21st Century: Foundations, Developments and Challenges*, Springer International Publishing Switzerland, 2015, pp. 389-420.
[38] C. E. Levandowski, *Platform Lifecycle Support using Set-Based Concurrent Engineering*, Ph.D. Thesis, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, 2014.

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Part 5

Product Systems

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Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Benchmark on Human Simulation Tools: A Transdisciplinary Approach

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Abstract. Nowadays companies have to face a competitive market that requires small volumes with a high level of customisations. In this context, assembly quality and timeliness is crucial. To guarantee flexibility and personalization, manual operations still have a crucial role for a lot of manufacturing sectors, so that workers' conditions and ergonomics are important factors to achieve a better product quality and overall cost reduction. Ergonomics evaluation in manufacturing is a challenging and expensive activity that requires a transdisciplinary approach, to merge technical and social sciences to finally have a consolidated and reliable evaluation. This paper compared two digital human simulations tools offered by Siemens Tecnomatix: Jack and Process Simulate. They were applied on the same industrial case study, concerning the hood assembly of an agricultural machine, comparing results on ergonomics reports and usage time. Results confirmed the advantage of adopting a digital approach to predict the human effort and ergonomic risk related to a series of tasks. At the same time, they showed the major strengths and weaknesses of the two analysed tools and defined how they can be successfully adopted by companies. The paper finally provided guidelines to drive companies in choosing the best tool according to their needs.

Keywords. digital manufacturing, digital human simulations, transdisciplinary engineering, ergonomics, human-centered design.

Introduction

In the new industrial 4.0 and digital era, a fundamental role is played by factory ergonomics for the optimization of working conditions [1]; safeguarding the health of operators has become an increasingly crucial issue for most companies whose production process is based on manual production and assembly activities [2]. Generally, ergonomic assessment requires a great effort in terms of time and costs and a certain level of expertise during the analysis. Moreover, in traditional approaches, ergonomic analysis is carried out at the shop-floor, when the plant is already created and changes to workstations are challenging and expensive [3]. Consequently, an urgent need for companies is to improve and speed up the ergonomic analysis carried out on plants and production lines [4].

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Assembly is still one of those activities in smart factories carried out by humans, especially to satisfy production flexibility and personalization on small batches. Assembly lines of manufacturing industries are very complex to design, because production processes are affected by several variables, such as technological, environmental, logistics and ergonomics. In particular, ergonomic assessments are often barely considered during the design phase, due to the complexity; this implies the need to correct the design later when ergonomic issues occur during the production phase, with high-cost of redesign [5]. Moreover, the extreme pressure for companies to achieve their businesses to be competitive in their markets could have a negative impact on the workers' mental workload and well-being. In the manufacturing sector, the effective implementation of ergonomics aspects in processes has been proven to decrease costs related to musculoskeletal disorders (MSD), extratime hours, medical care or fines for risk-events [6]. In addition, according to the literature, harmful ergonomic risk factors affect not only human well-being on work but also human performance, decreasing the product quality. For this reason, companies should be convinced that incorporation of an ergonomic approach in the production system would be profitable in the short and long term [7].

Digitization is one of the main pillars of the Industry 4.0 revolution; digital tools can support the simulation of industrial processes in order to optimize the production process and to enhance workers' conditions [8]. Transdisciplinary engineering (TE) methods can be successfully applied to solve complex problems linked to Digital Manufacturing (DM) [9]. To include people in the production process, DM tools help engineers and technicians to predict critical working conditions, bridging the gap between technical and social sciences [10]. The aim of this paper is to critically compare two of the most used Digital Human Simulation (DHS) software toolkits, Jack and Process Simulate (PS), in order to drive companies in the adoption of these tools in an effective way, through performance indicators.

1. Research background

Nowadays companies have to adopt digitization to be in line with market trends; this fact can highly benefit also ergonomics, moving from a corrective to a predictive approach [11]. In detail, the available digital tools include sophisticated digital human models, regional anthropometric databases, and the latest ergonomic methods. Digital simulations are used to analyze humans' working conditions in different contexts, from driving to manufacturing, supporting the evaluation of the user comfort and the workstation designs to assure the proper ergonomic conditions for the workers. Nevertheless, these human simulations are generally carried out by human factors engineers or ergonomists, using dedicated tools, whereas the production simulations are carried out by production engineers [12]. Diversely, a real benefit could be achieved by merging these two activities. Indeed, the adoption of virtual mannequins into process simulation can help designers and engineering to consider the human factors from the early design phases, to produce more human-centered vehicles, equipment, assembly lines, manufacturing plants, interfaces, and interactive systems in general [13]. The scientific literature shows numerous examples of successful applications of DHS in the manufacturing context, under the name of DHS systems [14-16]. In particular, DHS are widespread for assembly task evaluation, in which a knowledge-based decision support tool could facilitate the optimization of workflow [17], from a human-centered perspective. A preventive ergonomic approach is useful to drastically reduce time-to-market of manufactured products, and consequently their costs. Indeed, 70 to 80 percent of the life-cycle costs of a product are determined by decisions taken by designers during the early stages of the design process. Therefore it is important to apply ergonomic assessment as early and as accurately as possible [18].

For these purposes, several ergonomic analysis methods and techniques have been recently developed within the DHS softwares, to support engineers. Two DHS softwares have been identified, Jack and PS by Siemens, to be compared for industrial applications. Jack is a specific module dedicated to comfort analysis; it is probably one of the most popular and currently used DHS software as demonstrated also by Mühlstedt [19]. On the contrary, PS is integrated in the Siemens PLM offer and allows starting from the production digital scenario and implementing one or more workstations. Each software has its strengths and weaknesses. Therefore it is not only important to take the analysis with these softwares, but also to be able to interpret and apply their outputs [20].

2. The approach for system comparison

A transdisciplinary approach starts from a real-world problem and connects complex and interdependent social and engineering issues [21]: DHS is a key technology that allows human factors to be addressed during both the digitalized product design and production-planning phases. The proposed approach aims to compare the above-mentioned DHS softwares in order to recognize advantages and weaknesses in a real case study. Both of them allow the creation of process simulations and ergonomic analysis, improving decision-making capacity of engineers and production planners as required by a transdisciplinary approach [21]. The comparison could be useful for companies to identify the best solution that fits their needs, in order to solve ergonomic issues. The study has been developed in collaboration with a tractor manufacturer, focusing on the real activities carried out by workers on the production plant.

2.1. Comparison methodology

The proposed methodology was conceived in order to give a holistic evaluation of the two systems under evaluation. For this purpose, a set of performance indicators has been defined in order to evaluate both qualitative and quantitative aspects and to finally generate the overall ergonomic report. The proposed comparison is based on subjective and objective indicators as described in Table 1. The first section describes the selected indicators adopted for subjective assessment, as expressed by the experts involved in the study. The second and third section list two classes of objective indicators, respectively about time performance and ergonomic assessment by a set of selected metrics.
Subjective indicators consider the effort to digitize the assembly task sequence, to carry out the simulation until the analysis of the ergonomics results. The evaluation was carried out by experts using the 5-point Likert scale taking into account a set of software features in order to give a qualitative performance assessment. In particular, the identified indicators are measured considering:

- Easiness of scene creation: ease of importing virtual models in the scene;
- Easiness of scene navigation: usability of scene navigation commands;
- Easiness of object manipulation: simplicity of moving parts in the virtual scene;

- Easiness of joint manipulation: straightforwardness in positioning the virtual mannequin in a realistic way.

Objective indicators refer to time performance and accuracy of the ergonomic assessment. About time performance, indicators consider the time to accomplish the main tasks:

- Scene creation;
- Simulation implementation;
- Ergonomic report creation;
- Ergonomic analysis.

Accuracy of the ergonomic assessment is evaluated considering the score obtained using internationally-recognized ergonomic methods, suitable to assess the risk to develop muskulo-skeletal disorders, according to the specific analysis to be performed. The selected indicators are as follows:

- Ovako Working posture Analysing System (OWAS): it is a concise system for postural assessment that provides an holistic evaluation of workers physical effort. Each posture is designated by a 4-digit code that depends on the classification of the current posture with respect to four predefined levels of danger. It takes into account the postures assumed by the worker and evaluates each posture according to the position of the back, arms, legs, and to the weight lifted;
- Rapid Upper-Limb Assessment (RULA): this method uses a checklist in which each body part is carefully evaluated, according to a set of predefined limit positions. It evaluates the overall comfort of a working posture analyzing the position of the trunk, neck, legs, wrist, upper and lower limbs as well as the presence of loads. A general score is assigned to each posture, which indicates the necessity of changing the workstation layout, in order to reduce the risk of potential physical disorders to the operator;
- Ergonomic Assessment Work-Sheet (EAWS): it is a tool for the holistic evaluation of physical workloads, based on standardised process languages such as Methods-Time Measurement (MTM) and Universal Analyzing System (UAS). EAWS focuses especially on existing CEN and ISO standards, evaluating working postures, action forces, manual materials handling and repetitive loads of the upper limbs. It evaluates the physical effort with three zones (traffic light scheme) rating system;
- Cumulative low Back Loading (CBL): this tool evaluates the spinal forces acting on a workers's lower back, under any posture and loading condition. It calculates the low back compression, anterior/posterior shear and lateral shear at L4/L5 vertebral joint and shows if loads exceed NIOSH threshold limit values or expose workers to an increased risk of low back injury forces.

Ergonomic indicators' scores extracted from the two softwares can be also compared with a video-based ergonomic analysis carried out by experts or by specific, dedicated software tools (e.g. motion capture systems).

3. The industrial case study

The industrial case study is based on the assembly process design of a medium-sized tractor hood. In the company, this type of process is accomplished by a completely manual procedure. The use of DHS was useful to design the process taking advantage of the digital support. Both tools were used and compared according to the proposed methodology. After that, the assembly line was really implemented and real workers were video-recorded to carry out the traditional, video-based ergonomic analysis by experts. Four experts were involved in the study; they judged the tool usage by the proposed methodology and carried out a video-based traditional analysis for the evaluation of the ergonomic indicators.

Table 1. Comparative indicators.

	Indicators	**Unit of measurement**
Subjective	Easiness of scene creation	1-5 Likert scale
	Easiness of scene navigation	1-5 Likert scale
	Easiness of object manipulation	1-5 Likert scale
	Easiness of joint manipulation	1-5 Likert scale
Time performance	Time for scene creation	Hours
	Time for simulation implementation	Hours
	Time for ergonomic report creation	Hours
	Time for ergonomic report analysis	Hours
Accuracy of the ergonomic assessment	OWAS	Level of risk (green, yellow, red)
	RULA	1-15 scale
	EAWS	Level of risk (0-25, 26-50, >50)
	CBL	kNs

3.1. *Case study description*

The case study was originally analyzed together with the company engineering team, which highlighted the necessity to design the assembly sequence by acting both on the product and the workstation, due to the possible operator's difficulties in reaching some parts and viewing the hood fixing points. Figure 1 shows the digitization of the workstation as originally designed by the company.

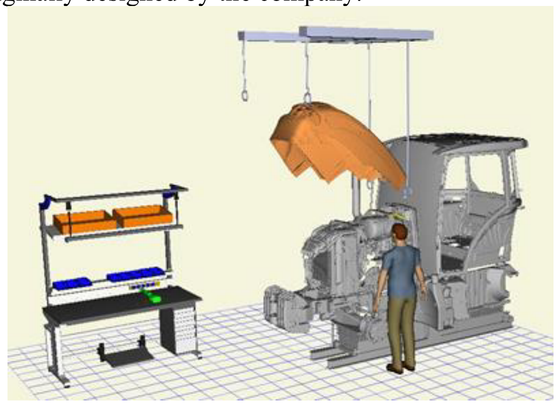

Figure 1. Digitization of the workstation as originally designed.

The as-is task sequence of the hood assembly, as considered in this study, is made-up of 10 steps and described in Table 2.

Table 2. Use case tasks.

N° of task	Task description
1.	Pick up the hood from the conveyor with a hoist
2.	Lower the hood with the hoist onto the tractor body
3.	Guide the hood with hands to center the four threaded pins in the holes of the hood support bracket
4.	Pick up n.2 bolts from the box storage
5.	Start the bolts manually
6.	Pick up n.2 nuts from the box storage
7.	Start the nuts manually
8.	Pick up electric screwdriver from the trolley
9.	Tighten the nuts with the electric screwdriver
10.	Place the electric screwdriver on the trolley

Moreover, precise indications were submitted regarding boundary conditions such as the maximum hood's opening angle (50°), the hood positioning direction (the hood must be collected from the right side of the tractor body) and the number of operators (one operator per side). In order to correctly implement the simulation, objects' weights need to be simulated to properly evaluate the physical effort of operators. The weights of the parts to be handled are: the tractor hood (50 kg), the two nuts (0,03 kg), the 2 screws (0,04 kg) and the electric screwdriver (4 kg). In addition, a report about loads (forces and momentums) that workers have to apply during the assembly was reported by the engineering team.

3.2. Case study simulation

The case study was virtually recreated in the two simulation environments, as shown in Figure 2. Regarding Jack, the simulation was implemented with the use of the Task Simulation Builder (TSB) plugin, in which the user could define the workers' tasks step by step. Similarly, the worker task sequence was created in PS using the same pattern included in the main software.

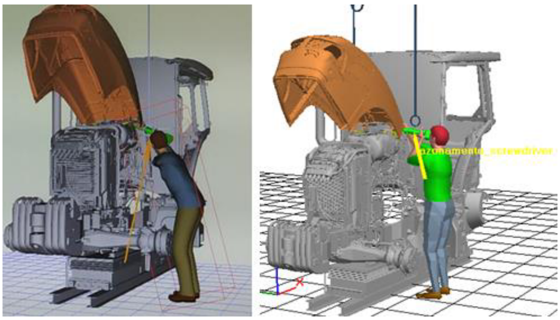

Figure 2. Simulation of a worker in Jack (left) and PS (right) environment.

4. Results from the comparative study

4.1. *Subjective evaluation*

Results from the subjective evaluation are reported in Figure 3 as average scores on the four experts involved, using the 5-point Likert scale. Regarding the scene creation, the operations to load 3D CAD models or create the mannequins do not require particular skills, so this highlights that Jack is more intuitive and easy to use compared to PS. On the contrary, the latter seems to be more direct about scene navigation, as shown in Figure 3, because Jack requires a combination of keyboard and mouse commands to rotate and zoom the virtual environment. Furthermore, the object manipulation is more accurate and straightforward on PS than Jack. Instead, the manikin joint manipulation is very similar on the two softwares and there is not particular criticality.

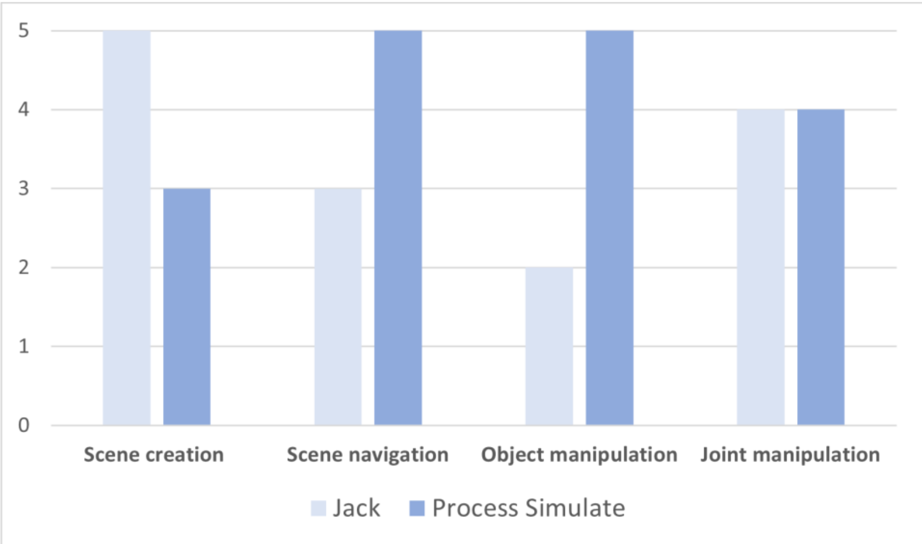

Figure 3 . Subjective assessment.

4.2. *Objective evaluation*

Objective evaluation included the analysis of time performance and the accuracy of the ergonomic assessment. About time performance, Table 3 synthesizes the comparison between Jack and PS, as average values obtained by all experts. Results demonstrated that analysis in Jack is more effective for scene creation (-33% on average), but it is globally more time consuming (+70% on average), mainly due to the higher time requested to create the ergonomic reports and their analysis. In both cases, the simulation implementation time is comparable between the two softwares. As far as the accuracy of the ergonomic assessment, the scores extracted from the two softwares analysis on the whole task sequence and the video-based ergonomic analysis by experts were compared. In the interest of brevity, values indicated in Table 4 take into account the overall scores on the entire process. For OWAS and RULA, the average score on the entire sequence was considered.

Table 3. Comparison on time performance indicators.

Tasks	Jack (h)	PS (h)
Scene creation	2	3
Simulation implementation	6	6
Creation of ergonomic reports	10	3
Ergonomic report analysis	8	3
Total	26	15

Table 4. Comparison on accuracy of ergonomic assessment (**average values of the entire task sequence)*

Ergonomic Index	On field assessment	Jack	PS
OWAS*	yellow risk	yellow risk	yellow risk
RULA*	4,8	4,7	4,5
EAWS	37,3	43,0	35,1
CBL [kNs]	4214,4	3958,3	4365,9

From these results, we can state that:

- OWAS comparison does not highlight any significant differences in terms of risk level between Jack, PS and expert video-based ergonomic analysis, considering the average score during the entire simulation. Some minimal differences in the score of the single postures are revealed. The application on the use case spotted an issue in PS that badly evaluated the task in which operators apply forces.
- RULA comparison demonstrated a good match by scores obtained by Jack, PS and expert video-based ergonomic analysis as well. Only notable difference is the risk band associated with the Apply Force task that is part of the nut tightening phase; in fact, PS underestimate the risk respect Jack in this kind of tasks;
- EAWS comparison underlined that PS is a more reliable tool for this calculation, providing an overall score closer to the experts evaluation. This could be due to the fact that this index is automatically calculated only in PS software but not in Jack, where is required a post processing of data postures in an external dedicated excel checklist;
- Finally, the CBL comparison observed that the cumulative compression value on L4/L5 (considered in a shift of 8 working hours) from Jack and PS simulations have given approximately the same results, that were far below the NIOSH limit. We could say that Jack mildly underestimates the risk, but we did not measure this risk on the field.

To sum up, the main strengths of both systems are listed in Table 5, to help companies to choose the system that better satisfies their needs.

Table 5. Points of strengths of Jack and PS.

Software	Points of strengths
Jack	easier and faster scene creation
	more reliable results on apply force tasks in OWAS an RULA evaluation
PS	more intuitive object manipulation and scene navigation
	faster creation and analysis of ergonomic assessment report
	automatic and more accurate EAWS evaluation

5. Conclusions

The paper investigated the application of DHS in manufacturing tasks to support the design of human-centric workstations, considering two software toolkits, Jack and Process Simulate from Siemens. In particular, the paper proposed a methodology to compare any type of DHS softwares, defining a set of subjective and objective indicators. Ergonomic problems investigated by different analysis tools benefit from a transdisciplinary approach that merges the engineering point of view with the social sphere, considering the well-being of the operators [22][23]. The aim of the research is to guide companies in the selection of the most suitable software that fits their needs, encouraging the application of transdisciplinary tools. The comparison study demonstrated that Jack is probably the best choice to optimize the scene creation effort and ease of use, and to execute formative analysis on brief, static postures. Moreover, Jack makes us obtain more reliable results in case of huge force applications. On the contrary, PS allows an easier object manipulation and virtual scene navigation compared to Jack. Furthermore, PS is more suitable to carry out an overall ergonomic evaluation considering an entire process, providing a more detailed ergonomic report and allowing to save time during the ergonomic analysis itself. In particular, the EAWS evaluation in PS is immediate, using a dedicated plugin, that provides accurate results. In brief, Jack could be effectively used for quick static posture evaluation, instead PS is advisable for ergonomic studies with dynamic simulation.

The main limitations of the study are due to the limited number and complexity of the simulated tasks of the case study. For this reason, the comparison could be extended to other application fields, including both assembly and maintenance operations.

References

[1] M. Gášová, M. Gašo and A. Štefánik, Advanced industrial tools of ergonomics based on Industry 4.0 concept, *Procedia Engineering*, 2017, Vol. 192, pp. 219-224.

[2] Y. Cohen, M. Faccio, F.-G. Galizia, C. Mora and F. Pilati, Assembly system configuration through Industry 4.0 principles: the expected change in the actual paradigms. *IFAC-PapersOnLine*, Vol. 50(1), pp. 14958-14963. 2017,

[3] M. Peruzzini, S. Carassai and M. Pellicciari, The benefits of human-centred design in industrial practices: re-design of workstations in pipe industry. *Procedia Manufacturing*, 2017, Vol. 11, pp. 1247-1254.

[4] L. Hanson, The Need for Faster and More Consistent Digital Human Modeling Software Tools, *Advances in Transdisciplinary Engineering*, Vol. 11, 2020, pp. 299-310.

[5] F. Caputo, A. Greco, M. Fera and R. Macchiaroli, Workplace design ergonomic validation based on multiple human factors assessment methods and simulation. *Production & Manufacturing Research*, 2019, Vol. 7(1), pp. 195-222.

[6] M.-F. Brito, A.-L. Ramos, P. Carneiro and M.-A. Gonçalves, Ergonomic Analysis in Lean Manufacturing and Industry 4.0 - A Systematic Review.in A.C. Alves et al. (eds.) *Lean Engineering for Global Development*, Springer Nature Switzerland, 2019, pp. 95-127.

[7] M. Zare, M. Croq, F. Hossein-Arabi, R. Brunet and Y. Roquelaure, Does ergonomics improve product quality and reduce costs? A review article. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 2016, Vol. 26(2), pp. 205-223.

[8] G. Chryssolouris, D. Mavrikios, N. Papakostas, D. Mourtzis, G. Michalos and K. Georgoulias, Digital manufacturing: history, perspectives, and outlook. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 2009, Vol. 223(5), pp. 451-462.

[9] E. Rauch, D. T. Matt, C. A. Brown, W. Towner, A. Vickery and S. Santiteerakul, Transfer of industry 4.0 to small and medium sized enterprises. *Advances in Transdisciplinary Engineering*, 2018, Vol. 4, pp. 63-71.

[10] M. Peruzzini, N. Wognum, C. Bil and J. Stjepandic, Special issue on 'transdisciplinary approaches to digital manufacturing for industry 4.0', *International Journal of Computer Integrated Manufacturing*, 2020, Vol. 33(4), pp. 321-324.

[11] N. A. Stanton, A. Hedge, K. Brookhuis, E. Salas and H. W. Hendrick, *Handbook of human factors and ergonomics methods*, CRC press, Boca Raton, 2004.

[12] A. Iriondo Pascual, D. Högberg, A. Syberfeldt, E. Brolin and L. Hanson, Optimizing Ergonomics and Productivity by Connecting Digital Human Modeling and Production Flow Simulation Software. *Advances in Transdisciplinary Engineering*, 2020, Vol. 13, pp. 193-204.

[13] N. Badler, Virtual humans for animation, ergonomics, and simulation. *Proceedings IEEE Nonrigid and Articulated Motion Workshop*, 1997, pp. 28-36.

[14] H. Honglun, S. Shouqian and P. Yunhe, Research on virtual human in ergonomic simulation. *Computers & Industrial Engineering*, 2007, Vol. 53(2), pp. 350-356.

[15] M. C. Schall Jr, N. B. Fethke and V. Roemig, Digital human modeling in the occupational safety and health process: An application in manufacturing. *IISE transactions on occupational ergonomics and human factors*, 2018, Vol. 6(2), pp. 64-75.

[16] W. Zhu, X. Fan and Y. Zhang, Applications and research trends of digital human models in the manufacturing industry. *Virtual reality & intelligent hardware*, 2019, Vol. 1(6), pp. 558-579.

[17] T.-A. Abdullah, K. Popplewell and C.-J. Page, A review of the support tools for the process of assembly method selection and assembly planning. *International Journal of Production Research*, 2003, Vol. 41(11), pp. 2391-2410.

[18] M. Saravi, L. Newnes, A. R. Mileham and Y. M. Goh, Estimating cost at the conceptual design stage to optimize design in terms of performance and cost, In: R. Curran et al. (eds.) *Collaborative product and service life cycle management for a sustainable world*, Springer, London, 2008, pp. 123-130.

[19] J. Mühlstedt, *Entwicklung eines Modells dynamisch-muskulärer Arbeitsbeanspruchungen auf Basis digitaler Menschmodelle*, PhD thesis, TU Chemnitz, 2012.

[20] P. Polášek, M. Bureš and M. Šimon, Comparison of digital tools for ergonomics in practice. *Procedia engineering*, 2015, Vol. 100, pp. 1277-1285.

[21] R.W. Scholz and G. Steiner, The real type and ideal type of transdisciplinary processes: part I-theoretical foundations, *Sustainability Science*, 2015,Vol. 10, No. 4, pp.527–544.

[22] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, W. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, Vol. 7, 2018, pp. 753-762.

[23] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, W. Verhagen, Transdisciplinary systems engineering: implications, challenges and agenda, *International Journal of Agile Systems and Management,* 2019, 12(1), pp. 58–89.

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Design of a Wire Cut EDM End-Effector with Strict Robotic Constraints

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Abstract. Wire Electric Discharge Machining (WEDM) stands out as a non-contact and nearly force-free machining technique able to cut complex workpieces, delivering dimensional accuracy and superior surface finishing, especially for exotic super-hard materials. On the other hand, machining with six-axis industrial robots (IR) has received much attention due to its notorious advantages over CNC machines to deliver cost efficiency, large envelope, and complex tool kinematics. However, robot machining suffers from severe limitations regarding the tool payload, chatter, repeatability, accuracy error, complex programming and frequently poor surface finishing. This paper investigates the benefits of combining a robot with WEDM to exploit the advantages of both techniques. However, the new system design is not trivial and will involve a transdisciplinary approach and inventive problem solving to design and control a WEDM end-effector. The present study adopts the TRIZ algorithm approach to design a novel WEDM end-effector and define actions to be taken to achieve a flexible and accurate robotic machining system for hard-to-cut materials.

Keywords. Wire Electric Discharge Machining, Robotic WEDM machining, WEDM end-effector, TRIZ, transdisciplinary design

Introduction

Technological progress has pushed the boundaries of materials and design. The demand for high-performance materials such as superalloys, composites, ceramics, semi and superconductors are a hot topic. However, the same properties that make these materials appropriate for high-end applications imposed significant cutting challenges while using traditional machining techniques [1]. As a solution, electric discharge machining (EDM) has been successfully adopted to cut any hard material offering at least 0.01 S/cm of electric conductivity [2]. The process consists of an electrode steering a series of high-frequency electric discharges that gradually melts the workpiece's surface into small particles flushed by the dielectric fluid. In EDM, there is no contact between the electrode and the workpiece and nearly no forces. Thus, stresses, chatter and vibrations from traditional machining can be avoided. Up to the present day, to control the electrode path, EDM is configured on computer numerically controlled (CNC) machines. However, CNC machines are designed for stiffness to cope with the high forces and vibration of traditional machining. As a result, CNC has a limited working envelope that frequently leads the workpiece to be segmented in

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multiple stages, demanding tricky fixtures, resulting in lower precision and additional costs [3].

To overcome CNC limitations, traditional machining using 6-axis industrial robots (IR) have been extensively investigated, looking for cost-efficiency and design freedom [4]. Besides, since IRs can attach a plethora of different end-effector tools (EE), sensors and control mechanisms, IRs can deliver multi-functionality with improved productivity [5]. Nevertheless, due to IR's intrinsic design, they lack stiffness and cannot hold heavy loads either cope with high forces of traditional machining, particularly on exotic hard-to-cut material. That is why most of the correlated research efforts focus on solving IR machining problems originated from the lack of IR stiffness resulting in machining vibration, poor surface finishing, lack of precision and repeatability [6].

On the other hand, the EDM process, particularly wire EDM (WEDM), has been suggested as a promising solution for IR lack of stiffness and limited forces [7]. Other technical obstacles persist and are fundamentally spread by their transdisciplinary nature. Among the most notorious, the following are a few: limited payload, complicated programming, accuracy error, and complex control. Therefore, the present research will adopt the Theory of Inventive Problem Solving (TRIZ) algorithms to find conceptual transdisciplinary engineering solutions to design a WEDM end-effector with strict robotic constraints. The research is organised as follows. Section 2 describes the methodology. Section 3 presents the results, and lately, section 4 is the conclusion.

1. Methodology for End-Effector design by TRIZ

Initially developed by G.S. Altshuller in the 1940s, the technique of TRIZ has been exploited more fully in the 1990s. It consists of algorithms and 40 transdisciplinary principles for driving creative thinking on problem-solving, rather than an intuitive and monodisciplinary trial and error approach. Therefore, the first step in our methodology is to map the usual problems from IR machining and WEDM to apply the TRIZ approach.

Classical TRIZ have available several different tools whose selection depends on the problem and context, making it challenging to select the appropriate tools. To properly formulate an inventive problem that forms a contradiction and respective application of TRIZ principles, we adopt the algorithm suggested by Cameron [8] to later incorporate the concepts into the WEDM end-effector design. Figure 1 summarises the adopted methodology.

To map the problems and main aims, a systematic review [9] on literature from 2010 to 2020 was conducted from scientific databases as well as patents, industry articles, and reports not included in academic repositories.

2. Results

2.1. Problem mapping on wire EDM and robotic machining

The literature was tabulated in chronological order to find recurrent problems on WEDM and potential sources of TRIZ contradictions. Next, the problems were classified into identified five main categories of material removal rate (MRR), surface roughness (SR), wire break or performance (W.P.), design freedom (D.F.) and dimensional or geometrical error (DGE). Table 1 summarises the findings.

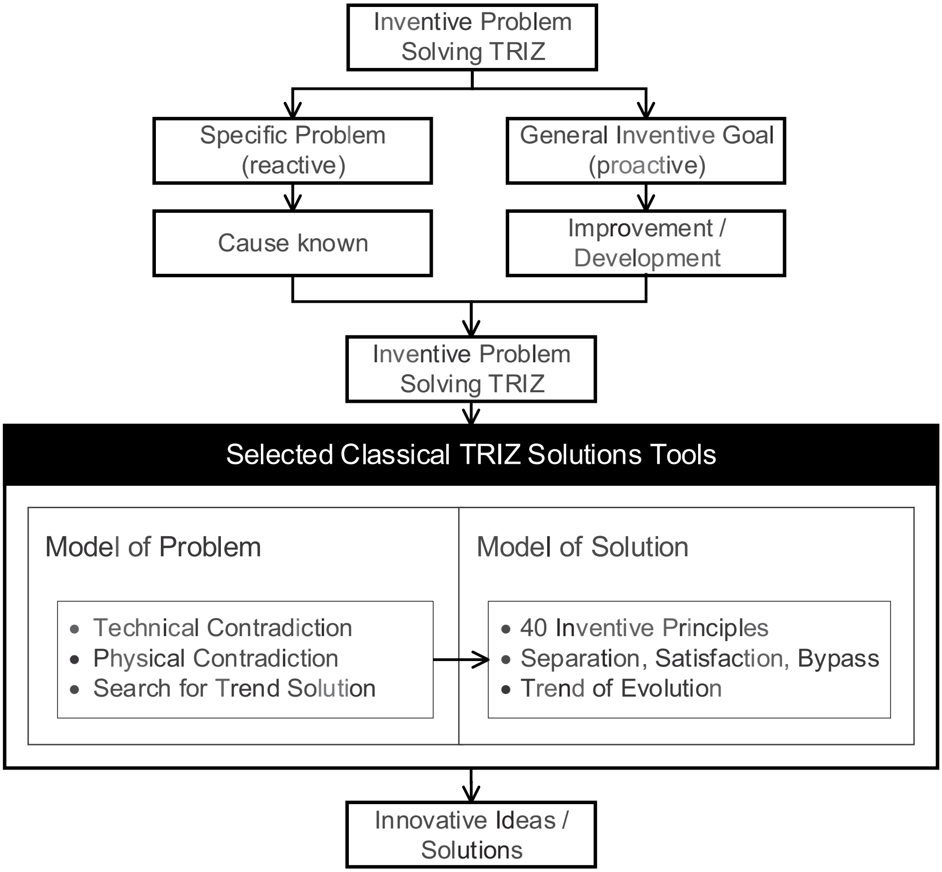

Figure 1. Algorithm for the use of narrowed TRIZ tools.

Similarly, to find recurrent problems on robotic machining and discover potential sources of TRIZ contradictions, the literature was again tabulated in chronological order while robotic machining problems classified into identified four main categories of accuracy, vibration, and compensation and low stiffness. Table 2 summarises the findings.

Table 1. Recurrent aims and problems on WEDM.

Year	Reference	Main aim	Problem				
			MRR	SR	WP	DF	DGE
2010	[10]	Adaptive fuzzy servo control to avoid wire breakage	•	•	•		
2012	[11]	Process optimisation of aluminium composite	•	•			

2013	[12]	WEDM control to avoid wire rupture in high thickness cut	●	●			●
2014	[13]	Review on process optimisation	●	●			●
2015	[14]	Process optimisation for SR based on wire geometry/speed & current	●	●	●		
	[15]	Adaptive real-time control for MRR, SR and stability	●	●			
	[16]	Process optimisation by adaptive neuro-fuzzy inference	●	●			
	[17]	Process optimisation for taper cutting	●	●		●	●
	[18]	Adaptive servo control based on current pulse probability	●	●	●		
	[19]	Real-Time control system for MRR	●		●		●
2016	[20]	Identify the most significant parameter for MRR and SR	●	●			
	[21]	Investigate wire movements and workpiece location			●		●
	[22]	Process optimisation for tapered parts	●	●		●	●
	[23]	Investigate burning surface in High-speed WEDM parameters	●	●			
2017	[24]	Machining parameters against harmful wire vibration	●	●	●		●
	[25]	New wire mechanism for improved SR and M.R. in tapper		●		●	●
	[26]	Improved accuracy and MRR with ultrasonically activated wire	●	●	●		●
	[27]	Adaptive servo control for variable thickness	●		●		
2018	[28]	New HS-WEDM with long wire with process parametrisation	●	●	●		
	[29]	Processes optimisation for Titanium Grade 6	●	●	●		●
	[30]	Influence of cut direction in SR	●	●			
	[31]	Processes optimisation for angular error in taper cutting					●
2019	[32]	Processes optimisation for Al (6082)/tungsten carbide composite	●	●			●
	[33]	High-performance wire	●	●	●		●
	[34]	Investigates different control strategies in wire EDM	●	●			●
2020	[35]	Processes optimization for Inconel 625	●	●			

Table 2. Recurrent aims and problems on robotic machining.

Year	**Reference**	**Main aim**	**Problem**			
			Accuracy	Vibration	Compensation	Low stiffness
2010	[36]	Investigate errors due to tool displacement	●		●	●
	[37]	Real-time dynamic error compensation	●		●	●
2011	[38]	Review on error sources in IR machining	●	●	●	●
2012	[39]	Robotic wire cutting process with design freedom	●			●
	[40]	Automated robotic deburring	●		●	
	[41]	Real-time compensation control	●	●		●
2013	[42]	Contact sensing-based for grinding process	●		●	●
	[43]	Propose CNC-like machining	●		●	●
	[44]	Multi-process programming	●		●	●
	[45]	Automated robotic deburring	●		●	
	[6]	Map primary sources of IR machining error	●	●	●	●
	[46]	Real-time compensation using piezo actuators	●		●	●
2014	[47]	Robot stiffness	●		●	●
2015	[48]	Automatic tool changing system	●			
2016	[49]	CNC-like machining	●			●
2017	[50]	Robot stiffness	●		●	●
	[51]	Wire cutting process	●			
	[52]	Trajectory (cutting path) for the grinding process	●		●	●
2018	[53]	Geometric design freedom	●			
	[54]	3D workpiece into wire cutting program	●			
2019	[55]	Contact sensing-based for grinding process	●	●	●	●
	[56]	Real-time control	●			●
	[4]	Literature review IR machining	●	●	●	●
2020	[57]	Evaluate dynamic and static stiffness models for robot pose	●	●		●

2.2. Transdisciplinary End-Effector conceptualisation by TRIZ

To conceptualise the end-effector, we focus on two primary sources. First, common problems in both WEDM and Robotic machining. Second, we list those problems with a high probability to occur due to this novel combination. As a result, a list of broad and transdisciplinary causes is found.

Once the problems were identified, TRIZ [8] is adopted to approach the problems and trigger innovative concepts to be later incorporated into the WEDM end-effector design. **Table 3** presents the results.

Table 3. Concepts for designing a robotic WEDM end-effector.

Problem description	TRIZ		
	Model problem	**Principle**	**Model solution(s)**
1. Wire erosion	**(T.C.)** Create intense erosion without being eroded	• Regeneration • Universalisation	• Debris stick to the wire creating a protective layer renewed along with the erosion process. • Apply graphite brush to provide electric power and compensate wear by filling up wire craters.
2. Flushing debris	**(T.C.)** Travel deep into the kerf but get out fast	• Mechanical vibration • Add a force field	• Use ultrasonic activation to achieve a stationary wire wave to stabilise and overcome wire warping. • The dielectric fluid nozzle is designed to create a laminar field flow.
3. Servo delay during short circuit	**(TrE)** Move away from to workpiece and back with nearly no time	• Segmentation	• Add to the servo system a piezo actuator able to move high frequency and microscale only for short-circuit events.
4. Wire tension	**(PhC)** Achieve a gravity field in any direction allowing robotic freedom	• Replace a mechanical system	• Use ferromagnetic brakes to create an attached magnetic field that moves with the end-effector
5. Wire composition	**(T.C.)** Needs combined materials in complex shapes yet less complexity	• Increase segmentation	• Use off-the-shelf technology from the electric or lifting industry to interlace single wires with different materials.
6. End-Effector weight	It needs a ticker and yet light structure	• Porous materials • Increase segmentation and dynamism from solid to jointed	• Adopt topologic optimisation and lattice structure made of 3D print • Segment the wire winding system to be on the floor. Next, use flexible shafts to transfer to the end-effector only the wire.
7. Surface burning in high-speed WEDM	**(T.C.)** Use the entire wire with no change in rotation	• Increase dynamism from solid to jointed • Think in time and scale, and transfer to the supersystem	• The wire has its ends precisely welded, running continuously in the same direction. • The robot detects the end of the wire, stop, move out, revolve 180º and restart cutting in the same direction.
8. Trade-off SR vs MRR	**(PhC)** Needs High energy pulse for more MRR at the same timeless for better SR	• Think in time and scale to separate in time	• Pulse generator with higher frequency removes more material per time unity yet using lower energy for better SR
9. Hard to reach the back of the workpiece		• Increase segmentation and dynamism, and separate in time	The additional 7th axis acts as a rotating table and work synchronised with the robot and allows full access to workpiece geometry.

10. Hard to flush in a tilt position	**(T.C.)** Flow misaligned with the gravity field	• Blessing in disguise	Add a nozzle directly into the end-effector for constant flow-wire alignment while the robot cuts in a constant optimum diagonal angle, always top to bottom.

Legend: **(TC)** Technical Contradiction **(PhC)** Physical Contradiction **(TrE)** Trend of Evolution

2.3. Designed WEDM end-effector

Following the finding of the TRIZ transdisciplinary approach, , CATIA V5-6 CAD software is adopted, and the system is completely designed. As a proof of concept, the most miniature ABB IRB120 robot system is selected to verify the current robots' ability in coping with WEDM forces and vibrations. The IR payload is only 3kg yet delivering nearly 0.7 m^3 of working space. Figure 2 depicts the robot.

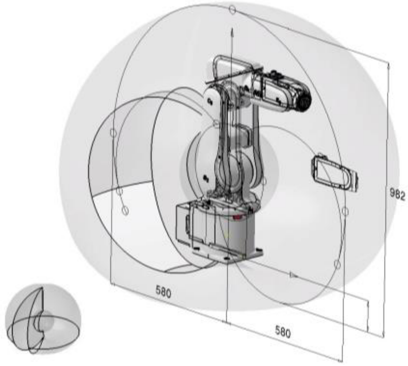

Figure 2. Size and workspace of ABB IRB120 for WEDM combination.

Figure 3 presents the mains subsystem of (1) WEDM end-effector, (2) separated wire winding system, (3) rotating 7th axis table, (4) pulse generator, (5) 6-axis industrial robot.

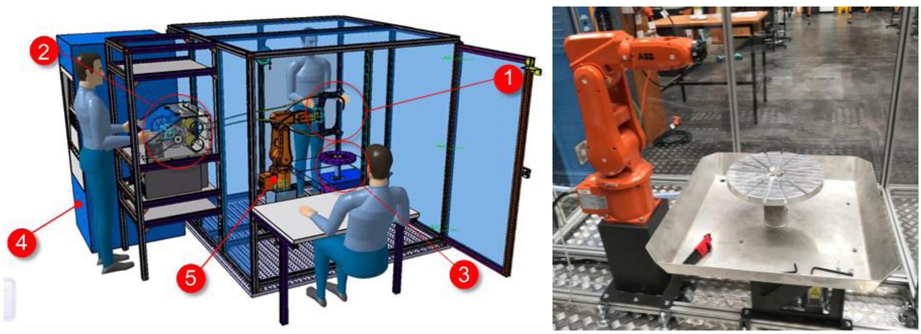

Figure 3. Robotic WEDM cell apparatus and main subsystems.

Next, in Figure 4, balloon 7, 3D-printed nozzles are designed to create a dielectric laminar flow travelling parallel to the wire to go deeper in the kerf for improved flushing. In balloon 6, a dual-axis piezo actuator is used to activate a stationary wave vibration on the wire. Also, it is possible to see the electric brush's use in direct contact with the wire providing power and, at the same time, regenerating the wire by filling craters with graphite.

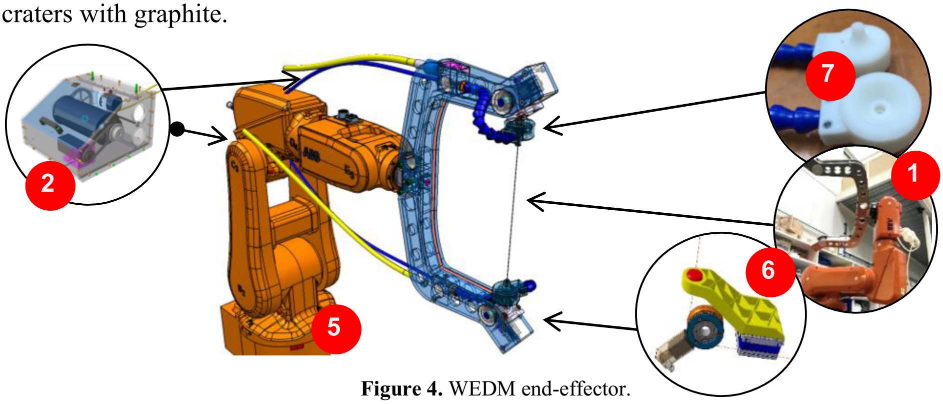

Figure 4. WEDM end-effector.

To verify the robotic system's ability to cope with wire EDM vibrations, ANSYS R19 software is used to perform modal harmonic simulation response while the robot is in a pose of low stiffness. It was found that the designed system can perform WEDM and yet avoid harmful vibrations if the pulse frequency is controlled. Figure 5-A displays severe vibration with amplitudes of 27mm under the natural frequency of 103 Hz. Figure 5-B shows that the maximal vibration amplitude is found over the wire yet lower than 1 micron when the frequency is above 6 kHz.

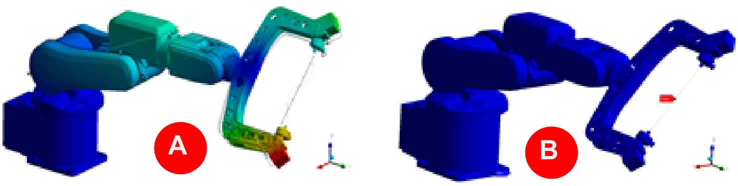

Figure 5. Robotic WEDM vibration response for ABB IRB120.

In Figure 6, a pulse generator with low-intensity iso-energy and pulse frequency up to 1GHz is prepared.

Figure 6. WEDM high-frequency pulse generator.

Although the TRIZ approach has innovative solutions, some ideas have been limited due to the lack of appropriate technologies to put them into the proposed design. For example, no feasible technology to weld a thin wire, yet keeping the external diameter (i.e. 0.15mm) was found. The next steps of the present research are to finish building the apparatus and perform a series of experiments to verify the capabilities of robotic WEDM regarding design freedom, vibration, MRR, SR, and precision.

3. Conclusion

Traditionally, WEDM has nothing to do with robots due to the nature of the process and structure of the equipment. The idea of combining these two totally different processes creates a series of transdisciplinary problems between mechanical, electronic, manufacturing engineering. There is a lack of prior researches on the challenges of combining these two systems. This paper presents a novel approach to scrutinise robotic and WEDM literature to discover recurrent and new obstacles in system design. TRIZ approach, which has been used extensively for user-oriented product design, is applied to analyse literature. The application of the TRIZ technique in this design process played a key role in finding the best combination and features of the robotic WEDM. The novel adaptation of TRIZ methodology has successfully designed a new combined process system that has the best chance to fulfil the expected system requirements and will deliver two main benefits: first, to cut exotic materials for complex, large, and monolithic workpieces; second, achieving robotic machining free of prohibitive chatter and vibrations, which have been reported to be detrimental to complex robotic compensation, such as backlash, pose, and dumping technics.

References

[1] K.-H. Park *et al.*, Tool wear in drilling of composite/titanium stacks using carbide and polycrystalline diamond tools, *Wear,* 2011, Vol. 271, no. 11-12, pp. 2826-2835.
[2] W. Konig, Sparks machine ceramics, *Powder Metallurgy International,* 1991, Vol. 23, No. 2, pp. 96-100.
[3] A.E.K. Mohammad and D. Wang, A novel mechatronics design of an electrochemical mechanical end-effector for robotic-based surface polishing, in *System Integration (SII), 2015 IEEE/SICE International Symposium on*, 2015: IEEE, pp. 127-133.
[4] W. Ji and L.H. Wang, Industrial robotic machining: a review, *International Journal of Advanced Manufacturing Technology,* 2019, Vol. 103, No. 1-4, pp. 1239-1255.
[5] M. Jonsson *et al.*, On force control for assembly and deburring of castings, *Production Engineering,* 2013. Vol. 7, No. 4, pp. 351-360.
[6] U. Schneider *et al.*, *Experimental Investigation of Sources of Error in Robot Machining*, Springer, Berlin Heidelberg, 2013.
[7] S. Almeida *et al.*, Strategic Approach to Develop Solutions for Shaping Complex Workpieces of Exotic Materials, *IOP Conference Series: Materials Science and Engineering,* 2020, Vol. 831, 012003.
[8] G. Cameron, *Trizics: Teach yourself TRIZ, how to invent, innovate and solve" impossible" technical problems systematically*. Create Space Publishinh Platform, 2010.
[9] W.J.C. Verhagen *et al.*, A critical review of Knowledge-Based Engineering: An identification of research challenges, *Advanced Engineering Informatics,* 2012, Vol. 26, No. 1, pp. 5-15.
[10] M.-T. Yan, An adaptive control system with self-organizing fuzzy sliding mode control strategy for micro wire-EDM machines, *The International Journal of Advanced Manufacturing Technology,* 2009, Vol. 50, No. 1-4, pp. 315-328.
[11] S. Singh and M.F. Yeh, Optimization of Abrasive Powder Mixed EDM of Aluminum Matrix Composites with Multiple Responses Using Gray Relational Analysis, *Journal of Materials Engineering Performance,* 2012, Vol. 21, No. 4, pp. 481-491.
[12] Y.S. Liao *et al.*, On-line Workpiece Height Estimation and its Application in Servo Feed Control of WEDM Process, *Procedia CIRP,* 2013, Vol. 6, pp. 226-231.
[13] V. Singh and S. Pradhan, Optimization of EDM process parameters: a review, *International Journal of Emerging Technology Advanced Engineering,* 2014, Vol. 4, No. 3, pp. 345-355.

[14] A.A. Khan *et al.*, Optimization of Surface Quality of Mild Steel Machined by Wire EDM Using Simulated Annealing Algorithm, in *2015 4th International Conference on Advanced Computer Science Applications and Technologies (ACSAT)*, 2015, pp. 3-8.
[15] S. Kwon *et al.*, Experimental investigation of the real-time micro-control of the WEDM process, *The International Journal of Advanced Manufacturing Technology,* 2015, Vol. 79, No. 9-12, pp. 1483-1492.
[16] I. Maher *et al.*, Improve wire EDM performance at different machining parameters - ANFIS modeling, *IFAC-PapersOnLine,* 2015, Vol. 48, No. 1, pp. 105-110.
[17] B.B. Nayak *et al.*, Parametric Appraisal of WEDM using Harmony Search Algorithm, *Materials Today-Proceedings,* 2015, Vol. 2, No. 4-5, pp. 2562-2568.
[18] L. Zhidong *et al.*, Automatic control of WEDM servo for silicon processing using current pulse probability detection, *The International Journal of Advanced Manufacturing Technology,* 2014, Vol. 76, No. 1-4, pp. 367-374.
[19] K.T. Hoang and S.-H. Yang, A new approach for Micro-WEDM control based on Real-Time estimation of material removal rate, *International Journal of Precision Engineering and Manufacturing,* 2015, Vol. 16, no. 2, pp. 241-246.
[20] M. Manjaiah *et al.*, Parametric optimization of MRR and surface roughness in wire electro discharge machining (WEDM) of D2 steel using Taguchi-based utility approach, *International Journal of Mechanical and Materials Engineering,* 2016, Vol. 11, No. 1, 7.
[21] T. Kamei *et al.*, High-speed Observation of Thin Wire Movement in Fine Wire EDM, *Procedia CIRP,* 2016, Vol. 42, pp. 596-600.
[22] G.S.B.J. Veerajothi, Experimental Study on Wire Electrical Discharge Machining of Tapered Parts, *Arabian Journal for Science and Engineering,* 2016, Vol. 41, No. 11, pp. 4431-4439.
[23] W. Wei *et al.*, Surface burning of high-speed reciprocating wire electrical discharge machining under large cutting energy, *The International Journal of Advanced Manufacturing Technology,* 2016, Vol. 87, No. 9-12, pp. 2713-2720.
[24] S. Habib, Optimization of machining parameters and wire vibration in wire electrical discharge machining process, *Mechanics of Advanced Materials and Modern Processes,* 2017, Vol. 3, no. 1, 3.
[25] H. Yan *et al.*, Large taper mechanism of HS-WEDM, *The International Journal of Advanced Manufacturing Technology,* 2016, Vol. 90, No. 9-12, pp. 2969-2977.
[26] V.-M. Nani, The ultrasound effect on technological parameters for increase in performances of W-EDM machines, *The International Journal of Advanced Manufacturing Technology,* 2016, Vol. 88, No. 1-4, pp. 519-528.
[27] H. Trung Kien, Development of a WEDM system with high machining efficiency, *2017 International Conference on System Science and Engineering (ICSSE)*, 2017, pp. 397-399.
[28] H. Ciwen *et al.*, Ultra-long Wire Reciprocated-WEDM with Dual Tensile Reels Winded, *Procedia CIRP,* 2018, Vol. 68, pp. 115-119.
[29] H.M.P. Maity, Predictive Analysis on Responses in WEDM of Titanium Grade 6 Using General Regression Neural Network (GRNN) and Multiple Regression Analysis (MRA), *Silicon,* 2018, Vol. 10, No. 4, pp. 1763-1776.
[30] K. Mouralova *et al.*, Influence of the cut direction through the semi-finished product on the occurrence of cracks for X210Cr12 steel using WEDM, *Archives of Civil and Mechanical Engineering,* 2018, Vol. 18, No. 4, pp. 1318-1331.
[31] B.B. Nayak and S.S. Mahapatra, An intelligent approach for prediction of angular error in taper cutting using wire-EDM, *Materials Today-Proceedings,* 2018, Vol. 5, No. 2, pp. 6121-6127.
[32] K.R. KumarNishasoms, Desirability-Based Multi-objective Optimization and Analysis of WEDM Characteristics of Aluminium (6082)/Tungsten Carbide Composites, *Arabian Journal for Science and Engineering,* 2019, Vol. 44, No. 2, pp. 893-909.
[33] Z.C.Z.Z. Li, Investigation on a novel surface microstructure wire electrode for improving machining efficiency and surface quality in WEDM, *International Journal of Advanced Manufacturing Technology,* 2019, Vol. 102, No. 5-8, pp. 2409-2421.
[34] A. Samanta *et al.*, Influence of different control strategies in wire electrical discharge machining of varying height job, *The International Journal of Advanced Manufacturing Technology,* 2016, Vol. 100, No. 5-8, pp. 1299-1309.
[35] M. Subrahmanyam and T. Nancharaiah, Optimization of process parameters in wire-cut EDM of Inconel 625 using Taguchi's approach, *Materials Today: Proceedings,* 2020, Vol. 23, pp. 642-646.
[36] E. Abele *et al.*, Prediction of the tool displacement for robot milling applications using coupled models of an industrial robot and removal simulation, *Proc. CIRP 2nd Inter Conf on Process Machine Interactions, Vancouver, Canada*, 2010.
[37] G.-C. Vosniakos and E. Matsas, Improving feasibility of robotic milling through robot placement optimisation, *Robotics and Computer-Integrated Manufacturing,* 2010, Vol. 26, No. 5, pp. 517-525.

[38] J. Pandremenos *et al.*, Machining with robots: a critical review, *7th International Conference on Digital Enterprise Technology*, 2011. pp. 1-9.
[39] M. Rippmann and P. Block, New Design and Fabrication Methods for Freeform Stone Vaults Based on Ruled Surfaces, in C. Gengnagel, A. Kilian, N. Palz, and F. Scheurer, (eds.) *Computational Design Modelling*, Springer, Berlin Heidelberg, 2011, pp. 181-189.
[40] Y.X. Song *et al.*, A method for grinding removal control of a robot belt grinding system, *Journal of Intelligent Manufacturing,* 2012, Vol. 23, No. 5, pp. 1903-1913.
[41] D. Surdilovic *et al.*, Advanced methods for small batch robotic machining of hard materials, *ROBOTIK 2012; 7th German Conference on Robotics*, 2012, pp. 1-6.
[42] F. Domroes *et al.*, Application and analysis of force control strategies to deburring and grinding, *Modern Mechanical Engineering*, 2013, Vol. 3, No. 2, pp. 11-18.
[43] A. Karim and A. Verl, Challenges and obstacles in robot-machining, in *IEEE ISR 2013*, 2013, pp. 1-4.
[44] S. Keating and N. Oxman, Compound fabrication: A multi-functional robotic platform for digital design and fabrication, (in English), *Robotics and Computer-Integrated Manufacturing,* 2013. Vol. 29, No. 6, pp. 439-448.
[45] M. Jonsson *et al.*, On force control for assembly and deburring of castings, *Production Engineering*, 2013, Vol. 7, No. 4, pp. 351-360.
[46] O. Sörnmo *et al.*, High-Accuracy Milling with Industrial Robots using a Piezo-Actuated High-Dynamic Compensation Mechanism, *COMET EU/FP7-project,* 2013, http://www.cometproject.eu/publications/icra2012.pdf, Accessed July 3, 2021.
[47] S. Caro *et al.*, Workpiece placement optimization for machining operations with industrial robots, *2014 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2014, pp. 1716-1721.
[48] I. McLaren and I. Gorlach, Development of a Tool Changer for a Reconfigurable Machine Tool, *Applied Mechanics and Materials*, 2015, vol. 798, pp. 324-328.
[49] A. Søndergaard *et al.*, Robotic Hot-Blade Cutting, in: D. Reinhardt, R. Saunders, and J. Burry (eds.) *Robotic Fabrication in Architecture, Art and Design 2016*, Springer International Publishing, Cham, 2016, pp. 150-164.
[50] Y. Bu *et al.*, Stiffness analysis and optimization in robotic drilling application, *Precision Engineering-Journal of the International Societies for Precision Engineering and Nanotechnology,* 2017, Vol. 49, pp. 388-400.
[51] M. Jovanovic *et al.*, Robotic fabrication of freeform foam structures with quadrilateral and puzzle shaped panels, *Automation in Construction,* 2017, Vol. 74, no. Supplement C, pp. 28-38.
[52] Y. Mao *et al.*, *Trajectory and Force Generation with Multi-constraints for Robotic Belt Grinding*, Springer International Publishing, Cham, 2017.
[53] P. Ruttico, Robots in Architecture, Research and Development, in M. Hemmerling and L. Cocchiarella, (eds.) *Informed Architecture*, Springer International Publishing, Cham, 2018, pp. 65-76.
[54] A. Søndergaard *et al.*, Robotic abrasive wire cutting of polymerized styrene formwork systems for cost-effective realization of topology-optimized concrete structures, *Construction Robotics,* 2018, Vol. 2, No. 1-4, pp. 81-92.
[55] F. Chen *et al.*, Robotic grinding of a blisk with two degrees of freedom contact force control, (in English), *International Journal of Advanced Manufacturing Technology,* 2019, Vol. 101, No. 1-4, pp. 461-474.
[56] Y. Ding *et al.*, Research and application on force control of industrial robot polishing concave curved surfaces, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* 2018, Vol. 233, No. 6, pp. 1674-1686.
[57] T. Cvitanic *et al.*, Pose optimization in robotic machining using static and dynamic stiffness models, *Robotics and Computer-Integrated Manufacturing,* 2020, Vol. 66, 101992.

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Method for Performance Analysis of Production Lines Based on Digital Models Powered by Real-Time Data

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Abstract. The intention to improve the performance of the processes involved is considered one of the main guidelines for companies' competitive advantage. Technological advances help to improve yields, operations, decision making and cost reduction when adopted in their daily processes, and assembly lines are constantly monitored, but the detection of adversities is still considered complex. Because of this difficulty, the proposal for a virtual model with greater fidelity to reality, such as the digital twin model, is promising. A virtual model of the shop floor system composed of physical characteristics present in the industrial environment, being fed with data that occurs in real-time, offers the simulation possible predictions of setbacks with greater fidelity. This monitoring provides the user with an improvement in the process control, assisting in the planning of operations, enabling changes in the virtual model of compliance verification, improving performance and productivity, reducing related times and costs for later application in the physical model. In this way, the objective of this work proposes the elaboration of an application method where it is possible to analyze the performance of productive lines through digital models integrated with the data feed system in real-time.

Keywords. Digital Twin, Industry 4.0, Simulation, Real-time data, Manufacturing System, Transdisciplinary.

Introduction

The highlight of many companies in relation to their competitors is linked to the use of competitive intelligence, helping in the process of innovating manufactured products as well as improving quality and reducing the costs involved in the procedures performed. Among the various technological advances present in the current market, the involvement of information, equipment and the communication of the entire system in real-time provide an agile and independent data analysis of both the process and the product, advising decision-making in the stages of product development.

In a transdisciplinary way, Industry 4.0 is related by its involvement in several areas such as information technologies, data exchange, the use of integrated systems, the use of the internet of things, cloud computing, modeling and information security. A smart factory based on Industry 4.0 involves a connection between mobility, structures, logistics and networks. Getting decision-making efficiently and in real-time through the

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joining of various technologies with the latest innovations serves as an incentive to practice Industry 4.0 [1].

The automotive industries use the concepts of Industry 4.0 because they consider productivity as central feasibility for the organization, featuring lean manufacturing characteristics, emphasizing the identification and elimination of waste constantly, aiming to reduce delivery times in the processes, improving the management of stocks through faster responses to market changes [2].

In line with Industry 4.0, the use of tools and techniques for monitoring and supervising industrial performance is associated with a competitive advantage. The use of predictive production techniques helps in the search for control of productivity loss points, enabling the anticipation of possible failures and even malfunctions of machines, which can be applied in several areas such as maintenance, planning, programming and even production [3].

A technology that can be considered when talking about monitoring is the digital twin, as it is a virtual representation of all the resources in the system. Ranging from the machine and shop floor layout, to the products, processes and tasks performed, entering the real times of the system, thus obtaining a continuous view of the functioning of the entire process.

The use of technologies based on simulations draws even more attention from companies as they allow the demonstration of possible solutions in the virtual environment before applying them to the physical itself. The great related value is in the fact that the user can experiment and evaluate in the virtual certain changes and combinations of factors present in the physical environment system [4].

Always present wishes in the automotive industry involve intelligent manufacturing and a way to assist this is through the virtual modeling of the system. Thus it provides companies with certain preventions, improvement and control of the processes carried out and the simultaneous monitoring of the activities carried out, assisting in the decision making of problems that may occur related to productivity [5].

Through a bibliographic survey, some points were related to support this research. When the search for the term system monitoring in real-time was carried out, little research was found involving the application of digital twin with industrial environments. If the search directs to the association between devices, with sensors and actuators, with the monitoring of the states of the connected devices through the Internet of Things (IoT) in a short period, what is found are only simulations, desiring its application in a real environment for a better evaluation of the method as well as the creation of a human-machine interface for its proper follow-up and monitoring [6].

Having some aspects observed in this bibliographic survey, this research is directed to the difficulties that many companies face in managing to improve performance issues of their systems and to adapt quickly to the production of a new item. The development of a method presented in this article will help to improve the company's flexibility and the difficulty in adapting to the exceptional.

Through the bibliographic survey carried out, it was observed the lack of applications in the practice of a digital model with the feeding of real data in real-time and with the monitoring in real-time, a gap that will be directed to this research. The rest of this work will be structured as follows: section 1 presents the main concepts on the relevant topics involved such as manufacturing systems, digital twin and assembly line. Section 2 describes the entire methodology for proposing the application of the digital model and finally, in section 3, the next steps for the physical application of the model and some preliminary results already obtained in the initial stages of the research and information for its continuity.

1. Background

In view of the wide possibility of using technologies to virtualize the resources of the processes present in manufacturing, a bibliometric study was carried out and the most relevant scientific productions were analyzed, thus obtaining the edge of knowledge for the themes involved with this research.

A pointed trend [1] is the implementation of digital twin through a structural system with all the elements connected. Making its modularity, autonomy and connectivity possible through installations and the use of sensors and actuators distributed by the system.

The need to use current software is presented [7] as a challenge for the rapid updating of data, such as the times of individual cycles and the degrees of use of workstations and robots. In addition, [8] the application of a digital twin model for production control in a continuous manner and updated in real-time must reflect exactly what is happening in the physical environment, allowing for optimizations, quick and concise decision making, intervening in a predictive manner.

A relevant point pointed out in another research [6] indicates that it is essential to detail the modeling concepts for more complex environments when analyzing the Internet of Things (IoT) devices, such as the industrial factory floor. Modeling tools often do not support simulation and analysis due to the high number of representations required in the virtual model of equipment such as machines, devices, sensors and actuators.

When the digital twin model is directed to the shop floor, it considers its own research [9] as an initial stage and points to future work the interconnection and intelligent interaction of the shop floor, a bidirectional connection between the physical and virtual environments, perfecting the virtual model with the increase of fidelity are fundamental for future applications of the digital twin shop-floor in intelligent fabrications.

The involvement of Industry 4.0 in a transdisciplinary way adds value to the client by presenting the real conditions of the process, with a high number of information implemented in the simulation, bringing the virtual representation closer to reality, obtaining more efficiently the indication of possible problems in the project and directing appropriate improvements in advance.

To demonstrate the main issues related to this research, the following will present relevant concepts and approaches found in reputable scientific publications. Firstly, it will be discussed on manufacturing systems, followed by an approach regarding digital twin and finally on production lines with a focus on performance analysis, flexibility and adaptability.

1.1. Manufacturing System

The manufacturing systems are constantly improving so that they can respond to the involvement of new technologies, quickly and efficiently directing their final objective, providing opportunities for the activities involved and improving the final quality.

In general, manufacturing systems can be seen as a set of complex activities because they involve people, a high diversity of machines and tools, as well as other equipment in its various levels of automation, such as robots and computers. A manufacturing system starts with the development of a product, proceeding to the manufacturing engineering, composing the development of the production processes, as well as the planning of the necessary resources for the effective production of the product and its delivery to the customer [10].

This whole set of activities and operations is associated with the necessary inputs, the transformation processes and the manufacturing life cycle. Depending on the degree of complexity of these variables, robust monitoring has great value, allowing the whole process to occur in the best possible way [11].

More and more [12] companies are inserting digital and intelligent manufacturing in their procedures, improving the modeling of design data, manufacturing, management and maintenance of the operations involved.

When all this transdisciplinary involvement is analyzed, there is a need for research regarding the involvement in data capture in an automated way and the generation of a database in real-time. Connecting the physical and real systems allowing access, exchanges and data processing, collaborating in the manufacturing systems and boosting Industry 4.0, we can mention the cyber-physical systems (CPS) [13].

Following the architecture of CPS with Industry 4.0 [14], the proposal of the five levels in the systems provides an intelligent analysis for integrity, allowing the modeling of the digital twin and assists in decision making. Working its connectivity in an advanced way in the collection of data in real-time of the physical environment with the management, analysis and computation of the data in a cybernetic environment.

When PHCs are used [13], aspects such as self-organization, security, remote diagnosis, real-time control, transparency, predictability, efficiency and possible corrections in the virtual model are expected to be improved. All these aspects add value to an organization based on Industry 4.0 by presenting autonomous optimization, promoting the digitization of the entire production, in addition to the involvement of workers, products and resources with intelligent instances.

Researches consider CPS as promising for its involvement with IoT, through the transdisciplinary distribution between the resources of computing, communication and control of physical systems, not to mention its use as a data provider for digital models. These models represent resources of the process assisting in decision making and production planning, because through their analysis actions are possible in the physical environment, such as exchanging information providing an improvement in the quality of services and suggesting in the proposal in the use of digital twin in a manufacturing process.

1.2. Digital Twin

A digital twin model can be seen as a set of virtual information to portray a product, a system or a physical process. From the minimum level of the machines, through the factory level as the assembly line, to the maximum possible as the organizational level for example [15]. Having been seen as a new technology inserted in the industrial environment, the analysis of the effects caused in the most complex scenarios present and its monitoring in decisions over time is essential.

When related to manufacturing, the digital twin can be defined as a virtual representation of the production systems to synchronize the virtual and real systems. This synchronization can be carried out [8] using connected smart devices allowing the communication of data in real-time, the basis of Industry 4.0 with its involvement of technological resources for the prevention and optimization of recurrent behaviors in the system.

Its use in manufacturing also makes it possible to simulate and optimize production systems as it encompasses several aspects, providing a visualization of the entire process, whether at the level of just one component or even the entire assembly line [16]. Emphasizing the areas of control, production planning, maintenance and also layout planning, aiming at increasing competitiveness. The digital twin is seen with great potential in planning and optimization simulations [9], in increasing efficiency and precision, obtaining considerable financial gains for production [8], and also because it is not just a large collection of digital artifacts, but a structured model with all the elements connected [1].

The digital twin model emphasizes the control and decision-making of processes due to the identification of deviations from the current operation of the equipment and its causes, helping to identify possible emergencies and generating alerts for the monitoring team about abnormal events and situations [17]. Among the advantages of its implementation, we can mention the use of production equipment with mechanisms and operations monitored by devices. The collection of the generated data takes place through sensors, actuators and optimized software.

Different levels of integration between the physical and virtual models are defined according to the modeling. A level can be a digital model when there is no automated exchange of data between the models, always taking place manually. It can also be a digital shadow when the automated data flow is unilateral, and any change in the physical environment has repercussions in the virtual, but the opposite path does not occur. And finally, the digital twin, in which the data exchange flow occurs in both directions, providing control on both sides, allowing interventions in the plant, physical environment, through the virtual environment, its executions and the responses of the physical environment being obtained in the virtual [16].

Therefore, the application of the digital twin in an industrial environment includes the improvement of situational knowledge of the entire process with the insertion of the real data of the system, enabling the improvement in the responses of the conditions of possible changes and optimization of future conditions with the permission of analysis of performing predictive maintenance in the process of production lines, such as automotive assembly lines.

1.3. Assembly line

There are several cases of application of digital twin in manufacturing processes, so there is an opportunity to apply it on an assembly line. The assembly lines can also be called progressive assembly precisely because there are associations and joints of parts as they travel through the workstations distributed on the factory floor, being sequentially incorporated one by one until the final product.

The execution of similar methods in the production of items such as automobiles, the transportation of equipment and the manufacture of household and electronic devices are considered important characteristics for an assembly line. As well as the sequential disposition of those involved in it, as operators and tools, as well as the machines and parts, used to produce the product.

The layout of an assembly line can be considered a direct influence on productivity, allowing for several dimensioning configurations for the line [18]. Another important feature is the access to the parts that will be used coming to the work stations, their displacement occurs by transporters or motor vehicles.

The complexity of the assembly lines is due to the high number of interconnected variables for their operation. These variables are related to technologies, environmental factors, ergonomic issues and the methods and times for the production of parts [19].

As soon as an assembly line is drawn up, the first characteristic that must be analyzed is its balance. For the construction of this line, some points must be considered, such as the verification of all the essential steps to manufacture each item of the product, the balance of the procedures along the line must be measured, the number of machines and their production rates is also important.

In an automotive assembly line, all components must be integrated sequentially as the product will be formed and transported by a transporter. As the product passes through the line, each operator performs a specific task for their workstation by placing supplies such as parts and tools at their point sequentially. The company's flexibility in adapting and incorporating new activities in the manufacturing process and in adapting to changes in actions and in the production flow quickly and effectively are important factors for a good manufacturing process.

2. Methodology

There are promising conditions for companies that are involved with the use of competitive intelligence. The use of knowledge involving intelligent manufacturing with the technologies of industry 4.0, as a way of assisting decision-making in production processes, whether new or existing, promotes the improvement of solutions for applications in production lines with higher quality.

The direction of this research relies on selected literature for a diagnosis of the problem in question and through observations on the procedures performed in the company of the application case. This investigation took place through interviews with the parties involved as process and project engineers together with the analysis of the documents and times for the procedures to be carried out.

The observation of the procedures and tasks carried out in the company were analyzed and resulted in the proposal of an analysis of the performance of the production line aiming at the reduction of costs involved with the detected problems. These problems may be related to the lack of a virtual model to enable checks and compliance with changes in the physical environment of the production line.

Changes to an existing project or the insertion of a new product on an assembly line, cause the responsible team to spend a lot of time between trips, attempts, errors and successes so that the job can be left with optimum performance. Because of this issue, a digital model was chosen. Therefore, this research aims to develop an application method to analyze the performance of the production lines, through a digital model fed with real data and in real-time providing simulation of ideas in a production environment.

The simulation provides an advantage for its virtual implementation. The team can have a vision of the assembly line and create scenarios in advance, because until then this task would only be possible after the complete definition of the project, resulting in numerous subsequent changes generating a high rate of rework. The simulation assists in boosting innovation so that it is possible to virtually carry out definitions, plans, creations, monitoring and control of all production processes.

The application of digital twin in the simulation of processes provides the company with greater security in decision making by presenting efficient monitoring and aptitude to the actions performed physically, increasing mobility, enabling the user to make changes and monitor remotely, without interfering and/or cause losses in the results obtained by the production. The balancing of the company's assembly line can be used to promote an increase in income, a reduction in the costs involved, thus increasing the profits generated. In addition, activities are sequentially distributed among workplaces according to their operating times, improving the use of operations as well as the equipment present.

When implemented in digital manufacturing, the use of digital twin virtually integrates design information and manufacturing processes. Aiming at reducing the costs involved in the development, anticipating and non-conformities of the system, providing innovation in the manufacturing area with higher quality products, allowing the creation and application of innovative models with their due representations and also with the simulation of possible scenarios in the search for optimization.

Another reason for the use of the digital twin model in this research is because it does not deal only with the design and optimization of a production system, but involves involving real data from the production environment, continuously offering a simulation of the system and contributing quickly in real-time feedback throughout the manufacturing process [20]. Some steps must be taken so that the proposed method can reach its final objective, as shown in Figure 1.

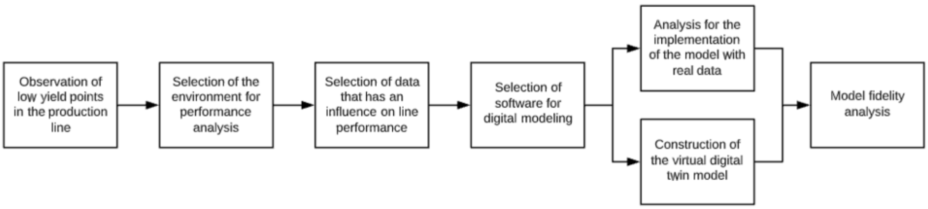

Figure 1. Performance analysis method.

Using the method developed for the performance analysis, observations were first made of the points that face problems in the assembly line. These points result in low yield, high index with failures in quality, low in capacity and gains in production. Through the analysis of a monitoring system present in the company of the application case, historical data was extracted from points where there were large numbers of line stops and directed to points with low performance.

In the next stage, an environment was selected to perform the performance analysis. A fraction of the assembly line that will be virtualized was selected since it does not have the full operation of the equipment involved in the procedures, it has considerable levels of non-quality of the final products and a large volume of rework.

Another fundamental point for choosing this cut was that this line has more automated factors and characteristics than the others, thus presenting greater conditions for the implementation of the digital twin model. This fraction of the assembly line can be considered complex due to the number of functions and actions performed, in addition to all the sequencing of activities performed by machinery present. This cutout corresponds to the part of the line where the wheels are mounted for their subsequent insertion in the vehicle.

After choosing the point to be virtualized, the selection of data to feed the digital model is essential. Data such as the type of wheels produced, the number of wheels audited, the number of wheels in compliance, as well as in non-compliance are some of the important data extracted from the devices of the line. Other relevant data for the virtual model are the factory and line layout, downtime and setup times, operating times and maintenance schedules. These data directly influence the performance of the line, and other data may also be collected for the construction of the virtual model.

The software to be chosen for the modeling must be available in the company in the case of an application for the implementation of the data in real-time, directly with data from the assembly line. The line data is recorded in a MOP (Marge OPérationnelle), prepared using the Node-Red tool based on the communication flow from the hardware devices to an online environment and then sent via the UDC protocol (User Datagram Protocol) to Spotfire, responsible for carrying out intelligent data analysis. Finally, the work and structured data will be sent to the GCP cloud (Google Cloud Platform).

The storage and processing of the information will be carried out in the GCP resulting in a dashboard with the relevant information for the virtual model. Other important data for the virtual model will be inserted in the simulation through interfaces present in the simulation software.

After having created the virtual model and the relevant data being fed, a fidelity analysis must be carried out to verify compliance. Observations of what happens in the digital model will be made according to what happens in the real environment, resulting in coherent replicas. Thus, this virtual model can be accepted for the proper continuation of the research. When changes in the virtual model are applied to the physical environment, observing its occurrence requires attention by comparing the results obtained through the virtual simulation in accordance with what occurs at the end of physical production.

3. Results/ Conclusion

Therefore, through the procedures demonstrated in this research, the method proposed in an organizational environment will seek an estimate of the realization of the processes, aiding in the prevention of possible mistakes and aiding in the company's decision-making in the case of application. The provision of a digital manufacturing process environment is conducive to the optimization of production systems and processes.

The digital twin is being carried out in several types of research recently and its targeting for the manufacturing area collaborates with the production planning and control. The use of real data in the virtual model with real-time feed is considered promising for the improvement of its application in production systems.

Another important point for the elaboration of this digital twin model is to make interventions on the assembly line via distance, avoiding that there are comings and goings to the factory floor to observe, analyze and, mainly, cause a line stop to perform some attempted change. These unnecessary displacements result in activities that do not add value to the company and unplanned line stops have an impact on production and quality losses.

Some data from the wheel production machines, which will be inserted in the virtual model, have already been pre-determined because they are considered essential for a simulation, such as the operating times, the line stop times, the average cycle times and the causes of line stop for predictive analysis. Other data will still be evaluated for insertion or not in the virtual model, always in the search to increase the degree of fidelity.

The realization of this research has some risks that must be taken into account, which may result in its planning. As your application will be carried out in a company in the automotive industry, you must have full access to information and data related to the production line. In addition to the data, access to the company's system as well as to the available software that is compatible with what is wanted.

Among the positive points, it can be considered that this project will bring gains for the company in the application case, by doing virtual modeling of the production line and mainly simulating with data inserted in real-time, making it possible to boost business competitiveness. With the mirroring of the virtual model, with what is happening in the physical environment, they support production planning and monitoring, reducing production downtime, impacting the costs involved with maintenance in addition to the increase in productivity resulting in profits for the company.

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References

[1] R. Rosen, G. Wichert, G. Von and G. Lo, About the importance of autonomy and digital twins for the future of manufacturing; *IFAC-PapersOnLine,* 2015, Vol 28, pp. 567-572.

[2] H. Faye and P. Falzon, Strategies of performance self-monitoring in automotive production, *Applied Ergonomics*, 2009, Vol. 40, pp. 915-921.

[3] B. R. Ferrer, U. Muhammad, W. M. Mohammed and J. L. M. Lastra, Implementing and visualizing ISO 22400 key performance indicators for monitoring discrete manufacturing systems, *Machines*, 2018, Vol. 6, 39.

[4] D. Mourtiz, M. Doukas and D. Bernidaki, Simulation in manufacturing: review and challenges, *Procedia CIRP*, 2014, Vol. 25, pp. 213-229.

[5] K. Agyapong-Kodua, R. Darlington and S. Ratchev, Towards the derivation of an integrated design and manufacturing methodology, *International Journal of Computer Integrated Manufacturing*, 2013, Vol. 26, pp. 527-539.

[6] P. Hirmer, U. Breitenbücher and A. C. F. da Silva, Automating the Provisioning and Configuration of Devices in the Internet of Things, *Complex Systems Informatics and Modeling Quarterly*, 2016, Vol. 9, pp. 28–43.

[7] F. Biesinger, D. Meike, B. Kras and M. Weyrich, A Case Study for a Digital Twin of Body-in-White Production Systems General Concept for Automated Updating of Planning Projects in the Digital Factory, *IEEE International Conference on Emerging Technologies and Factory Automation*, 2018, pp.19–26.

[8] E. Negri, L. Fumagalli and M. A. Macchi, Review of the Roles of Digital Twin in CPS-based Production Systems, *Procedia Manufacturing*, 2017, Vol. 11, pp. 939–948.

[9] F. Tao and M. Zhang, Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing, *IEEE Access*, 2017, Vol. 5, pp. 20418–20427.

[10] A. Bargelis, G. Hoehne and A. Cesnulevicius, Intelligent functional model for costs minimization in hybrid manufacturing systems, *Informatica*, Vol. 15, 2004, pp. 3–22.

[11] H. Elmaraghy, T. Aldeddawy, S. N. Samy and V. Espinoza, A model for assessing the layout structural complexity of manufacturing systems, *Journal of Manufacturing Systems*, 2014, Vol. 33, pp. 51–64.

[12] B. Yang, L. Qiao, N. Cai, Z. Zhu and M. Wulan, Manufacturing process information modeling using a metamodeling approach, *International Journal of Advanced Manufacturing Technology*, 2018, Vol. 94, pp. 1579–1596.

[13] L. Monostori, B. Kádár, T. Bauernhansl, S. Kondoh, S. Kumura, G. Reinhart, O. Sauer, G. Schuh, W. Sihn and K. Ueda, Cyber-physical systems em manufacturing, *Manufacturing Technology*, 2016, Vol. 65, pp. 621-641.
[14] K. M. Alam and A. El Saddik., C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems, *IEEE Access*, 2017, Vol. 5, pp. 2050–2062.
[15] R. Stark and T. Damerau Digital Twin. In: S. Chatti, L. Laperrière, G. Reinhart, T. Tolio (eds.): *CIRP Encyclopedia of Production Engineering*. second edition, Springer, Berlin Heidelberg, 2019, DOI: 10.1007/978-3-642-35950-7_16870-1.
[16] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, Digital Twin in manufacturing: A categorical literature review and classification, *IFAC-PapersOnLine*, 2018, Vol. 51, No. 11, pp. 1016–1022.
[17] K. Ponomarev, N. Kudryashov, N. Popelnukha, and V. Potekhin, Main principals and issues of digital twin development for complex technological processes, *Ann. DAAAM Proc. Int. DAAAM Symp.*, 2017, pp. 523–528
[18] D. Battini, M. Faccio, A. Persona, and F. Sgarbossa, New methodological framework to improve productivity and ergonomics in assembly system design, *Int. J. Ind. Ergon.*, 2011, Vol. 41, pp. 30–42.
[19] F. Caputo, A. Greco, M. Fera, and R. Macchiaroli, Digital twins to enhance the integration of ergonomics in the workplace design, *Int. J. Ind. Ergon.*, 2019, Vol. 71, pp. 20–31.
[20] M. Peruzzini, F. Grandi, and M. Pellicciari, Exploring the potential of Operator 4.0 interface and monitoring, *Comput. Ind. Eng.*, 2020, Vol. 139, 105600.

Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Associative Data-Process Model in Manufacturing Systems: Application Case in Automotive Industry

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Abstract. Considering the advent of Industry 4.0 and development of Cyber-Physical Systems, a large amount of data has been collected in production systems. Available business process recommendations, presented in Business Process Management Notation and Case Management Model Notation frameworks, have been enough to represent the systemic and relational characteristics of production systems and their components. Recommendations for data life-cycle management do not consider explicitly combining the elements of the modeled process and the representative data of the production system assets. In fact, process flows can represent data generated or consumed but do not have an explicit associated action to their data: generation, transformation and consumption. From a Performance Analytics perspective, approaching data and processes in an associated way can be an advantageous practice in management and decision-making. This study uses one investigative experience in the automotive industry, from two aspects: the As-Is mapping of a segment of the measurement system after the welding step, and the design and implementation of Big Data Analytics architecture related to the same process. The result is a proposal of an associative framework between processes and related data, which are following the recommendations of currently applied frameworks for Business Process Management and Big Data Analytics.

Keywords. Big Data Analytics, Business Process Management, Manufacturing Process, BDA Architecture, Transdisciplinary

Introduction

With the advent of digital transformation and new technologies, the data generated in processes has increased in their production systems. To ensure greater competitiveness, quality and efficiency, companies have adapted to these new data analysis processes through CPS and IoT, capable of consuming and generating data. Therefore, there was a need to better understand and apply the data analysis processes and the relationship with the respective stages of the production process. There are studies related to the development of processes for data analysis based on industrial processes such as maintenance presented by [1][2], and research and practice related to Big Data architecture [3][4][5]. However, little aspects has been studied about the correlation between each domain, or the its contributions which characterizes the transdisciplinarity phenomenon.

The Business Process Management (BPM) area has a solid framework stabilized by a good theoretical framework and stabilization through continuous practice. The components of the framework adequately express the operational aspects (e.g., sequences, transition conditions, etc.) and attributes inherent to their participation in the process (e.g., identification, names, other attributes). Another aspect to be highlighted is the adoption of the standard by practitioners in industry and research, concerning to representing and improving processes. In one of its derivations, the CMMN stands out allowing a more flexible representation of the process, in an appropriate way and without losing its stability as a framework notation. The root domains related to Big Data (e.g., engineering, processes, applied mathematics) are characterized by the strength of their definitions proven by years of practice and research. A lot has evolved in the last 20 years, allowing the stability of the resources that support the current Big Data infrastructure, mainly those related to Cloud Services. Research and practice suggests an approximation between components related to the Big Data architecture and the application object of process management.

The present study has as main objective to identify if the process management can contribute in an assertive way with the structuring of a Big Data architecture, without a mischaracterization of the needs of the latter one. To this end, a case study was developed in the automotive industry related to the Big Data infrastructure of a Car Frame production system in which weld measuring data is obtained, stored, transformed and used in the production line management decision process.

1. Literature Review – Business Process Management and Data analytics

1.1. Business Process Management

To develop a business process it is important that the model describes well the steps that make up the development of a process. Therefore, this model must understand all its activities, users and attributes to achieve milestones. Process models for data analysis need to have greater flexibility in their flow and automation of their processes. Hence, to develop a process considering the data flow, allowing its flexibility, we consider the PAIS methodology (Process Aware Information Systems). According to [6], PAIS aims to meet the demands of information systems through a logical process that manages, executes and analyzes processes of an organization based on specific models seeking agility and flexibility. When performing a PAIS based on models of executable processes, it is important to consider the process variables, they may have different characteristics and needs. For example, we must consider that there are well-structured processes whose behavior can be totally pre-specified. As well as, highly dynamic processes [7].

According to [7], it is important to develop the business model considering a high level of abstraction so that they serve as a basis for analysis, simulation and processes visualization. Therefore, the model must understand all the activities of the process and its attributes, as well as the control and flow of data between the activities so that we can develop a more detailed process. For the development of the process we will use the BPMN notation (Business Process Management Notation), through the method known as Case Management Model and Notation (CMMN). According to [8] [9] the CMMN is an unstructured data centered management process language with a high degree of flexibility, which means that the main and permanent assets are the data. In addition, the notation has a central concept that contains all of the process data information, also is a type of business process technology that uses the flow of control to describe the business process. The construction of process management using the CMMN demonstrates that the focus is not only on the process, but it is also on the actors who are responsible for the business objectives and use the systems as a tool to achieve those objectives. Consequently, to develop a reliable business process management models using CMMN depends more on the judgment of the actors than on the process control flow [10]. For the development of the architecture of data analysis processes, we use the study [11] where the authors recommend the use of the main areas to be considered for the development of a business process for data analysis: Data Gathering, Data Preparation, Data Analytics, Data Visualization and Data Stakeholder. In the present study we will consider these steps as the main ones for the construction of a framework for the application of the process.

1.2. Big Data Analytics

The infrastructure used for the life cycle of data related to the production line and the processing of this same data must follow the guidelines that recommend zoning, according to the characteristic and stage of data maturity in its workflow, from generation to consumption [3][12][13]. As recommended in the studies of [3][4][5][14], the zones used for processing and storing intermediate data (transient, raw, trusted and refined) must meet the minimum specifications for security, retention, content, and data sensitivity. The transient zone must accommodate the data recently ingested from the operation without any transformation that would alter its originality. The goal of the agent responsible for this intake is to move the data from the source and, so on, store it in this zone. At this stage, the *Velocity* characteristic of Big Data environments is present, which justifies the mission defined for the data transition agent: with speed, obtain the data and store it immediately. The Raw zone is now accommodating basic data for further processing with a certain degree of adjustment and cleanliness. In the model proposed by [11], cleaning, harmonization and other Data Wrangling tasks can occur according to the needs or business rule. The agents who operate in this area, follow the same compliance guidelines and adapt to the flexibility proposed in the model. The trusted zone is for store data without its sensitive part (which does not apply in all the cases). Finally, the Refined zone is intended to contain the refined and harmonized data with meaning to the aspects of the business and operation, ready to be consumed by decision support systems and business analytics dashboards.

2. Conducting the research

The development of the study was carried out through technical visits and experience in the production operation plant. Diagnostics are concentrated in two major areas: processes and data.

2.1. As-Is Process

The process developed in the framing line occurs in 6 different lines where the data capture takes place in 4 points. Figure 1 represents a step in the process that consists of welding the plates that make up the product. The first stage is the reception of the car Frame, where the internal parts of the product are added, these parts are glued and their tabs are folded, these tasks are performed by machines on the line. Then, the application of the anti-noise sealant is carried out manually. After that, the frame geometry is executed as well as some spot welds in the same stage. After calibration, two more spot welds are carried out using mechanical arms. Finally, there is the verification of the weld geometry using image sensors that calculate the size and geometric location of the weld point. This step also generates a validation of the weld point, to check if it is in accordance with the reference parameters, allowing to obtain the data for analysis.

After completing the steps described above, it is possible to make decisions based on the data analysis: (i) If the welding point is in conformity, the Frame is sent to the next step; (ii) If the welding point is not in conformity, a user must check the error alert, define a correction for this error, and share the decision with a multidisciplinary team. This last decision in particular can result in the complete compromise of the Frame due to the flaws identified at the weld points. Otherwise, the correction will be carried out and the respective unit will be sent to the next step.

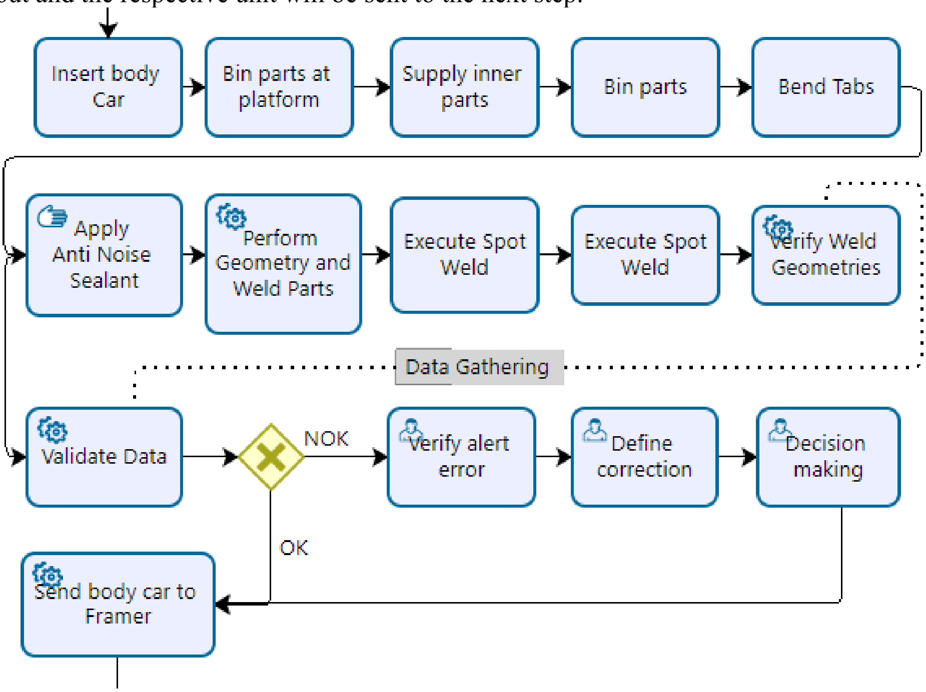

Figure 1. Framing Line Process (BPMN)

2.2. Data Life-cycle

The data obtained in the welding measurement process are stored in an intermediate area in tabular files, containing information about the unit and the corresponding coordinates measured. As for the coordinate information, it was possible to observe that not only the deviations are reported (e.g. relative deviations) but also the absolute deviation information in relation to the measurement reference points. This characteristic makes the files containing the measurement information, formed by several columns with floating point numerical data (float point representation). Such files are significantly larger than expected for measurements of this nature. Figure 2 shows the meta-process of the data life cycle.

These files are transferred to another area where they are subjected to the inherent Big Data architecture process envisaged. The Big Data architecture is structured in four zones: (i) transient, containing the pure data received from the measurement readings; (ii) raw, containing data already divided by measurement unit; (iii) refined, containing refined data, already harmonized and available for decision support dashboards. This structure follows the recommendations for Big Data architecture for transition zones [2][3][4][13][14]. The movement between the zones follows transition and transformation criteria that are part of the specific business and are not subject to appreciation in this study. The trusted zone is not included in the structure because there is no sensitive data, both for the business and for the organization, that deserve its concealment or encryption.

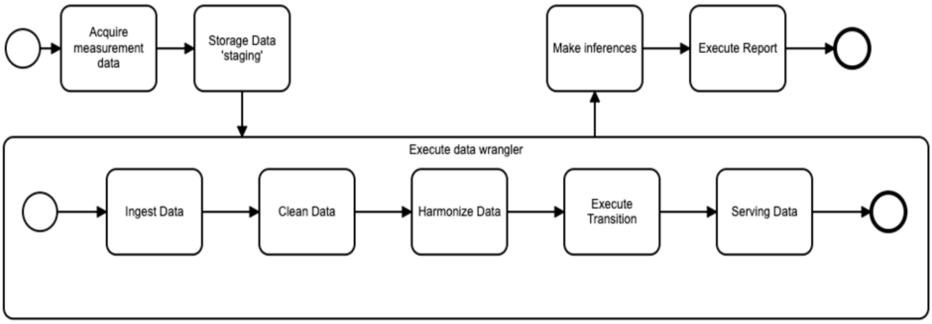

Figure 2. Meta-process of the data life cycle.

3. Diagnostic

During the research stage at the operations plant, it was possible to observe aspects related to decision making and the use of data obtained from the production line, according to the following items:

3.1. Formal and Execution Processes Correlation

The researchers identified a high degree of empiricism in the process execution and in the use of the data. Likewise, the use of data for the decision-making process follows subjectively, with a low degree of formalism in conducting transformations and transposition in the Big Data stages. Another aspect that aggravates the scenario is the low level of workflow documentation for new agents. Such a scenario is the result of the following phenomena:

- Low level of workflow formalism;
- Subjectivity of the workflow and data flow correspondence;
- Empiricism and distribution of responsibility in decision making.

3.2. Process and Data Correspondence

It was possible to identify a correspondence between the process workflow and the data transformation and transition flow between its generation and use in decision making. At each stage of the process, there is a correspondence in the transition or transformation of data with characteristics of the business, such as, for example, the referencing of equipment or factories, part numbers and product number (PIN).

4. Main Findings

During the research process, it was possible to identify that the support structure for the production process did not have a formal definition based on the concepts of business process management, despite the existence of some schematic documentation on the process. With the design of the *As-Is* process, both researchers and practitioners had the opportunity to identify improvement points, especially regarding decision-making, as the *data journey* did not meet strictly the recommendation of the agents roles in an Big Data architecture (e.g.: cleaners, transformers, harmonizers, etc.). The CMMN process developed in this paper use the concepts of Big Data Analytics provided in source [11]. The authors describe, through the literature review, how to conduct a data analysis process and its main steps. As shown in Figure 3, the main steps are: Data Collection, Data Preparation, Data Analysis, Data Visualization and Data Stakeholder. To apply the case study, it was necessary to make some adaptations and improvements in the process presented in source [11].

The data transformation agents depend on the performance of the actors involved in the production process, who have assumed the responsibility of structuring the data in relevant information for decision making. This characteristic shows the empiricism level adopted in the studied process and use old data in analysis. The Figure 4 presents the map of the recommended process according to CMMN notation, aligned to the recommendations produced from the observation of the current scenario.

The process developed in Camunda Modeler Software aims to represent the relationship of the actors and their tasks related to obtaining, processing, analyzing and visualizing the data. The development of the stages was based on the studies presented by source [11] where the authors present the stages to be considered in the development of the architecture of a data analysis process. With that, it was possible to define the following structuring view of the process as a recommendation for use in the observed operation. The process begins with the project start of the digital transformation team and stakeholders. The Digital transformation team is made up by data scientist and data analysts. Also, the stakeholder team is made up by organization participants who works directly with the main process. Meetings will occur in a time based stages, which happens frequently and depends on each team.

The first stage is Data Gathering which has the data extraction criterion as an exit criterion, however in the case study the captured data has some important characteristics to be highlighted in the its process flow, some process tasks need to be completed before closing. They are: (i) define data source, in this case the data being extracted is offline; (ii) check the data volume; (iii) check the speed of data capture; (iv) to vary the value of the data and its variety; (v) explore the data; (vi) define a tool for data storage (AWS). The second step concerning to data processing/preparation, has the exit criteria to generate the transformed and refined data and a meeting of the digital transformation team to present the first findings. At this stage, the data life cycle is an important fundamental, as it adapts the data to processing, eliminating inconsistencies, adjusting values and referring to aspects of the business (harmonization), the tool used was Alteryx Software. The third step is the data analysis where the users must define how to apply the statistical model through the study of forecast and timeseries model, in this step the usage tool is defined to carry out the analysis (Python notebooks). Finally, the data visualization step, which consists of the definition of a data analysis tool by the user (Tableau and Power Bi), that user will check the experience and usability of the generated data, as well as view the data. At that moment, it will be possible to reach the milestone of the process, which is the BDA report, which should happen with the condition of the decision making and the meeting between the digital transformation team and the stakeholders.

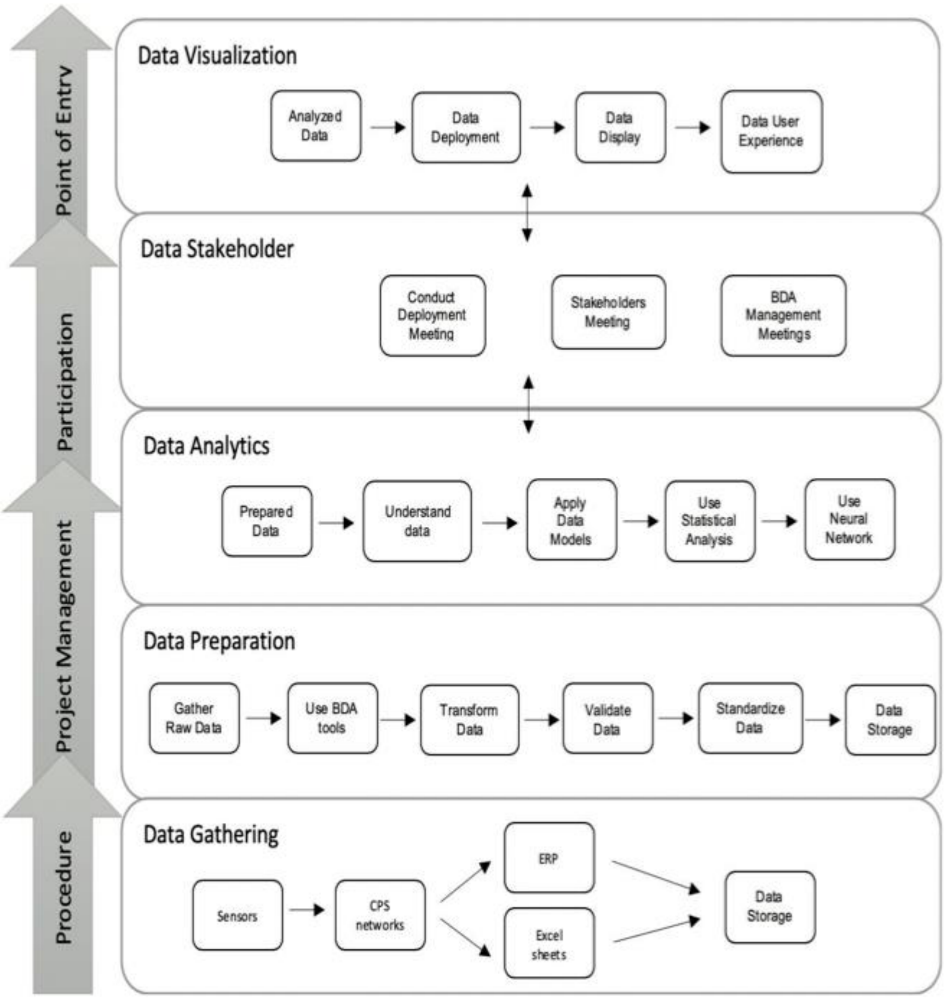

Figure 3. Framework for Big Data Analytics Process Architecture. [11]

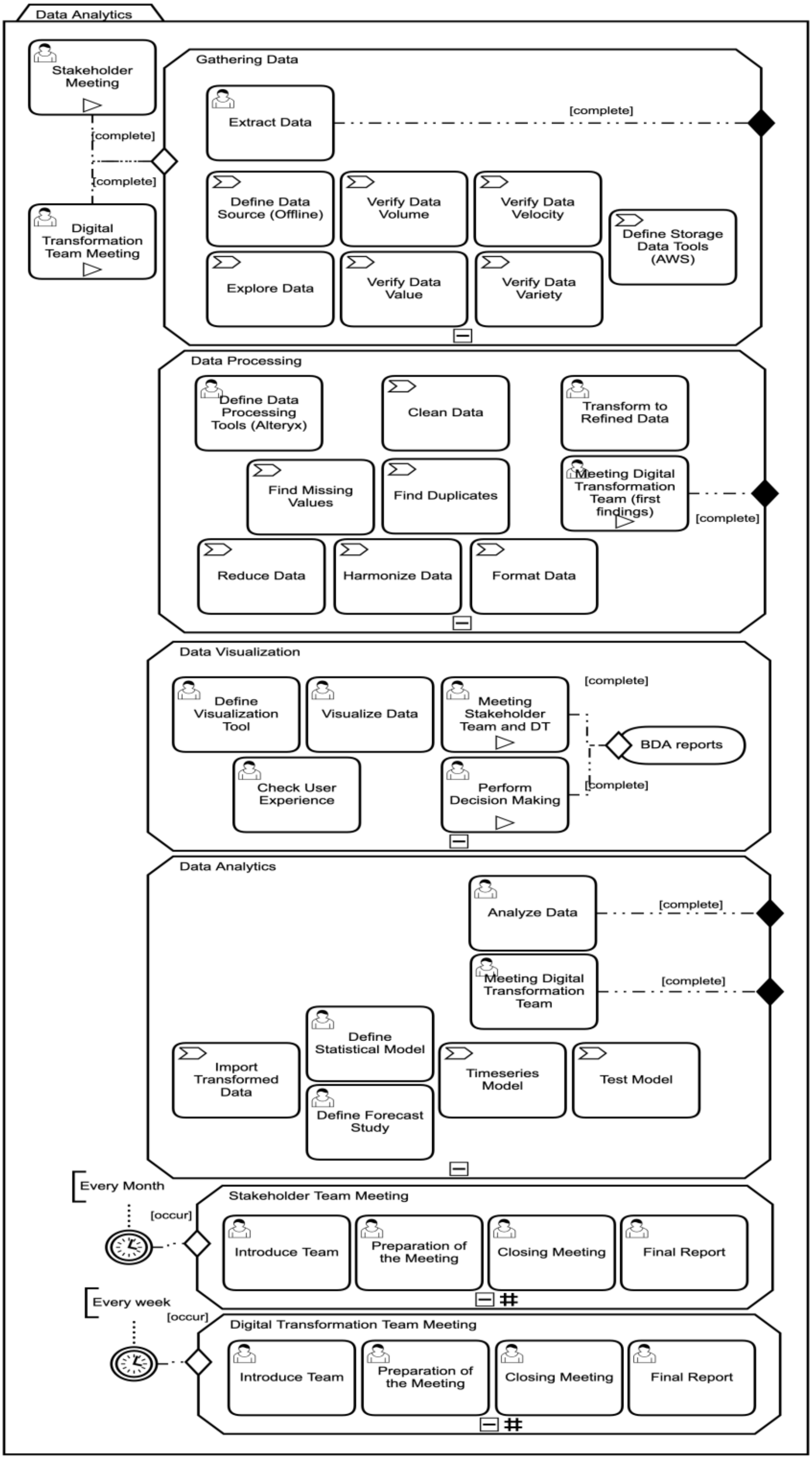

Figure 4. Recommended Data Analytics Process for Automotive Industry.

5. Conclusions

The data engineering process applied to big data can benefit from the recommendations and contributions of BPM, in the design, planning and definition of components, chronology and agents. Keeping the appropriate specific reserves for each domain, it was possible to perceive a correspondence between its components in addition to the way of mapping them. The actors mapped in the production process Dimensions to be addressed: actors, operational, time, information, organizational, strategic perspectives for cost and quality optimization. The experience allowed to outline a framework that flexibly guides the relationship between process and data in a prescriptive and descriptive manner, standardizing the steps of a Big Data architecture aligned to the process in which it is applied.

6. Future Works

Future works can explore in depth the relationship between the two domains, which includes derivation from CMMN notation or with BPMN. It is possible to conduct a study to the sequences of tasks related to data processing, when its mandatory. Another point that can relate the results of this study is the marking of the structured data or information components regarding their position in the process which it belongs. An exclusive decision support solution software can be designed, considering the chronology aspects and characteristics of the data obtained on the production line.

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References

[1] Y. Zhang and S. Ren, Big data based analysis framework for product manufacturing and maintenance process. *IFIP Advances in Information and Communication Technology*, 2015, Vol. 460, pp. 427–435, https://doi.org/10.1007/978-3-319-22759-7_50

[2] Z. Balogh, E. Gatial, J. Barbosa, P. Leitão, and T. Matejka, Reference Architecture for a Collaborative Predictive Platform for Smart Maintenance in Manufacturing. *INES 2018 - IEEE 22nd International Conference on Intelligent Engineering Systems, Proceedings*, 2018, pp. 299–304. https://doi.org/10.1109/INES.2018.8523969.

[3] M.J. Mortenson, N.F. Doherty, S. Robinson, Operational research from Taylorism to Terabytes: A research agenda for the analytics age. *European Journal of Operational Research*, Vol. 241, Issue 3, 16 March 2015, pp. 583-595.

[4] T.P. Liang, Y.H. Liu, Research Landscape of Business Intelligence and Big Data analytics: A bibliometrics study. *Expert Systems with Applications*, 2018, Vol. 111, pp. 2–10.

[5] M. Kiran, P. Murphy, I. Monga, J. Dugan, S.S. Baveja, Lambda architecture for cost-effective batch and speed big data processing. *Proceedings - 2015 IEEE International Conference on Big Data, IEEE Big Data 2015*, 2015, pp. 2785–2792.

[6] C. Ayora, V. Torres, B. Weber, M. Reichert and V. Pelechano, VIVACE: A framework for the systematic evaluation of variability support in process-aware information systems. *Information and Software Technology*, 2015, Vol. 57(1), pp. 248–276. https://doi.org/10.1016/j.infsof.2014.05.009

[7] M. Reichert and B. Weber, *Enabling flexibility in process-aware information systems: Challenges, methods, technologies*, Springer-Verlag, Berlin Heidelberg, 2012, https://doi.org/10.1007/978-3-642-30409-5

[8] M. Kocbek Bule, G. Polančič, J. Huber and G. Jošt, Semiotic clarity of Case Management Model and Notation (CMMN). *Computer Standards and Interfaces*, 2019, Vol. 66, 103354.

[9] M. Marin, R Hull and R. Vaculin, *Data Centric BPM and the Emerging Case Management Standard : A Short Survey Case Management Modeling and Notation (CMMN), An emerging OMG standard*. IBM Research - Business Process Management Workshops, 2012, 257593(257593), 24–30. Retrieved from https://acm2012.blogs.dsv.su.se/files/2012/09/2012-09-03-marin-hull-vaculin-on-emerging-OMG-case-mgmt-standard.pdf

[10] M.A. Marin, *Introduction to the Case Management Model and Notation (CMMN)*, 2016, pp. 1–23. Retrieved from http://arxiv.org/abs/1608.05011

[11] L.A.S. Rosolem, F. Deschamps, E.P. Lima and J.M.A.P. Cestari, Big data analytics process architecture for manufacturing industries: a literature review. *ICPR-Americas 2020 - SPECIAL SESSION: Machine Learning and Big Data in industrial processes*, 2020.

[12] R. Wallis et al., Intelligent utilization of digital manufacturing data in modern product emergence processes, *Advances in Transdisciplinary Engineering*, 2014, Vol. 1, pp. 261-270.

[13] J. Sheng, J. Amankwah-Amoah, X. Wang, A multidisciplinary perspective of big data in management research. *International Journal of Production Economics*, 2017, Vol. 191, pp. 97–112.

[14] S. Deshmane, *Using the Lambda Architecture on a Big Data Platform to Improve Mobile Campaign Management BIG DATA*. Talentica Software, 2015, https://www.talentica.com/wp-content/uploads/2018/01/Big-Data-Using-Lambda-Architecture.pdf, Accessed July 3, 2021.

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Advanced Planning and Scheduling (APS) Systems: A Systematic Literature Review

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Abstract. Planning and scheduling are important functions for industrial systems to operate effectively. Their principal aim is to detail how production resources will be used so that its demand is timely met. In literature, there are several works that propose mathematical models for production planning and scheduling for different production scenarios, accounting for different resources configurations and other limitations. However, it was only recently that advanced planning and scheduling systems (APS), making use of these models, started being more widely used and discussed. This work presents the results of a systematic literature review, developed by applying the ProKnow-C method, on APS systems. An overview of the main publications is provided, classifying them in new methods, models or approaches; heuristic approaches; Lagrangian relaxation techniques; and genetic algorithms. The future of APS systems is also discussed, particularly regarding difficulties such as human dependence, use of spreadsheets, and their role in Industry 4.0 with the use of technologies such as the RFID and Cloud computing.

Keywords. Advanced Planning and Scheduling Systems (APS), Industry 4.0, Systematic Literature Review

Introduction

Advanced Planning Systems (APS), also known as Advanced Planning and Scheduling, are described in APICS Dictionary [1] as "any computer program that uses advanced mathematical algorithms or logic to perform optimization or simulation on finite capacity scheduling. These techniques simultaneously consider a range of constraints and business rules to provide real-time planning and scheduling, decision support, available-to-promise, and capable-to-promise capabilities" [2]. APS are transdisciplinary in nature, once they encompass and integrate knowledge in areas such as mathematical modelling, information technology, and production systems, among others.

Material Requirements Planning (MRP) was the first generation of planning systems, built around a bill of materials (BOM). Later, MRP systems were improved to deal with capacity requirements planning, as they provided feedback of information that led to the ability to adjust plans and regeneration, and became known Manufacturing Resource Planning (MRP II). In 1990, the term Enterprise Resource Planning started to be used, as software tools were gradually integrated on another areas of application, such as

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forecasting, long-term planning and critical resource planning [3]. The ERP can provide initial plans, but it often does not provide tools that assist the planner in analyzing and updating the proposed planning. Trying to fill the void of limited functionality in ERP solutions, advanced production planning (APS) software systems emerged [4].

Unlike traditional ERP systems, APS seeks to find viable plans close to optimum, while potential manufacturing bottlenecks are considered explicitly [5]. Many ERP and APS systems make it possible to include suppliers and customers in the planning procedure and thereby optimize an entire supply chain in real time [6, 7]. The APS has far surpassed the planning and scheduling functionality of the ERP system and has become an impressive and important tool in planning. A strong feature of APS is the ability to "simulate" different planning scenarios before the plan's launch. APS does not replace, but complements existing ERP systems. The ERP system handles basic activities and transactions, such as customer orders, accounting, etc. while the APS system deals with the daily activities of analysis and decision support [3].

The purpose of this work is to analyze publications on APS systems. An overview of the main publications is provided (Sections 2 and 3), after presentation of the research design (Section 1), classifying them as dealing with new methods, models or approaches; heuristic approaches; Lagrangian relaxation techniques; and genetic algorithms (Section 3). The future of APS systems is also discussed (Section 4), particularly regarding difficulties such as human dependence, the use of spreadsheets, and their role in Industry 4.0 with the use of technologies such as RFID and Cloud computing. In the conclusion (Section 5), further perspectives for the advancement of APS are drawn.

1. Research Design

For this study, the bibliographic review method used to achieve the proposed objectives was the Knowledge-Constructivist Development Process (ProKnow-C). The process consists of four steps: (a) definition of the research question and research objectives; (b) selecting a portfolio of articles on the research topic; (c) bibliometric analysis of the portfolio; and (d) systemic analysis [8].

Research objective was established as gaining an understanding of the literature regarding advanced production planning systems. The Web of Science and Scopus reference databases were searched using the terms "Advanced Planning System" and "Advanced Planning and Scheduling" in the title, keywords and abstract fields limited to a period of 20 years (from 2001 to 2021). A total of 649 articles were retrieved, and after excluding duplicates, a total of 455 articles were selected for analysis of their alignment to the research objetives. By reading the titles, 140 articles were considered aligned. Scopus and Web of Science were searched again, this time to get the citation count of each one of the 140 articles. A threshold of 6 citations was established, which encompassed 46 papers that had 90% of the total citations of the set, forming repository K. The remaining 94 articles formed repository P.

Articles from repository K had their abstracts read and 29 were selected as fitting the objetives of he research, forming repository A. Authors of these articles were identified and formed a bank of authors (BA). Repository P was further analyzed for recent authors (published between 2018 and 2021), in a total of 12, and for articles that were authored from someone belonging to the bank of authors, in a total of 17. These 29 articles from repository P formed repository B. Abstracts of articles in repository B were read, eliminating 3 articles, that were merged with the 29 articles from repository A, forming repository C with 55 articles. Of these, 19 articles were not possible to be retrieved in full because of access restrictions, and the total number of articles to have their content analyzed was 36. Content of these articles is presented in the next two sections (2 and 3), with an analysis of this content performed in section 4.

2. Advanced Planning and Scheduling (APS) Systems

In the research field, APS studies mainly focus on theoretical perspectives including model complexity, problem scope and design of algorithms [9]. Other studies show that there are several problems involved in using planning software such as high complexity, lack of training and knowledge among managers and personnel, low-data accuracy, and lack of support from the software vendor [10, 11]. The advanced planning and scheduling (APS) problem has received increasing attention from the research community in recent years, as seen next.

Palmer [12] and Sundaram and Fu [13] discuss the integrated process of planning and scheduling; Gupta *et al.* [14] consider the two-machine flowshop scheduling problem, which seeks to find a minimum total flow time schedule subject to the condition that the makespan of the schedule is minimum; Hankins el al. [15] discuss the advantages of using alternative machines tool routings to improve the productivity of a machine shop. Holloway and Nelson [16] suggest an alternative formulation of the job shop scheduling problem, based on the concept that capacity constraints and operation precedence relations are allowed to be violated if keeping due dates is more important; Biskup and Jahnke [17] analyze the problem of assigning a common due date to a set of jobs and scheduling them on a single machine assuming that the processing times of those jobs are controllable and considering a situation in which it is only possible to reduce all the processing times by the same proportional amount; Lin [18] discuss the problem of minimizing either the maximum tardiness or the number of tardy jobs in a two-machine flowshop with due date consideration; Sung and Min [19] consider a scheduling problem for a two-machine flowshop incorporating batch processing machines (BPMs), which considers the earliness/tardiness (E/T) measure and a common due date; Hastings et al. [20] use a form of forward loading to schedule jobs on the available capacity; Sum and Hill [21] propose a new framework for manufacturing planning and scheduling systems; Cheng and Gupta [22], Baker and Scudder [23] and Gordon et al. [24] consider the general planning and scheduling problem, in which the most common objective is the minimization of the makespan, due to the growing interests in JIT production strategy in industry; Kim and Kim [25] explore a problem of short term production for products having multi-level structures, with the objective of minimizing the weighted sum of tardiness and earliness of the items based on Group Technology (GT). Shen et al. [26] reviews the APS from theoretical aspects in terms of planning, scheduling and their integration, particularly on agent based approaches. David et al. [27] implement APS in an aluminium conversion industry; Neumann,et al. [28] propose an APS to support supply chain planning under the observed limited resources.

3. Methods, Algorithms and Mathematical Models

Advanced planning systems use complex mathematical algorithms to forecast demand, to plan and schedule production within specified constraints, and to derive optimal sourcing and product-mix solutions [3]. In this research we grouped the different works into four main categories regarding how they approached the solution to the APS problem, after analyzing the content and grouping the works in the bibliographic portfolio: new methods, models or approaches; heuristic approaches; Lagrangian Relaxation Techniques; and genetic algorithms. Other approaches exist, but were not categorized within any of these groups and are not presented here. These categories and a summary of works follow.

Studies focused on **new methods, models or approaches**: Palmer [12] develops a method based on simulated annealing (SA); Taal and Wortmann [29] describe an intuitive planning method that integrates MRP with finite capacity planning, based on scheduling techniques; Lasserre [30] proposes a decomposition approach to solve the APS problem; Moon et al. [31] suggest an advanced planning and scheduling model which integrates capacity constraints and precedence constraints to minimize the makespan only; Hsu et al. [32] develop a cloud-based advanced planning and scheduling (CAPS) system because the cost to implement the APS systems in Small and medium-sized manufacturing enterprises (SMEs) are to high for satisfying the specific production characteristics and planning constraints; Zhong et al. [33] propose an RFID-enabled real-time advanced production planning and scheduling shell; Bose and Pekny [34] present a method using the model predictive control concept for solving planning and scheduling problems; Guo et al. (2009) [35] use particle swarm optimisation to integrate planning and scheduling in an application to achieve meaningful APS; Smith et al. [36] discuss a particular constraint-based solution framework as well as a specific architecture for configuring the APS system, in order to establish APS in complex application domains; McKay and Wiers [37] use standard software for designing an APS, which integrates the HPP concept in a factory; Torabi et al. [38] present a holistic three-level fuzzy HPP and scheduling methodology was introduced for multi-product and identical parallel machines in a batch process environment; finally, Brandimarte and Calderini [39] develop a two-phase hierarchical Tabu search for efficient planning and scheduling.

Some of the researchers took a **heuristic approach** to solve the APS problem: Nasr and Elsayed [40] present two heuristics to determine an efficient schedule for the n jobs/m machines problem, with alternative machine tool routings allowed for each operation; Kolisch and Hess [41] introduce three efficient heuristic solution methods: a biased random sampling method, and two tabu-search-based large-step optimization methods for the problem of scheduling multiple, large-scale, make-to-order assemblies under resource, assembly area, and part availability constraints; Chung et al. [42] consider a kind of job shop scheduling problem in which each job has its due date; Bahl and Ritzman [43] provide an integrated model and a heuristic solution procedure which decomposes the overall problem into smaller sub-problems and solves them in an iterative form; Faaland and Schmitt [44] devise a two-phase heuristic technique to generate feasible schedules by solving a sequence of maximum flow problems; Agrawal et al. [45] exploit a precedence network to represent the precedence relationships among items and then developed a heuristic approach to generate near-optimal schedules, employing critical path concept.

Other researchers based their research on solving the APS problem focused on the **Lagrangian Relaxation Technique**: Czerwinski and Luh [46] chose an improved Lagrangean relaxation technique to address the APS problem with the objective function containing quadratic earliness and tardiness penalties, but the solution oscillation has not been completely eliminated, which slows convergence of the algorithm; Shin et al. [47] focused on scheduling area by developing two improved Lagrangean relaxation methods that are able to satisfy the special requirements; Hoitomt et al. [48] and Luh et al. [49] discusses that both the Langrangean Method and its applications prove that is is flexible enough to deal with a variety of scheduling problems; Yoneda [50] presents two of the Lagrangean relation method features to improve its potential for practical application: its scalability and its simple logic; Kuroda et al. [51] and Kuroda [52] apply the algorithm to a variety of situations, in order te explore the possible applications of the Lagrangean reIaxation method to dynamic scheduling problems; Shin et al. [53] develop a feasibility study that applied the Lagrangean relaxation method to Available To Promise (ATP) logic in a simple order based APS environment.

Likewise, some researchers based their research on solving the APS problem on the development of a **genetic algorithm (GA)**: Pongcharoen et al. [54] develop a genetic algorithm-based tool which includes a repair process to rectify infeasible schedules for the planning and scheduling of complex products with multiple resource constraints and deep product structure; Chen et al. [11] develop a genetic algorithm (GA) to minimize cost of both production idle time and tardiness or earliness penalty of an order; Dellaert et al. [55] discuss the multi-level lot-sizing (MLLS) problem in MRP systems and develop a binary encoding genetic algorithm and five specific genetic operators to ensure that exploration takes place within the set of feasible solutions; Caraffa et al. [56] consider the problem of minimizing the makespan of n jobs in an m machine flowshop operating without buffers; Lee et al. [57] propose an operation-level APS model, integrated planning, and scheduling with outsourcing, as might apply to a practical manufacturing supply chains; Shao et al. [58] propose a modified genetic algorithm-based methodology for the integration of planning and scheduling.

4. Difficulties and Role in Industry 4.0

Throughout the analysis of the contents of the papers in the bibliographic portfolio, authors identified a set of difficulties for the future development of APS and their role in Industry 4.0. These are related to human dependence, use of spreadsheets, and the use of Industry 4.0 technologies, mainly RFID and Cloud computing. These topics are discussed next. These difficulties, together with the role APS play in Industry 4.0, constitute a transdisciplinary issue in the advancement of APS technology, that must be considered in future works.

4.1. Human Dependence

APS aim at automating and computerizing the planning processes by use of simulation and optimization. Still, the decision-making is done by planners with insight in the particular supply chain and know-how on the system constraints and feasibility of created plans. Thus, APS aim to bridge the gap between the supply chain complexity and the day-to-day operational decisions. This requires, however, that planners are able to model and setup decision rules for the planning and optimization [3]. In addition, the role of the human planner has been a widely addressed topic. Humans possess both cognitive strengths and weaknesses that influence the quality of planning [4]. And reasons for not following the planned orders have a wide variety: The planner does not trust the techniques generating the schedule, the planner does not update the parameters of the ERP system that are needed, or the planner has more information than the system. It can also be that the planner has the feeling that an increased mental effort will increase the outcome of the resulting plan or schedule, which is not necessarily true [59, 60, 4].

APS systems were established to predict future production schedules by exact mathematical optimization techniques and heuristics. However, APS systems lack of a part of flexibility, such as the control strategies for sequencing that are permanently defined. The current APS systems cannot provide the optimal configuration of the control strategy based on the current situation [61]. In addition, a solution of the possible combinations of control strategies regarding the dependencies of individual jobs and machines is too complex for humans [32].

4.2. Use of Spreadsheets

Spreadsheet applications as the primary medium for planning is one of the major contributors to planning developments in practice, in which planners need to analyse the plans, analyse issues and looks for resolving of problems [62]. Many have recognized the need for improving existing planning solutions by introducing (improved) spreadsheet solutions throughout the years [63, 64, 65].

Likewise, Hsu, T. H., et al. [32] conducted a study of small and medium-sized manufacturing enterprises (SMEs) in Taiwan and found that most of the manufacturing industries (e.g., metal manufacturing, machinery and equipment manufacturing etc.) still heavily rely on the spreadsheet-based production planning and scheduling with ERP systems. Very few SMEs have implemented the advanced planning and scheduling (APS) systems due to the high implementation cost for satisfying the specific production characteristics and planning constraints.

This is in contradiction to the late push for digitalization, where more advanced and integrated IT systems are seen as the solution for planning and control [66] and big developments are seen in computing power, algorithm development, with a growing research focus on concepts such as digitalization and Industry 4.0, which focus heavily on automation of decision-making by using big-data and advanced algorithms on one hand, and production planning and scheduling not showing significant improvements in practice over the last twenty years on the other especially with the use of spreadsheets [2].

4.3. RFID applications

The use of RFID in APS has attracted a lot of attention from researchers in recent years. Brewer et al. [67] adopted RFID for dynamic scheduling on a manufacturing shop-floor to control the logistics operations. Johnson [68] used RFID to guide the repair work in a car production line. Huang et al. [69] proposed an RFID-based scheduling system for walking-worker assembly islands with fixed-position layouts [33].

There are several typical characteristics in RFID enabled production applications. First, paper-based operations are eliminated [70]. Second, manufacturing data become real-time, accurate, complete and consistent. Third, changes and disturbances could be captured on a real-time basis. Finally, the physical movements of materials and information flows are tracked and traced and synchronised [71, 33].

These characteristics have positive impacts on production decision making. RFID data enable realtime visibility and traceability, forming the fashion of ‘what you see is what you do and what you do is what you see’ [72]. Decisions could be made on a timely basis by means of feedback from manufacturing sites with much reduced transfer delay.

Real-time visibility and traceability enable better cooperation among different parties, improving the overall production efficiency [33].

However, decision makers are still facing challenges. First, the use of RFID technology speeds up the decision-making process, demanding more prompt actions from decision makers. In such a case, it is more difficult for them to make precise and on-time decisions because they often suffer from conflictive and dynamic objectives [73]. Second, they lack a collaborative mode in terms of decision-making procedures and corresponding information systems, which can effectively and efficiently guide their behaviours [74]. Finally, it was first mentioned that two challenges cause a gap between the highly synchronised information flow at manufacturing sites and unstandardised procedures for decision making. The gap presented earlier might be bridged by advanced planning and scheduling (APS) [33].

4.4. Cloud APS

In the past, enterprises often invested high capital in many physical devices and servers. The pressure not only comes from the high capital investment but also the time and manpower to install and maintain the operating systems and software services [75, 76]. The characteristics of cloud manufacturing is to connect production resources to the cloud and virtualize them, thus the cost of manpower and equipment can be shifted on to cloud suppliers to save the operating costs. Enterprise pays for the requirement of actual operation instead of high investment [77] and It does not require high-end devices to have high-speed computing ability, as long as they are in the network environment [33].

5. Conclusions and Futures Perspectives

Production planning systems are not keeping up with the latest advances in the field of technology, especially when we talk about the new concepts of digitalization, digital transformation and industry 4.0, with the application of big data, Cloud hosting, automation, IoT and advanced algorithms. We found some approaches focusing on RFID, but their applications are still somewhat timid. There is a lack for a transdisciplinary perspective in dealing with all of these topics.

We can see that the human factor is still decisive for the correct functioning of an APS system (as seen in Section 4.1), that the systems depend on data inputs, that they depend on generating of scenarios and that the manager needs to have a great knowledge about the factory and the process to be able to parameterize all the resources of the APS,in order to generate reliable programming scenarios. Often, these managers use spreadsheets to support APS, since the systems are still complex to be used and not very flexible. And these spreadsheets provide the flexibility to input and modify data, giving the manager more autonomy.

Another point observed is that there are many methods, approaches, algorithms and mathematical models, which have been taken into account by researchers over the past few years, but still in this bibliographic review, few studies were found that focus on the APS problem with the application of artificial intelligence algorithms.

Thus, there is still a very open field for research, which researchers can focus on in the future, especially when we bring the context of industry 4.0 to the APS. How can we have more flexible and more intuitive systems for the use of managers? How can we apply the concept of Big Data to APS? How can we design a Cloud systems architecture without affecting other systems and looking at the reality of each company? How can we apply artificial intelligence concepts to give more autonomy to APS systems and reduce the dependence on people for its correct use? Which IoT and RFID applications can be integrated into the APS context for the exchange of information and real-time operation of this system? These and other questions are transdisciplinary issues that must be addressed in an integrative perspective for the study and advancement of knowledge regarding Advanced Planning and Scheduling (APS) Systems.

References

[1,7] Cox, J.F. and J.H. Blackstone. *APICS Dictionary*. APICS, VA, 2002.

[2,8] Lin, C. H., et al. The mythical advanced planning systems in complex manufacturing environment. *IFAC Proceedings Volumes (IFAC-PapersOnline)*, 2006, Vol. 39, pp. 703-708.

[3,1] H.H. Hvolby and K. Steger-Jensen, Technical and industrial issues of Advanced Planning and Scheduling (APS) systems. *Computers in Industry*, 2010, 61(9), pp. 845-851.

[4,2] De Man, J. C. and J.O. Strandhagen, Spreadsheet Application still dominates Enterprise Resource Planning and Advanced Planning Systems. *IFAC-PapersOnLine*, 2018, 51(11), pp. 1224-1229.

[5,3] H. Stadtler and C. Kilger, *Supply Chain Management and Advanced Planning – Concepts, Models Software and Case Studies*, 3rd ed., Springer, Berlin, 2005.

[6,4] J.C. Wortmann, Evolution of ERP Systems, in: Bititci, U.S., Carrie, A.S. (Eds.) *Strategic Management of the Manufacturing Value Chain*, Kluwer Academic, Boston, MA, pp. 11–23, 1998.

[7,5] M. Kennerly, and A. Neely, Enterprise resource planning: analysing the impact, *Integrated Manufacturing System*, 2001, pp. 103–113.

[8,6] J.E. Tasca, L. Ensslin, S.R. Ensslin, and M.B.M. Alves, An approach for selecting a theoretical framework for the evaluation of training programs. *Journal of European Industrial Training*, 2010, Vol. 34(7), pp. 631-655.

[9] H. Meyr, et al. Architecture of selected APS. *Supply Chain Management and Advanced Planning*, 2008, pp. 349–366.

[10] A. Petroni, Critical factors of MRP implementation in small and medium-sized firms. *International Journal of Operations & Production Management*, 2002, Vol. 22 (3), pp. 329–348.

[11] K. Chen, et al. A case study for advanced planning and scheduling (APS), *Journal of Systems Science and Systems Engineering*, 2011, Vol. 20(4), pp. 460-474.

[12] G. J. Palmer, A simulated annealing approach to integrated production scheduling. *Journal of Intelligent Manufacturing*, 1996, Vol. 7, pp. 163-176.

[13] R. M. Sundaram, and S. S. Fu, Process planning and scheduling. *Computer and Industrial Engineering*, 1988, Vol. 15, pp. 296-307.

[14] J.N.D. Gupta, V.R. Neppalli and F. Werner, Minimizing total flow time in a two-machine flowshop problem with minimum makespan, *International Journal of Production Economy*, 2001, 69, pp. 323-338.

[15] S.L. Hankins, R.A. Wysk and K.R. Fox, Using a CATS database for alternative machine loading. *Journal of Manufacturing Systems*, 1984, Vol. 3, pp. 115-120.

[16] C.A. Holloway and R.T. Nelson, Job scheduling with due dates and overtime capacity. *Management Science*, 1974, Vol. 21, pp. 68-78.

[17] D. Biskup and H. Jahnke, Common due date assignment for scheduling on a single machine with jointly reducible processing times. *International Journal of Production Economy*, 2001, Vol. 69, pp. 317-322.

[18] B.M.T. Lin, Scheduling in the two-machine flowshop with due date constraints. *International Journal of Production Economy*, 2001, Vol. 70, pp. 117-123.

[19] C.S. Sung and J.I. Min, Scheduling in a two-machine flowshop with batch processing machine(s) for 19,earliness/tardiness measure under a common due date. *European Journal of Operational Research*, 2001, Vol. 131, pp. 95-106.

[20] N.A.J. Hastings, P. Marshall and R.J. Willis, Schedule based MRP: An integrated approach to production scheduling and material requirements planning. *Journal of the Operational Research Society*, 1982, Vol. 3 (11), pp. 1021–1029.

[21] C.C. Sum and A.V. Hill, A new framework for manufacturing planning and control systems. *Decision Sciences*, 1993, Vol. 24 (4), pp. 739–760.

[22] T.C.E. Cheng and M.C. Gupta, Survey of scheduling research involving due date determination decisions. *European Journal of Operational Research*, 1989, Vol. 38 (2), pp. 156–166.

[23] R. Baker and G.D. Scudder, Sequencing with earliness and tardiness penalties: A review. *Operation Research*, 1990, Vol. 38 (1), pp. 22–36.

[24] V. Gordon, J.M. Proth and C.B. Chu, A survey of the state of-the-art of common due date assignment and scheduling research. *European Journal of Operational Research*, 2002, Vol. 139 (1), pp. 1–25.

[25] J.U. Kim and Y.D. Kim, Simulated annealing and genetic algorithms for scheduling products with multi-level product structure. *Computers and Operations Research*, 1996, Vol. 23 (9), pp. 857-868.

[26] W.M. Shen, L.H. Wang and Q. Hao, Agent-based distributed manufacturing process planning and scheduling: a state-of-the-art survey. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, 2006, Vol. 36 (4), pp. 563–577.

[27] F. David, H. Pierreval and C. Caux, Advanced planning and scheduling systems in aluminium conversion industry. *International Journal of Computer Integrated Manufacturing*, 2006, Vol. 19 (7), pp. 705–715.

[28] M. Nakhaeinejad, N. Nahavandi, Production scheduling for hot rolling processes with time windows in the steel industry, *International Journal of Agile Systems and Management*, 2014, Vol. 7(2), pp. 179-197.

[29] M. Taal and J.C. Wortmann, Integrating MRP and finite capacity planning. *Production Planning and Control*, 1997, Vol. 8 (3), pp. 245–254.

[30] J.B. Lasserre, An integrated model for job-shop planning and scheduling. *Management Science*, 1992, Vol. 38 (8), pp. 1201–1211.

[31] C. Moon, et al. Advanced planning and scheduling based on precedence and resource constraints for e-plant chains. *International Journal of Production Research*, 2004, Vol. 42 (15), pp. 2941–2955.

[32] R. Wallis et al., Intelligent utilization of digital manufacturing data in modern product emergence processes, *Advances in Transdisciplinary Engineering*, 2014, Vol. 1, pp. 261-270.

[33] R.Y. Zhong, et al. RFID-enabled real-time advanced planning and scheduling shell for production decision making. *Int. Journal of Computer Integrated Manufacturing*, 2013, Vol. 26(7), pp. 649-662.

[34] S. Bose and J. Pekny, A model predictive framework for planning and scheduling problems: a case study of consumer goods supply chain. *Computers & Chemical Engineering*, 2000, Vol. 24 (2–7), pp. 329–335.

[35] Y. Guo, W. Li, A.R. Mileham and G.W. Owen, Applications of particle swarm optimisation in integrated process planning and scheduling. *Robotics and Computer-Integrated Manufacturing*, 2009, Vol. 25 (2), pp. 280–288.

[36] S.F. Smith, O. Lassila and M. Becker, Configurable, mixed-initiative systems for planning and scheduling. In: A. Tate (eds.) *Advanced planning technology: technological achievements of the ARPA/Rome laboratory planning initiative*. Menlo Park, CA: AAAI Press, 1996, pp. 235–241.

[37] K.N. McKay and V. Wiers, Integrated decision support for planning, scheduling, and dispatching tasks in a focused factory. *Computers in Industry*, 2003, Vol. 50 (1), pp. 5–14.

[38] S. Torabi et al. Fuzzy hierarchical production planning (with a case study). *Fuzzy Sets and Systems*, 2010, Vol. 161 (11), pp. 1511–1529.

[39] P. Brandimarte and M. Calderini, A heuristic bicriterion approach to integrated process plan selection and job shop scheduling, *International Journal of Production Research*, 1995, Vol. 33, pp. 161-181.

[40] N. Nasr and A. Elsayed, Job shop scheduling with alternative machines. *International Journal of Production Research*, 1990, Vol. 28, pp. 1595-1609.

[41] R. Kolisch and K. Hess, Eficient methods for scheduling make-to-order assemblies under resource, assembly area and part availability constraints. *International Journal of Production Research*, 2000, Vol. 38, pp. 207-228.

[42] D. Chung, K. Lee, K. Shin and J. Park, An algorithm for job shop scheduling problem with due date constraints considering operation subcontract. *Proceedings of the 15th ICPR International Conference*, 2000.

[43] A.C. Bahl and L.P. Ritzman, An integrated model for master scheduling, lot sizing and capacity requirements planning. *Journal of the Operational Research Society*, 1984, Vol. 35 (5), pp. 389–399.

[44] B. Faaland and T. Schmitt, Scheduling tasks with due dates in a fabrication/assembly process. *Operations Research*, 1987, Vol. 35 (3), pp. 378–388.

[45] A. Agrawal, G. Harhalakis, I. Minis and R. Nagi, 'Just-intime' production of large assemblies. *IIE Transactions*, 1996, Vol. 28 (8), pp. 653–667.

[46] C.S. Czerwinski and P.B. Luh, Scheduling products with bills of materials using an improved Lagrangian relaxation technique. *IEEE Transactions on Robotics and Automation*, 1994, Vol. 10 (2), pp. 99-111.

[47] K. Shin et al. A practical scheduling framework for component manufacturers in an APS environment. *Journal of Japan Industrial Management Association*, 2004, Vol. 55(2), pp. 59-68.

[48] D. Hoitomt, P. Luh and K. Pattipati, A Practical Approach to Job-Shop Scheduling Problems. *IEEE Transactions Robotics and Automation*, 1993, Vol. 9, No. 1, pp. 1-13.

[49] P. Luh, et al. Schedule Generation and Reconfiguration for Parallel Machines. *IEEE Transactions on Robotics and Automation*, 1990, Vol. 6, No. 6, pp. 687-696.

[50] K. Yoneda, Lagrangean Relaxation Method and Production Scheduling (In Japanese). *Production Scheduling*. Asakura Shoten Pub, Tokyo, 2002, pp. 141-161.

[51] M. Kuroda, Y. Tookuni and M. Enometo Quasi-optimization of Realtime Scheduling with Lagrangean Relaxation Method (lnJapanese), *Proceedings of Production Scheduling Symposium*, 1998, pp. 65-70.
[52] M. Kuroda, Lagrangean Decomposition and Coordination Method and Dynamic Scheduling (In Japanese), *Operations Research*, 2000, Vol. 45, No. 6, pp. 263-269.
[53] K. Shin, M. Kuroda and K. Natsuyama, Feasibility Study of Real-Time Scheduling Using the Lagrangean Relaxation Method Under an APS Environment. *JSME lnternational Journal*, 2003, Vol. 46, No. 1, pp. 39-45.
[54] P. Pongcharoen, C. Hicks and P.M. Braiden, The development of genetic algorithms for the finite capacity scheduling of complex products, with multiple levels of product structure. *European Journal of Operational Research*, 2004, Vol. 152 (1), pp. 215-225.
[55] N. Dellaert, J. Jeunet and N. Jonard, A genetic algorithm to solve the general multi-level lot-sizing problem with time-varying costs. *International Journal of Production Economy*, 2000, Vol. 68, pp. 241-257.
[56] N. Caraffa, S. Ianes, T.P. Bagchi and C. Sriskandarajah, Minimizing makespan in a blocking flowshop using genetical gorithms. *International Journal Production Economy*, 2001, Vol. 70, pp. 101-115.
[57] Lee, Y.H. et al. Advanced planning and scheduling with outsourcing in manufacturing supply chain. *Computers and Industrial Engineering*, 2002, Vol. 43 (1-2), pp. 351-374.
[58] X.Y. Shao, X.Y. Li, L. Gao and C.Y. Zhang, Integration of process planning and scheduling - a modified genetic algorithm-based approach. *Computers & Operations Research*, 2009, Vol. 36 (6), pp. 2082–2096.
[59] J.C. Fransoo and V.C.S. Wiers, An empirical investigation of the neglect of MRP information by production planners. *Production Planning & Control*, 2008, Vol. 19, pp. 781-787.
[60] P.M. Stoop and C.S. Wiers, The complexity of scheduling in practice. *International Journal of Operations & Production Management*, 1996, Vol. 16, pp. 37-53.
[61] G. Schuh, T. Potente, C. Thomas and A. Hauptvogel, Cyber-physical production management. In: C. Prabhu et al. (eds.) *Advances in Production Management Systems. Sustainable Production and Service Supply Chains*, 2013, pp. 477-484.
[62] I.M. Ovacik, Advanced planning and scheduling systems: the quest to leverage ERP for better planning. *Int. Series in Operations Research & Management Science book series*, 2011, Vol. 151, pp. 33-43.
[63] A. Biahmou et al., Towards agile enterprise rights management in engineering collaboration, *International Journal of Agile Systems and Management*, 2016, Vol. 9(4), pp. 302-325.
[64] J.C. De Man et al., Automating scheduling tasks; experience of a real case. *2015 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*. 2015, pp. 1447-1451.
[65] W.S. Beversluis and H.H. Jordan, Using a spreadsheet for capacity planning and scheduling. *Production and Inventory Management Journal*, 1995, Vol. 36(2), pp. 12-16.
[66] H. Kagermann, J. Helbig, A. Hellinger and W. Wahlster, *Recommendations for Implementing the strategic initiative INDUSTRIE 4.0: securing the future of German manufacturing industry*; final report of the Industrie 4.0 working group, Forschungsunion. 2013.
[67] A. Brewer et al. Intelligent tracking in manufacturing. *Journal of Intelligent Manufacturing*, 1999, Vol. 10 (3), pp. 245–250.
[68] D. Johnson, RFID tags improve tracking, quality on Ford line in Mexico. *Control Engineering*, 2002, Vol. 49 (11), pp. 16–16.
[69] G.Q. Huang, Y.F. Zhang and P.Y. Jiang, RFID based wireless manufacturing for walking-worker assembly islands with fixed-position layouts. *Robotics and Computer-Integrated Manufacturing*, 2007, Vol. 23 (4), pp. 469–477.
[70] H. Cao et al. RFID in product lifecycle management: a case in the automotive industry. *International Journal of Computer Integrated Manufacturing*, 2009, Vol. 22 (7), pp. 616–637.
[71] C.K.M. Lee and T.M. Chan, Development of RFID based Reverse Logistics System. *Expert Systems with Applications*, 2009, Vol. 36 (5), pp. 9299–9307.
[72] T. Qu et al. A case of implementing RFID-based real-time shop-floor material management for household electrical appliance manufacturers. *Journal of Intelligent Manufacturing*, 2010, Vol. 23 (6), pp. 1–14.
[73] B. Saenz de Ugarte et al. Manufacturing execution system–a literature review. *Production Planning & Control*, 2009, Vol. 20 (6), pp. 525–539.
[74] O. Brock and O. Khatib, Real-time re-planning in high-dimensional configuration spaces using sets of homotopic paths. *Proceeding of 2000 IEEE International Conference on Robotics and Automation*, 2000, Vol. 1, pp. 550–555.
[75] R.Y. Zhong and W. Ge, Internet of things enabled manufacturing: A review, *International Journal of Agile Systems and Management*, 2018, Vol. 11(2), pp. 126-154.
[76] X. Xu, From cloud computing to cloud manufacturing, *Robotics and Computer-Integrated Manufacturing*, 2012, Vol. 28, pp. 75-86.
[77] X. Wei and H. Liu, A cloud manufacturing resource allocation model based on ant colony optimization algorithm, *Int J Grid Distributed Comput*, 2015, Vol. 8(1), pp. 55-66.

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Battery System Design for Electric Go-Kart

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Abstract. This article presents the results of work related to power supply system for electric go-kart. The power supply system is composed of battery cells, BMS (Battery Management System) and a DC/DC converter for some peripheral devices. During the design of the system, various possibilities of energy storage were considered, based in particular on different types of batteries. The MBD (Model-Based Design) methodology was used to develop the power supply system, consisting in the development of a simulation model of the system and the study of the space of possible solutions with the use of these models. The model of the drive system determined the energy demand to obtain the required power, torque and rotational speed for a given trajectory. Various driving scenarios were analyzed. On their example, we developed models showing the energy demand for given route. The results show the estimated driving time for various conditions. The system operating time may be shorter or extended. It depend on the driving style and the nature of the route. The developed simulation model allowed to select appropriate parameters of the power supply system and the drive system so as to meet the criteria assumed.

Keywords. Electric go-kart, Light electric vehicle, EV, power supply system, battery cell, LTO, LFP

Introduction

Electric vehicles are gaining more and more popularity. Electromobility is becoming an everyday form of mobility, making life easier for the user thanks to the gradually introduced autonomy. Electric powered vehicles are not only cars, but also vehicles that are used in the entertainment industry - scooters, skateboards, buggies, go-karts [1,2]. Electric vehicle power supply system is most often based on battery cells. Various types of cells have a number of limitations related to energy and power density, mass, charging and discharging currents, number of charging cycles, and meeting safety requirements. Appropriate selection and connection of cells into modules has crucial meaning for the subsequent operation of the system. The aim is to ensure the longest possible operation of the system. Currently, the most commonly used cells in vehicles are Li-Ion cells. They are used mainly due to the high energy and power density, long life cycle and no memory effect. As a result, Li-Ion batteries can be smaller and take up less space than batteries made of other cells [3,4]. Li-Ion cells used in the automotive industry are not the safest. There have been many cases of Li-ion batteries catching fire and exploding in vehicles. They are associated with various incidents: short circuits, mechanical damage, manufacturing defects [5,6]. Mechanical damage is type of defect that is most likely to occur in kart racing. Another issue in the case of electric go-karts for entertainment

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purposes is to ensure operation for at least one race (8-10 minutes) so that during the ride there is no need to recharge the cells or replace them.

In order to develop a model of power supply system cooperating with drive system, it was decided to use Model Based Design (MBD) method [7-12]. MBD method is often used to design complex mechatronic systems. The use of such a methodology is particularly advantageous when designing systems require cooperation with specialists from various fields. An example would be drive system, power supply system, and electronics. An innovative approach to solving the problem will allow to develop subsystem models and then integrate them into one system.

1. Energy demand

The power supply system for electric go-karts is dependent on several limitations, related to dimensions, weight, cell efficiency and range. The main problem that occurs in case of electric go-karts power supply system is the limited capacity of batteries, which results in a limited driving time [13]. The challenge is to ensure the longest possible operation time, quick charging and reduce weight of the vehicle. Mass of batteries should not be significant in relation to the weight of entire vehicle. These requirements are often contradictory, so in order to choose the right components and settings, we should looking for "golden mean" consisting in choosing the most optimal version.

The first way is to assemble a large number of battery cells. A large number of cells connected in parallel will increase capacity of battery, which will extend working time. The disadvantage is the mass of battery packs. Too much weight causes a greater load and faster wear of components, among others bearings, tires.

Another way is possibility of using cells with high charging currents. Certain limitations should be taken into account here, i.e. battery capacity, decrease in cell efficiency over time, reduce the number of charging cycles, differences in the internal structure of the cell due to the temperature, higher range or lack of charging infrastructure.

The last method taken into account is modular design of battery packs. It should ensure quick assembly and disassembly of batteries. Thanks to this solution, it will be possible to remove a discharged batteries and connect it to charging, and install a charged batteries. It is also possible to use a hybrid of above methods.

2. Concept model of power supply system

The initial works began with general operation diagram of the power supply system. Into this scheme drive system and other energy consumption sources was included. We took into account also all the elements that should be included in the system (Fig. 1).

The most important issue in the development of power supply system are battery cells, and more precisely the type that will be used. In order to select the most appropriate cells, it was decided to use morphological analysis. Analysis included among others performance, safety, cost, lifespan, power and energy density, operating temperature, charging times. The most important criterion was the safety of the vehicle users. For this reason, the cell types that meet high safety standards have been reduced to two cell types - LTO ($Li_4Ti_5O_{12}$ - Lithium Titanate) and LFP ($LiFePo_4$ - Lithium Iron Phosphate). These two types compared to the other cells considered do not burn and do not explode. Number of cycles for both types is high, the operating temperature range of cells is also very wide and sufficient to work in the initially assumed conditions. Comparing LTO and LFP cells, it can be seen that the biggest difference, and also the disadvantage of LTO cells, is their high price. LTO cell costs almost four time more than LFP per Ah (Wh). On the other hand efficiency, high charging and discharging currents work in favor of the $Li_4Ti_5O_{12}$(Fig.2). Considering number of cycles and the cost per cycle, LTO is cheaper than LFP. Longer working time of $Li_4Ti_5O_{12}$ causes that this technology is even 3 times cheaper than $LiFePo_4$. This comparison takes into account all lifespan of batteries.

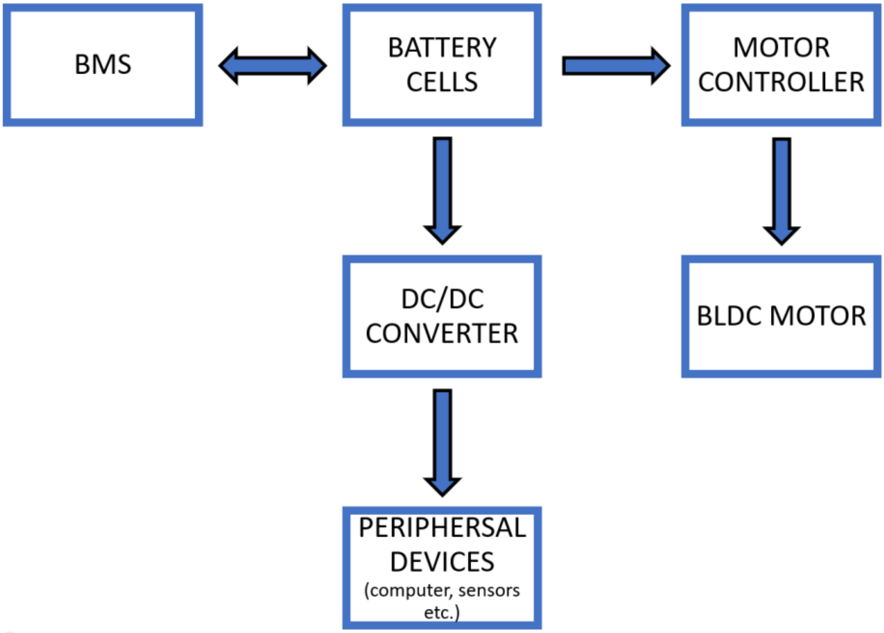

Figure 1. General diagram of the electric go-kart power supply system

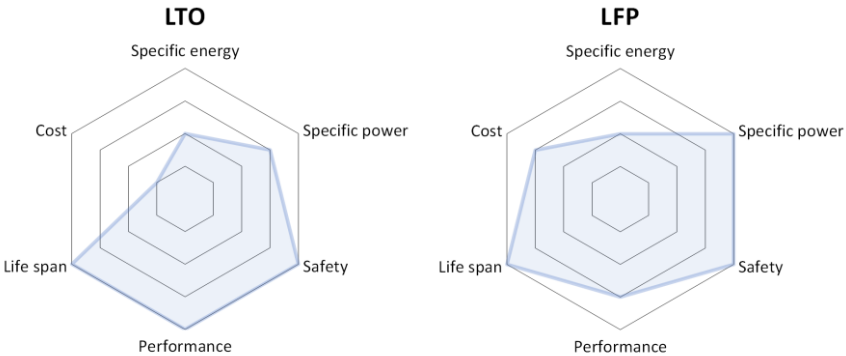

Figure 2. Comparison of LTO and LFP cell

At the same time, the sample locations for mounting the batteries on the go-kart frame and amount of space needed for batteries were analyzed. It was decided to place batteries symmetrically on both sides of the vehicle. The reason was to evenly distribute the weight of cells on the frame. Different battery cells have different values for energy density and specific energy. Li-Ion cells used in automotive industry (NMC - Nickel Manganese Cobalt, NCA - Nickel Cobalt Aluminum) have much higher these values then LTO and LFP. Table 1 shows the basic parameters of these cells.

Table 1. Specific energy and energy density of Li-Ion cells

Li-Ion type	Specific energy [Wh/kg]	Energy density [Wh/L]	Cycle life
NCA	220-260	600	500
NMC	150-220	580	1000-2000
$LiFePo_4$ (LFP)	90-160	325	>2000
$Li_4Ti_5O_{12}$ (LTO)	60-110	177	3000-7000

Cells which we intend to use for testing (LTO, LFP) have several times smaller amount of energy in mass/volume. Due to the low battery capacity of electric go-kart and the highest priority which is safety, it was decided to continue work based of these two types of cells.

3. System modelling method

The motor model was described by two equations (Equation 1,2). The first describes electrical part of electric motor, the second mechanical part [14].

$$U_s = R_s i_s + L_s \frac{\mathrm{d}i_s}{dt} + k_e \omega_R \quad (1)$$

$$k_m i_s = B\omega_R + J\frac{\mathrm{d}\omega_R}{dt} + M_s \quad (2)$$

Where:

$U_s - supply\ voltage$
$R_s - stator\ resistance$
$i_s - stator\ current$
$L_s - stator\ inductance$
$k_e - motor\ velocity\ constant, where\!: k_e = U_s - R_s i_s$
$\omega_R - rotor\ rotational\ speed$
$k_m - motor\ torque\ constant$
$M_{Sn} - nominal\ torque$
$B - viscous\ friction\ coefficient, where\!: B = k_m i_s - M_{Sn}$
$J - rotor\ inertia$
$M_s - load\ torque$

In above equations, input values are voltage U[V], current I[A] and torque Ms[Nm]. They will vary depending on the type of electric motor, nature of the ride or traveled route.

4. Case study – electric go-kart

4.1. Assumptions for electric go-kart

The drive and power supply system, which was included in the simulations, is characterized by the following parameters:

- Rated motor power: 10[kW]
- Max RPM(revolutions per minute): 3200
- Rated voltage: 48[V]
- Battery capacity: 40[Ah]
- Estimated working time: 20 minutes

One of the key criteria is to keep the go-kart batteries weight as low as possible and ensure sufficient capacity. During the simulations two types of cells were tested:

- $Li_4Ti_5O_{12}$ cells: 25 [kg] - 20 cylindrical cells connected in series
- $LiFePo_4$ cells: 20 [kg] - 16 prismatic cells connected in series

4.2. Power supply system simulation model for light electric vehicles

Two simulation models were developed - the BLDC (BrushLess Direct-Current) motor model (Fig. 3) and battery discharge model (Fig. 4). The simulation model developed in the MATLAB/Simulink environment is analogous to the general scheme of operation shown in Fig. 1. The combination of two simulation models into one system allowed to analyze:

- how the output power from electric motor loads the power supply system
- energy demand
- estimated operating time of the system for the given driving scenarios.

The data needed to simulate drive system was obtained from manufacturers of electric motors available on the market. Based on the preliminary assumptions, a motor with a rated power of 10[kW] and a maximum torque of 27[Nm] was selected.

Input values of simulation model were voltage U[V] and torque Ms[Nm]. These two values and internal electric parameters of BLDC motor allowed to obtained in the output two parameters – current I[A] which is drawn from batteries and rotary speed.

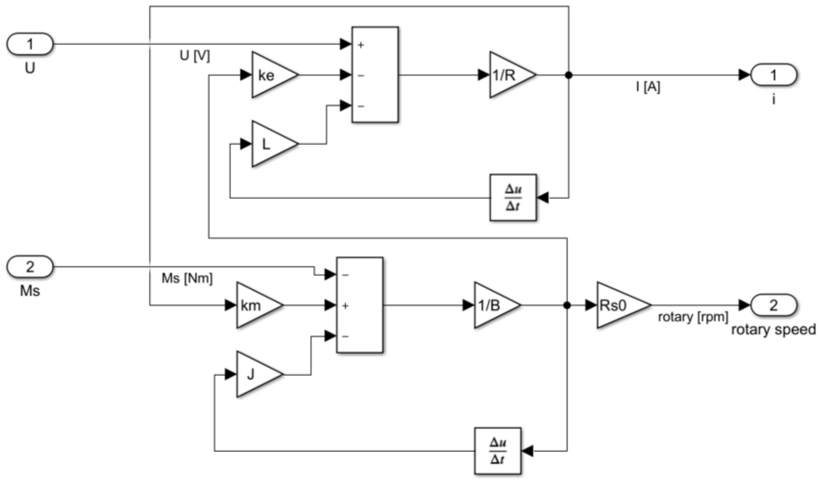

Figure 3. Model of BLDC electric motor

The battery discharge model was developed based on a ready-made library that was modified respectively for LFP and LTO cells. Thanks to this model, it was possible to carry out simulations that will show how the battery will behave after being loaded with set current values. The load current values were taken from output value from the BLDC motor simulation. As the output we received SOC(State of Charge)[%], current I[A], and voltage U[V] of batteries.

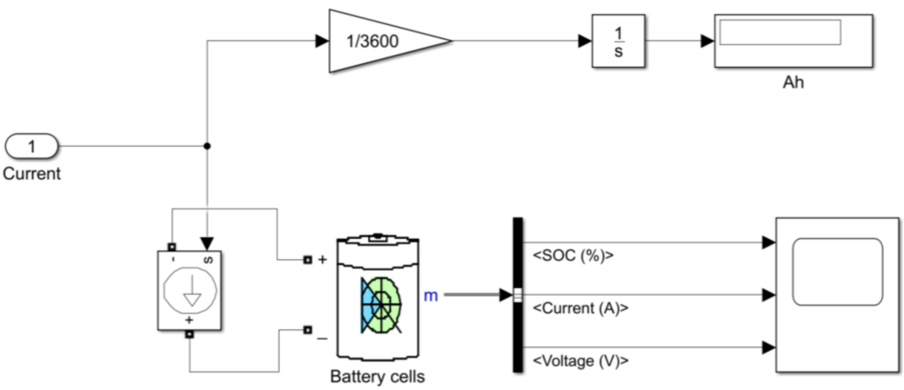

Figure 4. Model of discharging battery cells

4.3. Track types for simulation model

A simulation of driving and energy requirements was developed using simple example of race tracks (Fig. 5). The tracks contain basic elements such as straight lines, bends with different radius and angle. Thanks to them the power supply system can be analyzed in terms of go-kart use in real conditions.

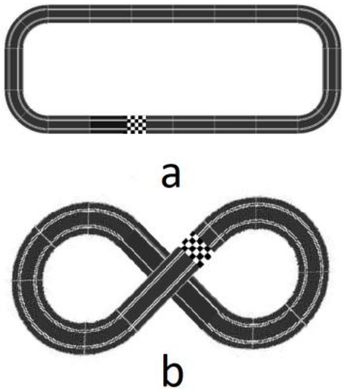

Figure 5. Types of track include in simulation – (a) oval track. (b) eight track

The first scenario is based on an oval track (Fig. 5a). It allowed to analyze the power supply system in terms of rapid changes in speed. After exiting a corner, the accelerator pedal is immediately depressed to the maximum in order to reach the top speed as quickly as possible. This simulation allows to know the driving time on an uncomplicated track. The basic parameters of the track are given below:

- Track length - 270m
- The length of the longest straight line - 95m
- Turning radius - 5m

The second scenario was developed on the basis of the number 8 shaped track (Fig. 5b). On a straight, the vehicle is able to reach maximum speed for a short period of time. Curves on track change the direction of travel by approx. 270 degrees. The simulation shows how much slowing down (approx. 40% of the route) will affect driving time. The basic parameters of the track are :

- Track length - 165m
- Straight length - 50m
- Turning radius - 10m

4.4. Analysis of energy consumption in various operational states

Energy demand for various driving phases has been developed using data contained in the catalog of electric motor manufacturer and in the software included with BLDC motor controller.

Table 2. Electric go-kart energy demand for different driving phases.

Driving phase	Energy demand [kW]
Smooth start	2,5
The moment of reaching the maximum speed and maintaining – Rated power	10
Boost – Peak power	13

The values of energy demand (Table 2) allowed to present characteristics how the power supply system will discharge during driving. First simulation of discharge was performed for LTO (Fig. 6), second for LFP (Fig. 7).

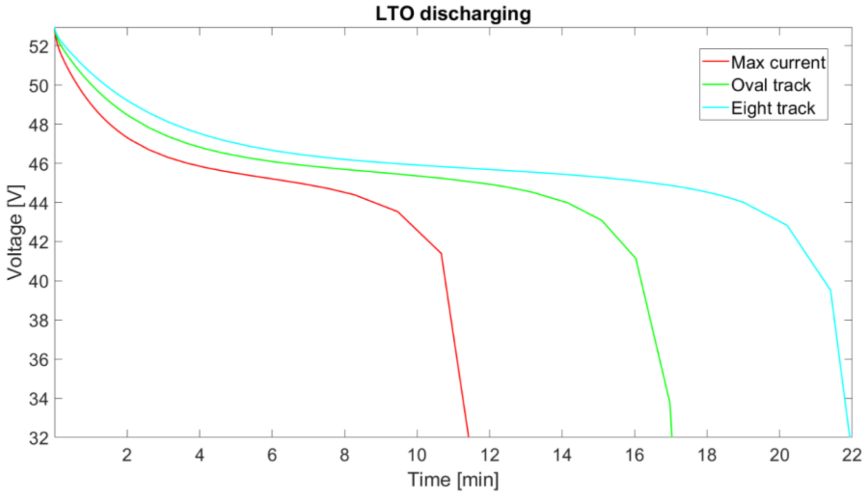

Figure 6. Graph of LTO discharge

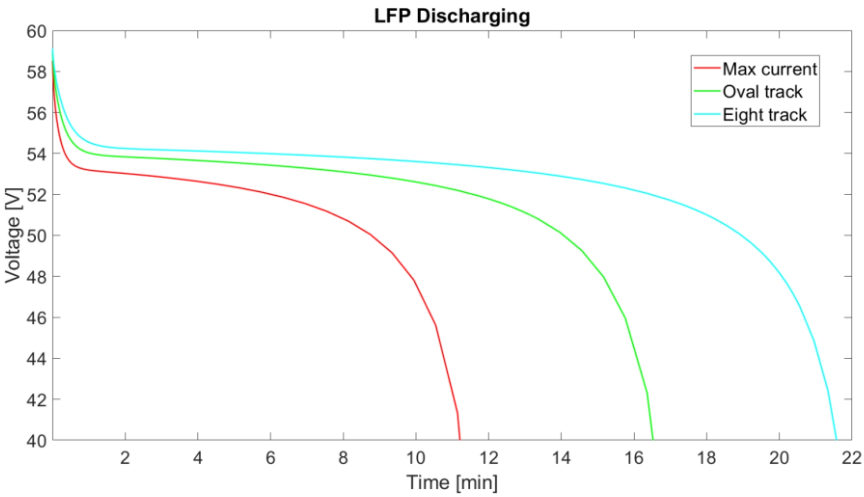

Figure 7. Graph of LFP discharge

By analyzing discharge charts of LTO and LFP batteries, it can be concluded that the discharge time of both are very comparable. The discharge characteristics are different from each other. The initial - maximum and final - minimum voltage for both cells are different, therefore the operating voltage of the batteries is also different. Characteristics of the voltage drop depending on the load also different. The biggest difference is the initial discharge period of a fully charged battery.

5. Conclusions

Power supply system for electric go-karts is not only the field of electrical engineering, but also mechanics, electronics, programming and chemistry related to the processes taking place inside the cell. We have to consider how many space we have for batteries, in what conditions vehicles will be working or who will be drive a go-kart. We can limit the power of go-kart in the software e.g. if child will drive the kart.

The developed simulation model of power supply system made it possible to analyze operation of two types of battery cells. Thanks to these simulations, it was possible to see how the load acting on the power supply system will affect to the operating time or voltage drop. An analysis of Figures 6 and 7 shows that the battery capacity was selected correctly to the assumptions. The discharging time for both batteries was very similar for each scenario (track). In the tested case study performance and safety are comparable for both batteries, however LFP is approx. 20% lighter than LTO. Driving time oscillating around 20 minutes is not too high. Increasing the battery capacity 3 times (to achieve 60 mins of driving), the difference between the LFP and LTO batteries will already be ~15 kg. In the case of racing vehicles, weight can have a significant impact on driving dynamics, travel time (laps) and loads.

In order to better select battery cells for the power supply system, each case should be considered separately. In our case study, we included LTO and LFP due to meeting high security requirements. For different tracks, tracks conditions or other restrictions, a different type of battery cells may be more appropriate. It is important to accurately determine the vehicle operation time necessary to travel the route and the amount of space to install the batteries. Performed simulations allow to know the estimated working time of electric go-kart. Further work must include development of simulation models for battery charging and more advanced trajectory. This second model will allow to observe dynamic changes in the load of batteries.

In order to fine-tune simulation model, it is planned to build a test stand. It will allow to more detailed analysis of the power supply system, among others in terms of voltage drops or overheating of cells. The finally developed simulation model will make it possible to find out about system limitations and critical points at design stage.

References

[1] A. Mönnig, C. Schneemann, E. Weber, G. Zika and R. Helmrich, *Electromobility 2035:Economic and labour market effects through the electrification of powertrains in passenger cars*, IAB Discussion Paper, 8/2019.

[2] B. Sanden and P. Wallgren, *Systems perspectives on electromobility*, Chalmers University of Technology, Göteborg 2014.

[3] Y. Ding, Z. Cano, A. Yu, J. Lu and Z. Chen, Automotive Li-Ion Batteries: Current Status and Future Perspectives, *Electrochemical Energy Reviews*, 2019, Vol. 2, Issue 1, pp. 1-28.

[4] Y. Miao, P. Hynan, A. von Jouanne and A. Yokochi, Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements, *Energies*, 2019, Vol. 12(6), 1074.

[5] L. Hollmotz, Safety of Li-Ion Batteries in Vehicles, *23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, Seoul, Korea, South, 5/2013.

[6] L. Kong, C. Li, J. Jiang and M.G. Pecht, Li-Ion Battery Fire Hazards and Safety Strategies, *Energies*, 2018, 11, 2191.

[7] W. Skarka, Methodology for the optimization of an energy efficient electric vehicle. In: *Proceedings of the 6th International Conference on Integrity-Reliability-Failure*, Lisbon, 2018, pp. 415-422

[8] M. Targosz, W. Skarka, P. Przystałka, Model-Based Optimization of Velocity Strategy for Lightweight Electric Racing Cars, *Journal of Advanced Transportation*, 2018, Article ID 3614025, [Online]. Available: https://doi.org/10.1155/2018/3614025

[9] R. Niestrój, T. Rogala, W. Skarka, An Energy Consumption Model for Designing an AGV Energy Storage System with a PEMFC Stack, *Energies*, 2020, Vol. 13, 3435.

[10] M. Tyczka, W. Skarka, Optimisation of Operational Parameters Based on Simulation Numerical Model of Hydrogen Fuel Cell Stack Used for Electric Car Drive, *Advances in Transdisciplinary Engineering*, Vol. 4, 2016, pp. 622–631.

[11] W. Skarka, Model-Based Design and Optimization of Electric Vehicles, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 566–575.

[12] K. Mateja, W. Skarka, Towards energetic autonomy of UAV, *Advances in Transdisciplinary Engineering*, 2020, Vol. 12, pp. 423-432.

[13] W. Gołębiewski, Concept of the construction of electric Go-kart (ekart), *The Archives of Automotive Engineering,* 2018, Vol. 80, No.2, pp. 53-63.

[14] A. Hughes, *Electric Motors and Drives, Fundamentals, Types and Applications*, Third edition, Newews, Amsterdam, 2013.

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Integration Across Knowledge Boundaries During New Product Introduction

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Abstract. New product introduction refers to all activities that are required to make a product possible to produce in planned volumes. To ensure smooth new product introduction, product and production developers work in a cross-functional and integrated way. Because of high degree of novelty during new product introduction and interdependencies between those involved knowledge boundaries are created. As prior research argues, different types of knowledge boundaries require different integration processes. For example, integration at a syntactic boundary is established by transfer of domain-specific knowledge across a boundary, while coping with semantic boundary requires a process of translation where learning about the differences and dependencies at the boundary is required. To be able to understand how to integrate product and production development across knowledge boundaries and hence support new product introduction it is important to understand what types of boundaries need to be crossed. To overcome the shortcomings of the prior research, this paper focuses on knowledge boundaries and prerequisites for successful integration in new product introduction. It is based on success stories from three large Swedish companies. This paper addresses transdisciplinary challenges and contributes to literature on boundary crossing during new product introduction and to practice.

Keywords. Transdisciplinary engineering, knowledge boundary, new product introduction, integration

Introduction

Today's trends in manufacturing are associated among others with shorter product life cycles, changing customer requirements, new technology, environmental and safety regulations, high-cost pressure, and increased degree of automation in production. To be competitive in a harsh market it becomes critical for a company to achieve successful new product introduction (NPI) [1][2]. NPI is associated with all activities that are necessary to adapt the product and production system to each other during development of a new product [3]. This among others include activities necessary to secure product manufacturability[1]. Successful NPI is associated with timely start of production and ramping-up the production according to plans in terms of volumes, cost, and quality [4] [5].

To succeed with NPI, companies need to secure integration between product and production development [6][7][8]. Traditionally, companies follow concurrent and transdisciplinary work methodology to reduce the time for NPI [9]. This implies that

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actors work in parallel with product and production development in an integrated way to bring downstream inputs as early as possible in the product design [5]. Hence, the actors are interdependent to the degree where each actor is constrained by decisions taken by the other party. Furthermore, NPI where new requirements from various stakeholders are implemented is associated with high degree of novelty [1] [10]. Because of different types of domain-specific knowledge, interdependencies and novel circumstances, knowledge boundaries between actors responsible for product and production development are created [11]. Prior research [12][11] recognizes the need for diverse integration processes to cross the different types of knowledge boundaries.

There is limited research as to the type of boundaries that exist during NPI. To be able to understand how to integrate product and production development across knowledge boundaries and hence support NPI it is important to understand what types of boundaries need to be crossed. To overcome the shortcomings of the prior research, this paper focuses on knowledge boundaries and prerequisites for successful integration in NPI. More specifically this paper has two objectives:

1. To describe knowledge boundaries between product and production development during NPI.
2. To outline prerequisites for successful integration of product and production development across knowledge boundaries during NPI.

By combining knowledge of product and production development from the technical discipline with knowledge of boundary crossing from social sciences, and through a combination of academic and scientific goals, two important transdisciplinary issues are addressed [13].

1. Types of knowledge boundaries and integration

Boundaries between actors from different domains evolve because of the properties of knowledge, namely difference, dependence, novelty [11]. Difference refers to the dissimilarities of the amount and type of knowledge that is accumulated between actors from different domains specialized in different engineering work; while the dependency implies that actors need to take each other into consideration if they are to meet their goals. Novelty implies that when new circumstances arise, new requirements for the actors from different domains occur and hence no or little common knowledge between them exists. Hence, when the differences, dependencies, and novelty increase, the complexity of a boundary across disciplines also increases. That is why prior research [12] formulate three types of knowledge boundaries that reflect the complexity at a boundary. These knowledge boundaries are referred to as syntactic, semantic, and pragmatic. Associated with the boundaries there are three knowledge integration processes: transfer, translation, and transformation (see Figure 1) [11].

Syntactic boundary implies that common knowledge and shared syntax about differences and dependencies between actors exist and managing this type of a boundary requires transfer of domain-specific knowledge [13]. When novelty increases, the amount of common knowledge and shared vocabulary is reduced, and a semantic boundary occurs between disciplines [14][9]. Novelty makes some difference in the type of domain-specific knowledge (e.g., language, tools, methods) unclear and some meanings ambiguous. In such a case knowledge translation and reaching mutual understanding are necessary. This is achieved by learning about and making explicit new sources of differences [15]. Pragmatic boundary implies that knowledge is ‘invested in practice' and actors are often reluctant to change their existing knowledge [11]. Crossing this boundary requires not only translation of different meanings but also negotiation of interests [12]. There is a need of transforming knowledge where actors alter the existing knowledge and create new. Prior research [12] acknowledges that an effective transformation process requires existing of both shared syntax and language, as well as shared meaning across the actors.

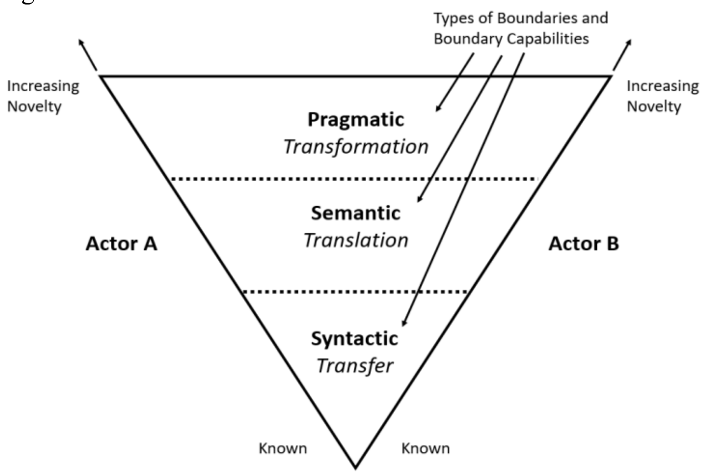

Figure 1. Type of boundaries and integration processes [11]

Several studies indicate that integration of product and production development across knowledge boundary requires objects, spanners, and arenas [1][2]. Research [12] points out that effective objects that support integration at a syntactic boundary need to establish a shared language (vocabulary) which is enough to represent knowledge, like repositories. Effective boundary objects that have the capacity to support knowledge translation are for example standardised formats and methods like design failure mode and effect analysis (D-FMEA) or process failure mode and effect analysis (P-FMEA) [11]. These objects are concrete means that have mutually understood format and structure. Further, they can help to reach knowledge externalization, which using Nonaka's [14] words means making tacit knowledge explicit. Effective objects that can facilitate negotiating and transforming common and domain-specific knowledge used in the past are for example sketches, drawings, prototypes, or simulations [11]. To enhance integration between product and production development, techniques associated with design for manufacture (DFM) and design for assembly (DFA) are used. Among these techniques are for example (1) reviews for assessment of product manufacturability; (2) guidelines for a specific manufacturing process; (3) general guidelines such as standardization, reduction of number of parts in a product for easy for assembly operations [15].

Integration between product and production development is also supported by boundary spanner, that are, individuals that establish linkages, share expertise between domains, and help to resolve conflicts [1]. In the context of NPI, research [16] points out the role of the boundary spanner (the technician) as important to overcome misunderstandings between product and production development. Lastly, encounters are meeting points or the arenas between specialized domains where the integration of knowledge take place [1], like the design reviews meetings [15].

2. Method

To fulfil the purpose and the objectives of the study, the empirical analysis is based on a multiple case study [17]. The main criteria for selecting the cases were that the companies were from the manufacturing industry, develop and industrialise products in-house, where new products must be rapidly developed. Three large-sized Swedish companies (see Table 1) were selected to participate in the study (from now on referred to Company Armature, Outdoor and Transportation).

Table 1. Overview of the sampled companies

	Company Armature	Company Outdoor	Company Transportation
Industry	Lighting solutions for indoor and outdoor applications	Outdoor power products	Products for sports and outdoor activities

Data was collected by semi-structured, open-ended interviews and through internal company documentation. Key informants were involved in NPI and represented roles such as R&D, engineering design, production, and project management. Data was collected from September to November 2020. The informants were asked to describe successful stories of integration between product and production development. In addition, various prerequisites which made the integration successful were requested. The interviews were carried out digitally via Microsoft Teams, recorded and transcribed verbatim, which increased the reliability of the study. The informants were able to review the results from the interviews during a workshop and hence the validity of data was strengthened. The data analysis followed the steps prescribed by [18], namely data condensation, data display and conclusion drawing/verification. Contrasting the literature to empirical results was crucial to secure the external validity of the study [17].

The types of boundaries and prerequisites for successful integration are seldom made explicit in the research on NPI. The conceptual model developed by [12] helped to structure our findings.

3. Case studies

3.1. Company Armature

Company Armature developed both standard and customer specific products. The company strove for automation at the Swedish production site. The managers expressed the need to remove the strict boundaries and improve coordination between product and production development.

Company Armature provided several examples of successful integration between product and production development. Related to a project, one of the informants stated *'... I believe the time pressure did a lot, that it was a deadline to relate to and that we could not – absolutely as a new, relatively new player on the market wanted to miss or mess up here'*.

To secure product manufacturability design review meetings involving product developers, quality engineers, purchasing, and production were important. The specialized domains had opportunity to analyse the product and associated risks. Checklist for design reviews was used. Company Armature also had industrialisation reviews where production technicians reviewed the product prior to its introduction in production. During the reviews, a checklist and a prototype were used. Checklist for assembly and painting to secure product manufacturability were used. The design and the industrialization reviews had a purpose to increase understanding between product and production development. The reviews encouraged a dialogue and provided arena for negotiations between the specialized domains.

Early test assemblies with prototypes where the product developer, the production planner and the assembler put together a product were perceived as positive to integrate knowledge between them. The product developer could see what changes had to be made and the assembler could get familiar early with the product and influence the product design. Test assemblies were carried out early in the product design.

To increase the understanding of the product developers for complex production, Company Armature had introduced trainings. During the trainings, production made presentations covering, for example, assembly methods, production methods, work carried out in different cells, as well as critical production aspects that needed to be considered by product developers when developing a new product.

Company Armature expressed that it used guidelines and design books linked to production methods, however, knowledge was mostly exchanged verbally. Product developers had to ask production if their solutions would work. The guidelines were simple related to the cells and the production lines and the information was mostly related to the max/min size and other dimensions but not tolerances. However, as Company Armature explained it was up to each product developer’s initiative to use and find out information related to the production aspects.

3.2. Company Outdoor

Company Outdoor perceived need to reduce time for NPI and increase efficiency of their production sites. That is why, the company worked with digitalisation and assembly automation.

Company Outdoor indicated that one of the activities to facilitate NPI was a workshop (2 to 3 days) involving product and production developers. The purpose of the workshop was to ensure product manufacturability and negotiate changes that had to be made on the product design for cost-effective manufacturing. The first workshop was when the first prototypes were developed. What made the integration successful during these workshops was that the product and production developers felt involved and were familiar with the new product. The use of prototypes was also mentioned as a prerequisite for success.

In general, successful integration required close physical proximity, where product and production developers provided updates and discussed new solutions to various problems during informal meetings. Moreover, keeping the same product and production developers from initial development until product launch was crucial for successful integration. Company Outdoor stated that for successful integration there was a need to allocate a person that was responsible for the integration itself.

According to the project manager, higher levels of assembly automation implied increased need of early integration between product and production development. Early integration during initial development gave opportunity to the production developers to set early product requirements related to increased automation and hence prepared the product for automated assembly. Company Outdoor worked with design for automated assembly (DFAA) and developed visual guidelines that helped with mutual understanding between product and production development. Production developers created standards that guided design decisions and communicated the new requirements for automated assembly.

3.3. Company Transportation

Company Transportation perceived need to improve alignment between product and production development. It started to use additive manufacturing to develop production tools and moved towards more automated production. The company needed to improve in terms of design for assembly (DFA).

Company Transportation described several examples of successful integration between product and production development. When it came to design for manufacturing (DFM) the company was skilled on a component level. The company had so-called ‘knowledge teams’ which were cross-functional teams with specialists from different domains. For example, in one knowledge team specialists from production, material, tool specialists, as well as purchasing participated. The idea with knowledge teams was to encourage sharing of experience and competence between individuals who could train each other and spread knowledge between the specializations. This was done to keep knowledge in house. Knowledge was considered person-based and was largely disseminated through meetings (formal and informal). Company Transportation also carried out training for newly employed product developers to increase their knowledge regarding production methods.

To ensure resource efficiency during production preparations physical models and 3D-printed prototypes were important. One informant mentioned *'it makes things much more effective in seeing ‘what are the problems and a little opportunity’’.* Prototypes were used for testing but also for communication where one *‘...see and understand the product in an easier way’*. One informant stated that CAD models were useful, but it was even better to have physical models to look at instead of just sitting and discussing. Otherwise, ‘*people can go from the meeting with different view of what the problem is’*.

Company Transportation described several projects were the integration between product and production development was successful. In the first project, there was a strong focus on automation of a product with high volumes. Product developers had close contact with production developers who were dealing with increased levels of automation. The way of work included regular meetings as well as early prototypes (3D printed physical models). In the second project, successful integration was encouraged by the role of a project manager who facilitated discussions between domains. In the third project, the company stated that successful integration was achieved with structured DFA analysis where the goal was to reduce the number of the components and improve the product manufacturability. In the fourth project, junior product developers shared early CAD models with the production developers to get inputs for what was possible and what was not possible to produce. The integration took place during weekly meeting and reconciliation workshops where product and production developers looked at the design and the technical solutions to find the best ones. The integration was facilitated with prototypes.

In general, Company Transportation expressed that how well different disciplines understood each other was affected by the people's experience and competence and how open they were to the opinions of others. The company further stated that successful integration was influenced by individuals who had the experience and understanding of what challenges related to the product design might occur for the suppliers who had to industrialize and produce a component. It was often the case that the product developers were not aware of problems that suppliers experienced with industrialisation because of a component design. An informant described a situation where he used reference parts (bad and good) and showed them to the product developers so that they could gain understanding *'It is important to be able to communicate with physical parts between product and production development to gain an understanding of things…It's very easy to talk about a part in that way, instead of talking in the air'*.

4. Analysis and discussion

4.1. Knowledge boundaries during new product introduction

The findings of this study indicated that the novel situations in which companies operate were important to describe the complexity of a boundary between product and production development during NPI. Literature on knowledge boundaries [12] describes different types of boundaries but it offers little insight into situations that can cause novelty at a boundary during NPI. To some extent, prior research [5] explains that the novelty level of product and production system (i.e., degree of change) defines the complexity with which product and production developers need to deal with during NPI. Furthermore, the prior research discusses that high novelty and difficult to analyse product/production system fit problems calls for higher levels of integration [5][19]. Higher degree of novelty requires integration through cross-functional teams, while low novelty requires integration via standards, schedules, and plans [5].

A clear pattern turned up among the case studies when looking at the long-term changes and challenges with which companies were faced. The challenges were related to the novelty in terms of new production technology, increased degree of automation, digitalization, and customization. The novelty added complexity at the boundary between product and production development, see Figure 2. The prevailing boundary described by the companies was the semantic boundary [11]. The three companies showed examples of semantic boundaries where changes in the production system increased the knowledge gap between product and production developers. The prevailing examples of semantic boundaries, in comparison to syntactic and pragmatic, was not a surprise. The degree of novelty required translation of differences as well as dependencies that occurred at the boundary between product and production development because of that novelty. There was a need to understand the sources of complexity and uncertainties that affected the integration at a knowledge boundary between the specialized domains. In the context of NPI, a boundary needed to be crossed mainly to secure product manufacturability and the fit of the product and the production system. The case studies corroborate prior research [11] stating that the line between semantic and pragmatic boundary is obscure and unclear. There were few examples of pragmatic boundary where product and production developers negotiated changes that needed to be made on the product design for cost-efficient manufacturing, but focus was mainly on reaching mutual understanding and not on making trade-offs.

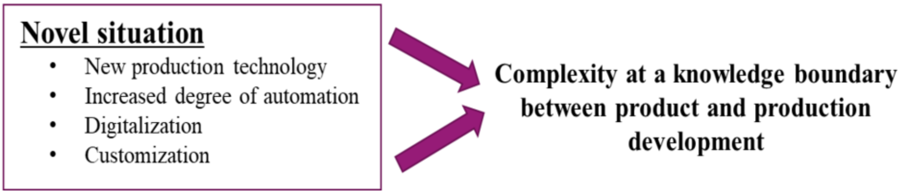

Figure 2. Complexity at a knowledge boundary

4.2. Prerequisites for successful integration across knowledge boundaries

The case studies indicated that successful integration across knowledge boundaries was influenced by individuals who were experienced and understood how product design could affect production. The findings indicated that considering determinants of novelty may help in identifying appropriate ways to integrate product and production development across knowledge boundaries. Carlile [12] argues that effective boundary object has the capacity to establish shared context necessary to represent knowledge, provides concrete means to facilitate learning and helps to transform common and domain-specific knowledge. The case studies indicated that for successful integration across semantic and pragmatic boundaries objects such as prototypes, guidelines, checklists, and test assemblies could be used. The use of protypes and test assemblies is in line with prior research [12]. Furthermore, the case studies indicated that guidelines and checklists were also important for integration across semantic and pragmatic boundaries. This could be explained with the fact that knowledge translation and transformation require existence of common lexicon and meaning [11]. Prior research argues that DFM and DFA are important methods that can facilitate the degree of adaptation between product and production system and hence support NPI [5] [1]. In that relation design guidelines and checklist are critical to transfer more routine information [15]. However, the case studies also showed that guidelines and checklists were critical to cross semantic and pragmatic boundaries. In addition to the boundary objects, the case studies indicated that successful integration at semantic and pragmatic boundaries required encounters or arenas which facilitated integration at a knowledge boundary. The encounters indicated in the case studies were review meetings, workshops, weekly meetings, and trainings. Furthermore, in one of the case studies the role of a boundary spanner was pointed as important to cross semantic and pragmatic boundaries. Encounters and boundary spanners in NPI are discussed by [1], however their study does not provide the link between the types boundaries and successful integration across the boundaries. Furthermore, the case studies showed that for successful integration across boundaries, a combination of different ways for crossing the boundary were implemented - for example, a combination of encounter and a boundary object.

The case studies further indicated that prerequisites for successful knowledge integration were not only limited to the use of boundary objects, encounters, and spanners. Successful integration also was determined by external factors that affected these boundary objects and encounters. The case studies indicated that several external factors; open climate, time pressure, time of meeting point during product development, close physical distance; affected the use of boundary objects and encounters. Hence these factors could be considered as important prerequisites for successful integration across knowledge boundaries during NPI. The prerequisites for successful integration across semantic and pragmatic boundaries are summarized in Figure 3.

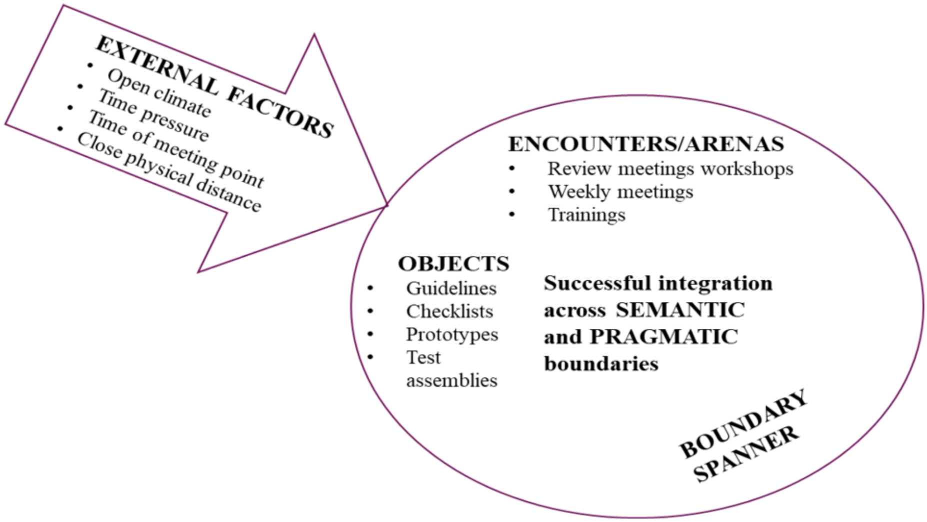

Figure 3. Prerequisites for successful integration across semantic and pragmatic boundaries

5. Conclusions

Integrating product and production development across knowledge boundaries during NPI is not an easy task [8]. In this paper, we describe type of knowledge boundaries between product and production development and outline prerequisites for successful integration across them during NPI. This study emphasizes on the need to consider determinants causing novelties and hence different levels of boundary complexity between product and production development during NPI. In today's manufacturing industry many of the novelties are related to the increased automation in production, digitalization and customization which create new requirements for the product and production development. That is why, this study is in line with the prior research [12] and states that sources of the novelty need to be understood for successful integration across knowledge boundaries. Furthermore, in this paper, we extend the literature on boundary crossing during NPI and provide a link between types of knowledge boundaries and successful ways of integration. In addition to the prior research [1] [2][12] this study indicates that prerequisites for successful integration across knowledge boundaries may require the use of not only boundary objects but also encounters and spanners. We further extend the literature on boundary crossing in NPI by proposing that prerequisites for successful integration across knowledge boundaries may also require a combination of boundary objects, encounters, and/ or spanners. Furthermore, prerequisites for successful integration are also associated with external factors to the boundary objects, encounters, and spanners. This study involves more than one discipline integrating engineering from product development (mechanical, electrical, and electronic engineering) as well as production development (production engineering, production planning, quality engineers and purchasing) and discusses how to integrate knowledge across a semantic and pragmatic boundary. Therefore, this study also brings insights into the transdisciplinary literature [9][21].

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References

[1] M. Gustavsson and K. Säfsten, The learning potential of boundary crossing in the context of product introduction, *Vocat. Learn.* , 2017, Vol. 10, No. 2, pp. 235–252.

[2] P. Wlazlak, Y. Eriksson, G. Johansson, and P. Ahlin, Visual representations for communication in geographically distributed new product development projects, *J. Eng. Des.* , 2019, Vol. 30, pp. 385–404.

[3] M. Bellgran and K. Säfsten, *Production development : design and operation of production systems*. Springer, New York London, 2010.

[4] S. Fjällström, K. Säfsten, U. Harlin, and J. Stahre, Information enabling production ramp-up, *J. Manuf. Technol. Manag.*, 2009, Vol. 20, No. 2, pp. 178–196.

[5] P. S. Adler, Interdepartmental interdependence and coordination: the case of the design/manufacturing interface, *Organ. Sci.*, 1995, Vol. 6, No. 2, pp. 147–167.

[6] M. Kleinsmann, R. Valkenburg, and J. Buijs, Why do(n't) actors in collaborative design understand each other? An empirical study towards a better understanding of collaborative design, *CoDesign*, 2007, Vol. 3, No. 1, pp. 59–73.

[7] P. Cash, E. A. Dekoninck, and S. Ahmed-Kristensen, Supporting the development of shared understanding in distributed design teams, *J. Eng. Des.*, 2017, Vol. 28, No. 3, pp. 147–170.

[8] A. Majchrzak, P. H. B. More, and S. Faraj, Transcending knowledge differences in cross-functional teams, *Organ. Sci.* , 2012, Vol. 23, No. 4, pp. 951–970.

[9] M. Goudswaard, B. Hicks, and L. Newnes, An appraisal and classification of the transdisciplinarity of existing design tools, *Advances in Transdisciplinary Engineering*, 2020, Vol. 12, pp. 50–59.

[10] P. G. Wlazlak and G. Johansson, R&D in Sweden and manufacturing in China: A study of communication challenges, *J. Manuf. Technol. Manag.*, 2014, Vol. 25, No. 2, pp. 258-278.

[11] P. R. Carlile, Transferring, translating, and transforming: An integrative framework for managing knowledge across boundaries, *Organ. Sci.*, 2004, Vol. 15, No. 5, pp. 555–568.

[12] P. Carlile, A pragmatic view of knowledge and boundaries: boundary objects in new product development, *Organ. Sci.*, 2002, Vol. 13, pp. 1–21.

[13] N. Wognum, C. Bil, F. Elgh, Peruzzini, M., Stjepandić, J. and W. J. C. Verhagen, Transdisciplinary systems engineering: implications, challenges and research agenda, *International Journal of Agile Systems and Management*, 2019, Vol. 12, No. 1, pp. 58–89.

[14] I. Nonaka, A Dynamic Theory of Organizational Knowledge Creation, *Organ. Sci.*, 1994, Vol. 5, No. 1, pp. 14–37.

[15] G. Boothroyd, P. Dewherst, and W. Knight, *Product Design for Manufacture and Design*, 2nd ed. Marcel Dekker, Inc., New York, 2002.

[16] B. A. Bechky, Sharing meaning across occupational communities: the transformation of understanding on a production floor, *Organ. Sci.*, 2003, Vol. 14, No. 3, pp. 312–330.

[17] C. Voss, N. Tsikriktsis, and M. Frohlich, Case research in operations management, *Int. J. Oper. Manag. Prod.*, 2002, Vol. 22, No. 2, pp. 195–219.

[18] M. Miles, A. Huberman, and J. Saldana, *Qualitative data analysis: an expanded sourcebook (4th ed.),* SAGE Publications, Thousand Oaks, 2019.

[19] P. Wlazlak, K. Säfsten, and P. Hilletofth, Original equipment manufacturer (OEM)-supplier integration to prepare for production ramp-up, *J. Manuf. Technol. Manag.*, 2019, Vol. 30, No. 2, pp. 506-530.

[20] K. Säfsten, G. Johansson, N.Lakemond, and T.Magnusson, Interface challenges and managerial issues in the industrial innovation process, *J. Manuf. Technol. Manag.*, 2014, Vol. 25, No. 2, pp. 218–239.

[21] S. Lattanzio, E. Carey, A. Hultin, G. Parry, L.B. Newnes, Transdisciplinarity within the academic engineering literature, *International Journal of Agile Systems and Management*, 2020, Vol. 13(2), pp. 213-232.

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An Approach Based on Advanced Manufacturing for Replacement Parts in Equipment Maintenance Context

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Abstract. Currently, in the context of equipment maintenance, new techniques for replacing parts and components are being discussed in order to ensure better performance. Seeking to optimize this process, this research proposes the development of a conceptual model that should work as methodology for the manufacture of replacement parts using the tools and concepts of Advanced Manufacturing. The research uses a methodology that excels in pre-processing information before modelling. First, a bibliographic research was carried out to obtain knowledge about Advanced Manufacturing in Industry 4.0, with emphasis on the domains of Additive Manufacturing, with a focus on testing by software. The method consists of the previous Project Feasibility Analysis, the Metrology fundamentals for data collection, until the manufacture of the part to be replaced. According to the analyses provided in this study, the results obtained meet the proposed criteria, in order to certify the quality of manufactured parts and making them feasible in terms of time and values. The research demonstrated an alternative to the traditional models of the maintenance process, using new techniques based on the Advanced Manufacturing models.

Keywords. Advanced Manufacturing; Pre-processing information; Industry 4.0.

Introduction

Increased productivity, time optimization and cost reduction are some of the pillars that companies are looking for currently, and within this context, a key point that guarantees the performance of machines and equipment, is maintenance, with the objective of maintaining the availability and eliminate defects that directly interfere with product quality. Thus, the replacement of damaged parts becomes a significant element in terms of corrective maintenance, based on the time of use or the physical condition of the part.

Many companies choose to purchase the parts to be replaced with the best applicability and quality in mind, ensuring the smooth operation of their equipment. This scenario results in high costs, due to the price of parts and the other taxes imposed on the importation of products and transport, as well as the estimated time for delivery, due to manufacturing and displacement until the replacement of the part in the field, requiring advanced planning, which is not possible in urgent cases, causing the machine to be unavailable for production due to the lack of the part immediately. The shorter the waiting time, the higher the service level of the supply chain [1].

This research focuses on optimizing the process of replacing parts for maintenance, ensuring the quality and applicability necessary for the proper functioning of machines and equipment.

The transdisciplinary nature of this study integrates the scientific and technical knowledge of manufacturing and the elements that govern the maintenance of equipment, developing a unified method on the different fronts of knowledge and science. As shown in figure 1, within the context of product development, Digital Manufacturing and Additive Manufacturing offer new standards, which can be adopted for such circumstances, featuring better flexibility in the corrective parts maintenance process, which has developed a method based on the foundations of Metrology, in which pre-processing of information stands out before modeling, helping in reducing costs in later phases and, as stated in literature [2], increasing productivity by producing better with less resources.

1. Materials and Methods

This research proposes, in a systemic way, the development of a method that structures the manufacturing of replacement parts in the scenario of Advanced Manufacturing. This study has an applied nature and a qualitative character [3]. As a conceptual basis, knowledge was obtained through a bibliographic study on two fronts: Additive Manufacturing and its manufacturing concepts, and Digital Manufacturing, with a focus on current structured methods.

Figure 1. Methodological Procedures.

In order to obtain a solid base on those of advanced techniques in relation to manufacturing, the Conceptual Background addresses a qualitative review on Digital Manufacturing methods and Additive manufacturing methods.

The Method Development consists on developing a method with an emphasis on information pre-processing, using the fundamentals of preventive and corrective maintenance, as well as the fundamentals of Metrology in an Advanced Manufacturing scenario.

The Application of this study will be based on an experimental case, applied to a mechatronic equipment present in a Brazilian Pulp and Paper industry, aiming to optimize the Corrective Maintenance process. The Results and Discussion integrates the analyzes carried out in this study, in order to demonstrate an alternative means for replacing Maintenance parts.

2. Conceptual Background

The conceptual background revolves in a qualitative literature review conducted in the online scientific portal of the Brazilian Coordination for Improvement of Higher education Personnel (CAPES), which is an aggregator of more six-hundred scientific bases (including Springer, Scopus, IEEE, and others). Researched themes were Digital Manufacturing Application Methods and Additive Manufacturing.

2.1 *Digital Manufacturing application methods*

According to literature, some of the found methods of application for Digital Manufaturing of products were analysed and organised in a schema which demonstrates their step-by-step approach. Figure 2 depicts the analysed methods.

Volpato *et al.*	CAD ->	CAM ->	STL ->	Obtaining the Model ->	Manufacturing ->	Post-Processing
Rodriguez *et al.*	CAD ->	CAM/CAPP ->	STL ->	File Slicing ->	Manufacturing ->	Finishing
Cunico *et al.*	CAD ->	STL ->		File Slicing ->	Post-Processing ->	Finishing
Canciglieri *et al.*	Pre-Processing Information ->	CAD ->	CAE ->	CAM ->	Manufacturing ->	Post-Processing

Figure 2. Digital Manufacturing application methods

As seen in Volpato [4], the CAM complements the stage of digital CAD development, with the orientations of the part and support structures, proceeding to direct manufacturing and post-processing in layers, defining the stage of finishing the part.

In Rodriguez *et al.* [5], The toolpaths for each layer in the CAM step and a CAPP post-processing, and sequentially, the fabrication of the part can be inspected to determine dimensional and/or geometric errors in the slicing step [6].

In contrast, in Cunico [7] five steps related to manufacturing processing, divided into CAD modeling, conversion into STL machine language, layers of processing; layer-by-layer construction; post-processing and finishing.

As seen in Canciglieri *et al.* [8], the method started by obtaining preliminary information from clients, characterised as patients in this study, applying the analysis in a Dental Product Case. Subsequently, the product was designed in CAD, and carried out tests in CAE software, as well as the planning of CAM process. When manufacturing, there is a need for post-processing of the printed part.

The method served as the basis for this study [8], given the opportunity to expand the method and go deeper in Pre-Processing, migrating to the manufacture of spare parts in an environment of maintenance of equipment and machines, with emphasis on the survey information and prior feasibility analysis, which characterize this project

2.2 Additive Manufacturing

Three-dimensional printing represents, in a generalized way, several techniques to create an object starting from the project in software or radiographic data. Each type of 3D printing exemplifies materials of different requirements, costs and effectiveness [9][10]. To provide a more comprehensive view, Figure 3 demonstrates 3D printing methods taking into account in this research.

Types	Composition	Process	Advantages	Disadvantages	Costs
SLA	Liquid Resin	UV Exposure	High Resolution	Long Printing Times	High Costs
Clip	Liquid Resin	Liquid Resin Pool	High Resolution	Long Printing Times	High Costs
MJP	Liquid Resin	Light Curing	Low Maintenance	Drops Materials	High Costs
BJP	Powder Base	By Layers	Small and Silent	Post Processing	Affordable Costs
SLS	Binding Substance	By Layers	Any Material	Limited Resolution	High Costs
FDM	Solid Thermoplastic Filament	By Layers	Most Common and Accessible	Low Resolution	Low Costs

Figure 3. Additive Manufacturing Techniques. Adapted from Crafts *et al.* (2017)

In a comparison of all methods SLA is a polymerization method where the precursor layers of the liquid are sequentially exposed to ultraviolet (UV) light, and thus selectively solidified [11][12]. The Multijet process (MJP) is very similar to the process of a conventional printer, where the material and an agent are ejected from the head, the same way as an ink printer, which the name makes an analogy [13]. Folder jet printing (BJP) differs from the other methods above, in which a powder base is used with the binding substance. After drying, materials added to the powder and binder may include metals, glass and sand [9]. SLM or SLS is a powder bed melting process, in which selective regions of the powder particles are melted and fused by a high intensity laser energy source, layer by layer according to computer aided design (CAD) [6][14]. The liquid thermoplastic FDM material is deposited in ultrafine layers on a substrate. The material is heated one degree above its melting point so that it immediately solidifies after extrusion [15].

According to literature, the printing methods have different characteristics, resulting in a range of printing options for each required application. The approach of this study corresponds to the FDM method, in which it is characterized by the simplification of printing and common availability in the academic, business and social environment.

2.3 3D Printing in Maintenance

The importance of maintenance for manufacturing systems leads to the creation of several maintenance goals, each of which is applicable to a specific manufacturing system [16].

According to Camargo et al. [17], the new technological revolution brings advantages for industrial maintenance, making it available in a shorter repair time and greater availability of machinery, given the savings in the purchase of preparation parts and ease in handling the 3D printer.

The technology has the ability to print from simple to more complex parts, so that they can replace part of the materials of original parts and meet the needs of the industry in terms of maintenance [18].

It is a relatively new field and could contribute to the expansion of development in this area, deepening the inclusion of these technologies in the development and implementation of maintenance activities and systems [19].

3. Proposal

This research is developed under the process of Corrective Maintenance of parts in mechatronic equipment, in which it is based on the analysis of the data and properties collected for purposes of comparison between the methods currently adopted in the companies.

The proposed method is a variation of the model "Conceptual proposal for an advanced manufacturing model with an emphasis on creating dental prosthesis prototypes in jaws" [8] adhered to the Manufacturing process, with emphasis on Pre-processing of information before modeling.

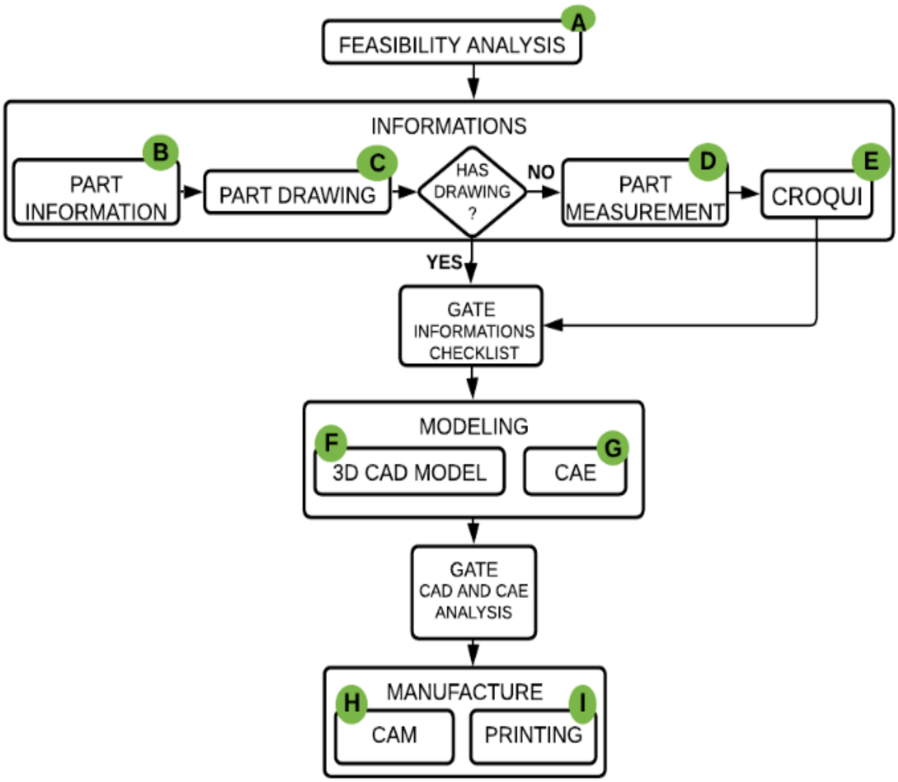

Figure 4. Proposed Method

Figure 4 describes the systemic method for the development of the project. The viability of the part consists of the analysis of data and information about the process of replacing parts in the current concept of the company. The analysis foresees the accounting survey of the acquisition of replacement parts, such as transport values, imports, insurance, taxes and material value.The costs raised in this analysis must be higher than the cost of manufacturing by additive manufacturing, to justify the application of this method, *in loco* to the company (Detail A of Figure 4).

The data collection covers technical characteristics present in the operation and maintenance manuals of the equipment, such as geometric diagrams, technical drawings and the work mode of the part.

According to the performance, the part undergoes constant efforts in its structure, and this factor generates deformations and wear with the time of use. The analysis corresponds to the way in which the part acts on the equipment, such as: direct contact of the part with the equipment structures, mechanical efforts, equipment under pneumatic or hydraulic pressure, performance under high temperatures, humid or submerged environments, among others (Detail B of Figure 4).

The technical drawing provides the necessary information for the understanding and construction of the part, thus facilitating the transposition of the information to a CAD software (Detail C of Figure 4).

In the absence of a technical drawing, this study values the techniques and foundations of Metrology to perform the necessary measurements of the piece, considering all faces and angles, which are fundamental for digital development (Detail D of Figure 4).

After collecting the measurements of the piece, the representation of the sketch is given by the practice of hand drawing, and according to the information represented, that the virtual model will be definitively molded in the modeling stage (Detail E of Figure 4). For the realization of the virtual model, a CAD software will be used, due to the ease of operation and interaction with the user. Among other characteristics, the models clearly demonstrate the architecture of the piece, being able to edit the project at any time during its projection (Detail F of Figure 4).

After the three-dimensional development, the analysis by the CAE system consists of testing the physical properties of the material, thus certifying the quality and applicability of the piece. With the result showing to be satisfactory, the stage proceeds to the manufacture of the part (Detail G of Figure 4). The CAM phase addresses the details of the manufacturing process, assisting the supervisory of the printing method in relation to the tool, material quantity, final touch and the time established according to the design of the part (Detail H of Figure 4).

The final step consists of printing the piece, based on the settings and parameters established during the study in a methodological manner, according to the printing characteristic (Detail I of Figure 4).

4. Application

The application of the study is characterized as a pilot study (preliminary application), which is directed to a Mechatronic equipment, present in a Brazilian company of Pulp and Paper. The analysis focuses on a pulley, which acts mechanically as a guide under a seal of internal sealing of the equipment, making it possible to analyze and develop the method covered in this research. Currently, the company has eight key small components of high impact in the manufacturingin process in a similar scenario as the selected part, in which the cost of purchasing and replacing original parts generates higher costs for the company. Such parts correspond to rollers, cable and hose carriers, equipment protections, specific tools, and obsolete replacement parts.

The focus of application is on the corrective maintenance process of the studied company. Corrective maintenance in the company occurs when the physical condition of the part in the field has deteriorated and use time has been overdue. The former occurs at random times during production and the latter is based on manufacturer's recommendation. In the fisrt scenario, there is tardiness in the maintenance response if there are more than two stops in a three-week period (average lead-time to receive replacement parts from manufacturer), resulting in the unavailability of the machine and generating consequences to the entire business chain, from spending on raw materials and wasted energy to delays in delivering the final product to customers. In another aspect, ordering extra replacement parts from the manufacturer imply in higher costs and aproximately doubles the storage cost for the parts in the company. Thus, the lead-time of arrival of replacement parts ends up generating costs and affects the whole operation.

The data obtained were taken from the company's software and contact with suppliers of the part. The cost per unit of the pulley is currently $ 17.00. Based on market research, the cost per kg of a material for the Additive Manufacturing method is $ 15.00, which considers the possible multiple manufacture of parts with only 1 kg offered in the national market.

The material of the pulley was possible to obtain under consultation to the manual and using the visual method, certifying the use of Polyacetal to manufacture the part. For the purpose of comparison and applicability, the properties of the Acrylonitrile Butadiene Styrene (ABS) material, used for manufacturing under the Additive Manufacturing method, were analyzed together. The collections of material information are represented in Table 1, based on sources [20] [21] [22]:

Properties	Polyacetal	ABS
Tensile Strength (MPa)	70	32
Toughness (MPa)	170	74
Short-Term Temperature (°C)	110	75
Long-Lasting Temperature (°C)	150	100

Table 1: Material Information

The mechanical and thermal properties of both materials, demonstrate a difference in relation to some parameters, highlighting a good performance in relation to temperature resistance. The application equipment has an average internal temperature of 45 ° C, which results in the good applicability of the ABS material, whose long-term temperature is 100 ° C. The higher the values of properties, the better the material's strength and applicability.

The design and measurements of the piece were obtained manually, using measurement instruments according to the concepts of Metrology, considering all the faces and edges of the piece for the previous elaboration of a sketch.

According to the Sketch, the modeling is performed with the aid of a CAD Software, as described in Detail A of Figure 5, in which later its properties are tested and certified according to the CAE Software. The modeling and simulation results in the CAE stage represented graphically the following analyzes in relation to their natural state, using the properties of the ABS material to carry out the simulations.

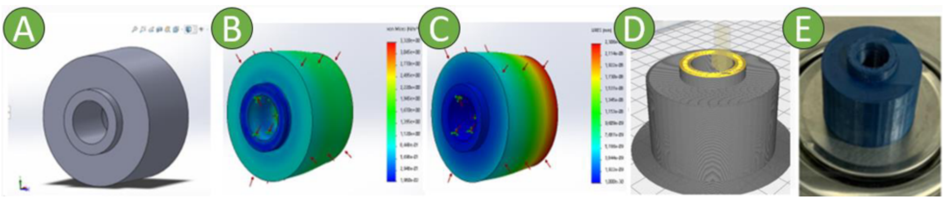

Figure 5: Modelling and Manufacturing

For the representation of Von Mises Stress simulation, we had a point where there was greater criticality, with the stresses of 4,161x10 ^ 02 N / m ^ 2. In general, the points at which the pulley is exposed to constant forces, present a result between 3.572x10 ^ 02 and 1.807x10 ^ 02, with no wear or deformation depending on the applied actions, as described in Detail B of Figure 5.

The static displacement analysis, described in Detail C of Figure 5 obtained a displaced sample in the fixation region, where it presents a value of 2.306x10 ^ -08 mm. The distributed result obtains values between 1,000x10 ^ -30 to 1,730x10 ^ -08, which does not imply significantly to the point of preventing the manufacture and use of the part with the selected material, due to the low impact on the performance of the equipment. The levels presented in the simulation demonstrate the resulting effect on the piece, in which the criterion of indications is adopted to guarantee the quality of the material in relation to its application. The results obtained in the analysis and information gathering certify the quality and applicability of the project, where the impact remains under the lowest levels in the simulation, which is adopted as an acceptable criterion, thus destining the manufacture of the part.

Detail D of Figure 5 represents the CAM stage and Detail E of Figure 5 the three-dimensional impression of the piece. According to the related works of this research, the FDM mode has been used to manufacture the part, according to the character of the 3D printer.

In this context, the application described is characterized as a pilot study of the method in a real application, in which it analyzes the results in an empirical way, being able to be applied in the other components in similar scenarios. Thus, in the scope of corrective maintenance, the application of the method addressed in this study can be extended to other processes in maintenance or manufacturing, involving different equipment and technical areas, reducing time and cost, ensuring the necessary quality for the proper functioning of the equipment.

5. Results and Discussion

The proposed method brings points in which the analysis allows its applicability, with emphasis on the questions of cost and time, describing the comparison between the current processes adopted by the company in relation to Corrective maintenance in equipment.

The pre-processing of information allowed a general analysis of the environment and the functionality in which the part and the equipment are located, aiming at the optimization of the process according to its feasibility.

In question, the company adopts a flow for the acquisition of spare parts, which describes itself from the need to check the condition of the part in the field, to the request for direct purchase with suppliers of the part or equipment. The estimated time after the purchase of the part takes the equivalent of 5 to 7 working days for the delivery of the product.

Variable	Before	After
Time	5 to 7 days	5 to 6 hours
Costs	17 $ per part	0.30 $ per part
Amount of Material	60g	20g

Table 2: Before and After Comparison

According to the application described in this study, the Additive Manufacturing method corresponds to an 86% reduction in delivery time, due to the fact that the manufacturing lasts an average of 5 to 6 hours, according to the expected quality.

Based on the analysis of the methods covered in the literature, according to the availability at the place of application of this study, the FDM printing method met the quality requirements.

Under the availability of material on the market, the sale of raw material to a 3D printer corresponds to 1 kg of material, in which multiple pieces can be manufactured, which use an average of 20g of material for each pulley, resulting in 50 units costing $0,30 cents a Dollar each. Production possibilities, and according to the analyzes and simulations by Digital Manufacturing, the material used for the manufacture of the pulley keeps the minimum requirements to guarantee a useful life time for the equipment.

In terms of materials, the comparison between the pieces is a 40g reduction using the Additive Manufacturing method, considering the absence of material loss in the manufacture and the quality guarantee using the ABS material for the manufacture of the piece, which aims at this study.

The modeling based on the principles of Advanced Manufacturing resulted in the guarantee that other materials can be adopted in the manufacture of the parts that will be replaced, maintaining the quality and applicability necessary for the proper functioning of the equipment.

As a result, the application of this method becomes feasible in order to manufacture the part *in loco* the company in which this study was developed, allowing the reduction of waiting time for the acquired part and the high cost due to the external purchase of the part, which requires advance planning.

6. Conclusion

In view of the preventive and corrective Maintenance scenario, this study proposed a systemic method in which it addresses the fundamentals of Digital Manufacturing with an emphasis on Additive Manufacturing, based on the pre-processing of information under Metrology principles.

The study showed improvement in the replacement parts scenario, addressing the requirements of time of acquisition and availability, and the cost of purchasing the necessary part, thus optimizing the process of replacing damaged parts. Therefore, it is possible to apply the method addressed in this case in face of other corrective and preventive Maintenance processes, as well as an alternative method for manufacturing parts for replacement.

As a future proposal for the application of the method described in this study, other processes in maintenance or manufacturing are suggested, involving different equipment and parts, covering various technical areas such as mechanics, electrical, electronics, among others. The results could improve the method and its limitations for optimizations in preventive and predictive analyzes in equipment, as well as providing a study related to Prescriptive Maintenance, intended for Industry 4.0.

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References

[1] D.J. Bowersox, D.J. Closs, M.B. Cooper, J. C. Bowersox, *Gestão Logística da Cadeia de Suprimentos*. 4. ed. Amgh, Porto Alegre, 2013.

[2] V.F. Campos, *TQC- Controle Da Qualidade Total - No Estilo Japonês*. 9. ed. Falconi, Belo Horizonte, 2013.

[3] D. E. Gray, *Pesquisa no mundo real*. Editora Penso, Porto Alegre, 2012.

[4] N. Volpato, *Manufatura aditiva: tecnologias e aplicações da impressão*, 3d. Blucher, São Paulo, 2017.

[5] E. Rodriguez, R. Bonnard, A. Álvares, Avances en el desarrollo de un sistema de manufactura aditiva basado en STEP-NC. *Revista Produção e Desenvolvimento*, 2018, Vol.4, No. 1, pp. 39-53. DOI: https://doi.org/10.32358/rpd.2018.v4.310.

[6] M. Gupta, *3D Printing of Metals*. Mdpi, Singapore, 2017. https://doi.org/10.3390/books978-3-03842-592-2.

[7] M.W.M. Cunico, *Impressoras 3D: o novo meio produtivo*. Concep3D Pesquisas Científicas Ltda, Curitiba, 2015.

[8] M.B. Canciglieri, A.F.C.S. Leite, A.L. Szejka, O. Canciglieri júnior, An approach for dental prosthesis design and manufacturing through rapid manufacturing technologies. *International Journal of Computer Integrated Manufacturing*. 2019, pp. 832-847.

[9] T.D. Crafts, S.E. Ellsperman, T.J. Wannemuehler, T.D. Bellicchi, T.Z. Shipchandler, A.V. Mantravadi, *Three-Dimensional Printing and Its Applications in Otorhinolaryngology: head and neck surgery*. Sage, Indianapolis, 2017.

[10] I. Gibson, D.W. Rosen, B. Stucker, *Additive Manufacturing Technologies: rapid prototyping to direct digital manufacturing*. Springer, New York, 2010.

[11] A. Biahmou et al., Towards agile enterprise rights management in engineering collaboration, *International Journal of Agile Systems and Management*, 2016, Vol. 9(4), pp. 302-325.

[12] Z. Weng, Y. Zhou, W. Lin, T. Senthil, L. Wu, *Structure-property relationship of nano enhanced stereolithography resin for desktop SLA 3D printer*. Elsevier, Beijing, 2016.

[13] V. CABREIRA, *Avaliação Dos Parâmetros De Processamento Em Impresão 3d Nas Propriedades Do Poliácido Lático*. 2018. 104 f. Monografia (Especialização) - Curso de Programa de Pós Graduação em Engenharia de M, Escola de Engenharia, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2018.

[14] S. Sun, B.R. Ramachandran, C.D. Wick, Solid, liquid, and interfacial properties of TiAl alloys: : parameterization of a new modified embedded atom method model. *Journal Of Physics: Condensed Matter*, 2017, pp. 1-12.

[15] T.s. Srivatsan, T.s. Sudarshan, *Additive Manufacturing: innovations, advances, and applications*. CRC Press Taylor & Francis Group, Boca Raton, 2016.

[16] A. Shahin, H. Shirouyehzad, E. Pourjavad, Optimum maintenance strategy: A case study in the mining industry. *International Journal of Services and Operations Management*, 2012, Vol. 12, No. 3, pp. 368–386.

[17] G.R.R. Camargo, P.A.G. Barbosa, F.d.A Santos, *3D Printing in Industrial Maintenance and Cost Reduction*. 2021. 26 f. Curso de Tecnologia em Gestão Financeira, Faculdade de Tecnologia do Estado de São Paulo, Osasco, São Pulo, 2021.

[18] G.A.A. Lopes, E.V.C. Galdamez, *Additive Manufacturing for the Production of Maintenance Parts*. 2018. 39 f. Curso de Engenharia de Produção, Centro de Tecnologia, Universidade Estadual de Maringá, Maringá – Paraná, Brazil, 2018.

[19] D.R.T. Velázquez, A.L. Helleno, C.R.C. Lima, L.H. Mastrapa, *Implications of Hybrid Manufacturing Technologies on Parts Repair and Remanufacturing Processes in Maintenance Context: A Systematic Review*. 2020. 21 f. Curso de Engenharia de Produção, Universidade Católica do Rio de Janeiro, Piracicaba, Brazil, 2020.

[20] B.d.S. Souza, *Replacement of polyacetal for polypropylene in the clothespin structure*. 2018. 57 f. TCC (Graduação) - Curso de Production Engineering, Santo Amaro University, São Paulo, 2018.

[21] M. Vasina, K. Monkova, P.P. Monka, D. Kozak, J. Tkac, Study of the Sound Absorption Properties of 3D-Printed Open-Porous ABS Material Structures, *Polymers* , 2020, Vol. 12, no. 5: 1062.

[22] FISQP - FICHA DE INFORMAÇÃO DE SEGURANÇA PARA PRODUTOS QUÍMICOS. **NBR-14.725**: TECARAN ABS grey - Semiacabados. 1 ed. Ensiger, São Leopoldo, 2020.

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Carbon Fiber Composites Application and Recycling in Kazakhstan and Neighboring Countries

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Abstract. The use of carbon fiber reinforced polymers (CFRPs) has expanded in many industries due to superior properties compared to traditional materials. Nevertheless, their recycling is challenged by immature recycling market and poor legislative support. This study evaluates the application and disposal of CFRPs within the different industries in Kazakhstan. The study adopted a market-based analysis approach to understand the up-to-date levels of application of CFRPs across manufacturing, construction, aviation, and other relevant industries of Kazakhstan. The study also considered CFRP markets and associated recycling practices in neighboring countries such as China and Russia which have a significant impact on Kazakhstan in terms of import and export of materials and waste. The research findings indicate that the application of CFRPs varies among industries, construction being the most prominent, however, their recycling is not as organized as in other waste types such as plastic, metals, etc. Russia and China will be generating thousands of tonnes of CFRP waste originating from the wind turbine and aviation sectors in future, from which Kazakhstan may also see some benefits. The findings of the study are deemed to be useful for the government of Kazakhstan and waste recycling associated stakeholders for future considerations.

Keywords. CFRP, recycling, Kazakhstan, Carbon Fiber Composites

Introduction

Carbon fiber reinforced polymer (CFRP) is an increasingly popular material in various industries ranging from aerospace engineering to wind turbine blades and sports equipment manufacturing. The main advantages of this material over other alternatives are superior mechanical resistance, higher stiffness, and lighter weight [1, 2]. The need for lightweight material, for example, in the automotive and aviation industries, as well as the urgent need for decreasing CO_2 emissions, can also be considered as drivers for CFRP-related market development. These advantages and drivers could be among the

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reasons boosting the global demand for CFRPs which is rapidly increasing and is expected to reach up to 200 kilotons by 2022, while the global revenue of CFRP is going to grow from $17.1 billion in 2020 to more than $31.5 billion by 2025[3]. The downside of this trend is the major environmental challenges resulting from composite materials manufacturing (up to 40% becomes waste during manufacturing CRFP which is predicted to translate into 31000 metric tons of waste in 2021) and end-of-life (EOL) products [4, 5]. Currently, only a few countries have carbon fiber recycling plants at an industrial scale (see Table 1). Moreover, most of the recycling plants tend to be located far from the waste collection and production locations which makes transportation costly and challenging. Overall, the carbon fiber composite materials recycling market is underdeveloped due to challenges, for example, with the supply chain. As a result, a great proportion of the CFRP waste ends up in landfills or sent for incineration, which are not complying with legislations and sustainability [6].

Table 1. Current CFRP recycling companies with a capacity of more than 1000 metric tons/year.

Recycling company	Recycling Technology	Capacity (ton/year)	Website	Sources
Carbon Conversions (USA)	Pyrolysis	1800	https://carbonconversions.com/	[7]
CFK Valley Stade Recycling GmbH & Co KG (Germany)	Pyrolysis	1000	https://www.cfk-recycling.de/	[8]
ELG Carbon Fibre (UK)	Pyrolysis	1700	https://www.elgcf.com/	[9]
Karborek RCF (Italy)	Pyrolysis	1500	http://www.karborekrcf.it/	[10]
SGL Automotive Carbon Fibres US site	Pyrolysis, uses released gas as an energy source	1500	https://www.sglcarbon.com/	[6]
Toray Industries (Japan)	Pyrolysis	1000	https://www.toray.com/	[6]

Another potential reason for the underdevelopment of composite waste management could be linked to poor legislative support and targeted regulations for composite materials disposal. For example, in the EU, there are only requirements for the amount of CFRP material that needs to be recovered or recycled from EOL vehicles according to the 2000/53/EC EU Directive stipulated. According to Delvere et al. [11], the amount of CFRP waste will reach 165000 metric tons in the USA and 145000 metric tons in Europe by 2050.

The industry range where CFRP is used is widening. For example, the demand for carbon fiber in the aerospace industry reached 26000 metric tons in 2020 due to the increased application of the material in commercial aircraft manufacturing such as Boeing 787 and Airbus A350 models [4]. Moreover, the sports inventory industry is actively applying CFRP in the production of sports equipment such as bicycles by creating an estimated demand for CFRP of 15 kilotons in 2020 [4]. Lastly, there is a growing trend in using CFRP in wind turbine blade manufacturing because the material allows making huge blades with less cost and weight.

This research aims to explore the current status of application of the composite materials in Kazakhstan and evaluate their recycling opportunities. The market of neighboring countries such as Russia and China were also considered in a comparative analysis due to their potential and volume of use of CFRPs. It was also important to consider these countries due to the high volume of import and export of materials and waste in and out of Kazakhstan. For this purpose, the markets of carbon fibers within Kazakhstan and neighboring countries were analyzed to reflect current levels of utilization across industries by bringing a transdisciplinary approach to the problem. Exploration of the current recycling state of composite recycling in the region requires not only a deep understanding of recycling techniques and economic aspects but also the linking of these concepts through a real-world context.

To achieve the aim, among others, the wind turbine and aerospace industry were analyzed in order to determine the potential CFRP waste volumes. Besides, the local market of carbon fiber products was analyzed to determine the main players and current development levels. It is important to mention that the data on carbon fiber materials supply and use balance was provided by the Bureau of National Statistics of the Republic of Kazakhstan.

1. Application of CFRP and recycling associated waste in Kazakhstan and neighboring countries

Kazakhstan and its neighboring countries such as Russia and China are reported to be associated with CFRP waste. This section investigates the industries where CFRP is used the most and attempts to evaluate the potential waste available in these countries.

1.1. Kazakhstan

In order to assess the impact of recycling carbon fiber waste in Kazakhstan, it was necessary to estimate the potential volume of CFRP waste originating from commercial aviation and wind power sectors, as the overwhelming majority of CFRP is used in mentioned industries (36% and 13% of global demand corresponded to aviation and wind turbine sectors respectively in 2020) [12]. However, based on the research findings it can be stated that air fleet size and wind turbine numbers in Kazakhstan are not increasing at the pace which would make recycling issues critical. The size of the fleet employed by the main commercial airlines does not exceed 100 planes which are mainly leased from foreign counterparts for specific time periods [13]. This implies that the airplanes are returned after the end of the lease term which means that the waste does not stay in Kazakhstan.

In terms of the wind turbines sector, currently there are 22 wind turbine stations operating in Kazakhstan with a total capacity of 404 MW energy generation whereas the total renewable energy capacity (including solar panels and hydroelectric power stations) is 1500 MW [14]. Assuming that 1kW capacity requires 10 kg of rotor blade (6% of which CFRP), the potential CFRP waste from the current installed wind turbines is estimated to be 242 tons [12]. However, 45% of all the renewable energy generated in Kazakhstan during 2020 was linked to wind turbines which shows the potential of this type of energy in the country [15]. Also, the Kazakhstani government is planning to increase the share of renewable energy power up to 10% and 50% in 2030 and 2050, respectively [16]. Based on these facts, it can be stated that the wind turbine sector of Kazakhstan might generate thousands of tons of CFRP waste in a foreseeable future and cause issues if not recycled or disposed sustainably.

According to the Bureau of National Statistics [17], carbon fiber products in a form of prepregs, mats, and laminates are not in great demand, though the usage of carbon fiber reinforced composites is becoming more popular. The application of carbon fibers varies among industries, construction being prominent. CFRP products are widely used for reinforcements in load-bearing structures such as columns and beams. Figure 1 represents the levels of carbon fiber utilization in Kazakhstan, which was extracted from the commodity nomenclature “carbon fibers and products from them” [17]. It is evident from Figure 1 that the total volume of CFRP used in Kazakhstan is increasing every year. However, it is noted that during the year of 2020 import levels of carbon fiber products to Kazakhstan have decreased due to the COVID-19 pandemic.

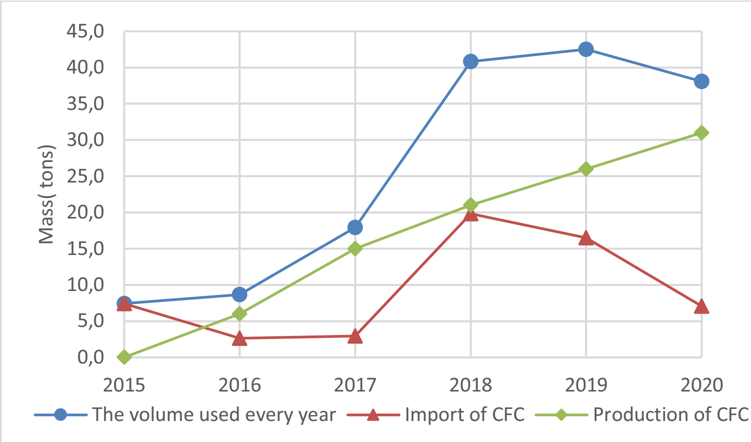

Figure 1. Carbon fiber materials’ turnover in Kazakhstan between 2015-2020.

As was expected, the import and export volumes of carbon fiber materials are extremely small in comparison to the export and import rates of cheaper composite material - glass fiber products as illustrated in Figure 2. This is because glass fibers are cheaper and extensively used in a range of industries such as automotive, construction, energy sector, etc. [18]

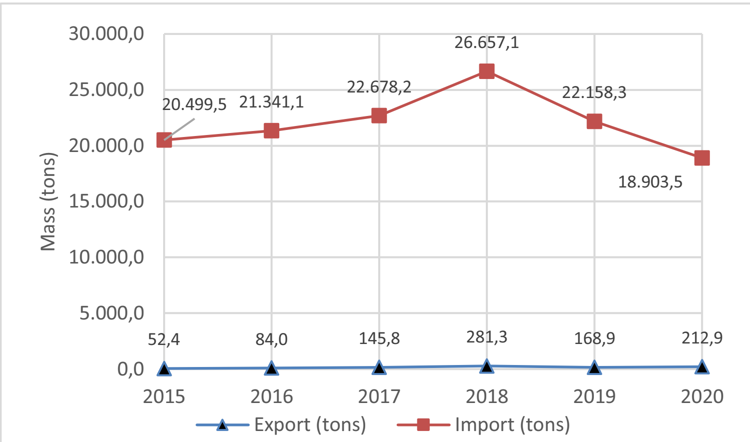

Figure 2. Import and Export of Glass Fiber Materials in Kazakhstan 2015-2020.

The recycling of CFRP in Kazakhstan is not as organized as in other waste types such as plastic, metals, etc. Although there is a wide-scale supply of CFRPs to the market, there is no comprehensive system in place which would allow the same scale recycling.

1.2. Players in Carbon Fiber Market in Kazakhstan.

It is clear from the previous section that the application of carbon fiber in Kazakhstan is limited in terms of total volumes, though there are several companies that are involved in manufacturing or retailing carbon fiber products. For example, a company called "Kaztechnoinnovations" deals with the manufacturing of composite parts up to 6 m in length using the methods of molding, vacuum bagging, and pultrusion [19]. There is another worth-mentioning company "Most&K" (the official representative of "Compozit" LLC Russia, partner of UMATEX) which strengthens structural parts of old buildings, industrial facilities, and bridges using carbon fiber composites. The company had prior success in strengthening reinforced concrete structures of a shopping mall and a 24-story building in two cities using carbon fiber tapes and lamels in Kazakhstan [20]. The company also promotes chopped and milled carbon fiber as a filler for application in concrete structures. The other companies are only involved in the retail and wholesale of carbon fiber products mostly produced in Russia and China. The list of mentioned companies is provided in Table 2.

Table 2. Companies in Kazakhstan selling carbon fiber products.

Company name	Description	Website
KAZTECHNOINNOVATIONS	Small machine shop of composite manufacturing parts up to 6 m in length	http://www.kti.kz/
VASTE	Manufacturing of glass fiber composites, the largest wholesaler of carbon fiber materials in Kazakhstan	https://vaste.satu.kz.
MOST&K	A young company specializing in the retail of carbon fiber products, including chopped and milled fiber	https://mostandk.kz/
Industrial.kz	Retailer of carbon fiber films	https://industrial.kz
BVBAlyans	Retailer of carbon fiber tubes	https://bvbalyans.kz/
Specmet.kz	Retailer of carbon fiber films	https://Specmet.kz

1.3. China

China is reported to have one of the largest carbon fiber and composite materials manufacturing setup. However, the country does not have legislative regulations or requirements for recycling CFRP waste. The EOL products are discharged mainly to landfills. However, currently, several research works are carried out to investigate the implementation of more cost-effective and efficient ways of CFRP recycling. For example, some authors propose using CFRP in the production of eco-efficient cement-based materials [12], and others study microwave thermolysis claiming to be more efficient compared to conventional thermolysis [21].

The main sectors where CFRP is predominantly used are commercial airplanes and wind turbine blade manufacturing. Akbar and Liew [12] have estimated the potential CFRP waste amounts in both sectors in China. Assuming 25 years lifespan, they estimated that around 22 and 75 thousand tons of waste from commercial aircraft and wind blades disposal respectively will be accumulated in landfills by 2044 if no recycling activities are undertaken [12]. Moreover, the Chinese wind power industry started developing rapidly from 2010 onwards, therefore, a substantial amount of waste is projected to be disposed from the year 2035 and will increase sharply exceeding the CFRP waste from the aeronautical sector [12].

CFRP material is used in different applications and subject to different operating conditions while in service. However, composite materials are designed to withstand high loads and complex fatigue for decades. For example, composite blades of wind turbines remain resistant to loads even after service time (20 – 25 years) [22]. China remains one of the leaders in the onshore wind industry and the number of composite material used in the wind energy sector is only increasing. In 2019, a record wind energy capacity was installed, and the total energy generation capacity reached almost 30 GW [23]. According to Liu and Barlow [24], 40% of the global blade waste will come from China (Figure 3), reaching several thousands of tons that need to be processed as early as possible. The immense future flows of potential CFRP waste from the aeronautical and wind turbine sectors can not be underestimated and necessary actions should be taken to address the issue.

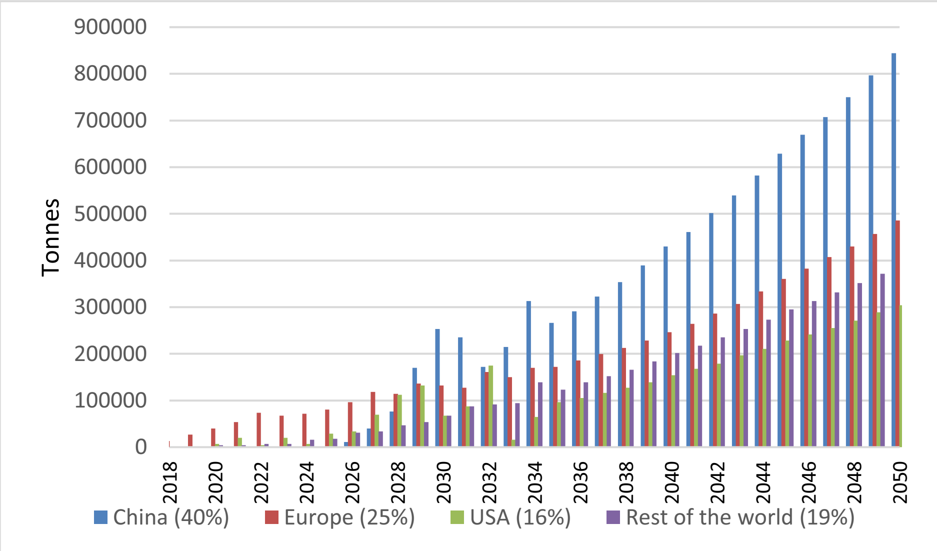

Figure 3. Potential wind turbine blade waste from 2018 to 2050 [24]

1.4. Russia

Russian waste management system is not well developed, with about 90% of waste going to landfills, and with no well-established culture of recycling, waste separation, and incineration [25]. The capacity of existing landfills is reaching its limit and they are extremely dangerous for the environment as toxic gases are released. However, the public and government raised a concern related to the growing number of landfills and waste management issues. Therefore, in 2018, the new national project named “Ecology” was initiated to protect the environment according to which all unauthorized landfills should be liquidated by 2024. These steps towards waste management are expected to eventually lead to the need for CFRP waste management too. At present, Russia does not only utilizes products made from CFRP but also produces them. “UMATEX group”, for example, which is a part of the state corporation “Rosatom”, produces carbon fiber composites used in construction, shipbuilding, automotive, and other industries. Key customers of their products are local wind turbine blades and aircraft manufacturers [26].

The ZUKM plant, a division of mentioned “UMATEX group”, is testing new fiber cutting equipment that is envisaged to solve the problem with carbon fiber production-associated waste. This composite recycling system will allow the production of new products for the key enterprises of the Russian industry [27].

As was expected by experts’ estimation, the total volume of production of products from composite materials in Russia should have reached 120 thousand tons by 2020. However, this represents an insignificant share of the global composite market, which is dominated by China (28%), the United States (22%), the EU (14%) [28].

The Russian wind turbine energy industry is not at a comparable level as the Chinese, but the potential growth of this sector is inevitable. According to Russian legislation, the goal in the wind energy sector is to reach 3.35GWof power generation by 2024 and 4.5 GW by 2030 [29]. Assuming that to generate 1kW power 10kg of material (6% of which is CFRP) is used, the potential waste from wind turbine blade manufacturing is estimated to be 2.7 kilotons. As a result, Russia is expected to face the problem with composite materials related waste later and on a lesser scale due to the immaturity of the industry.

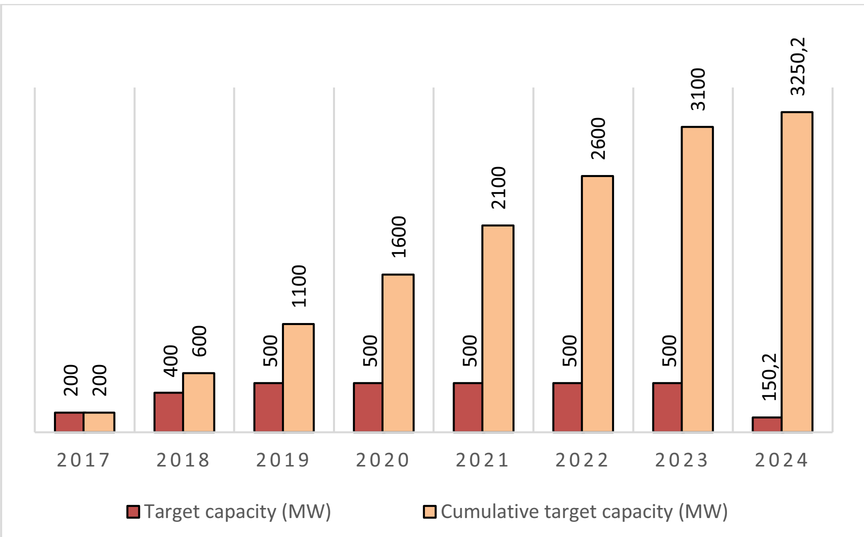

Figure 4. The Russian goal for installed wind power by 2024 [29].

In addition to the wind energy sector, Russian manufacturers use CFRP in the production of military and commercial aircraft. Until present, outdated aircraft are left at aircraft scrapyards after they are disposed which includes dismantling of the remaining important components [30]. The current disposal procedures would not be viable in the future as air transport building materials are replaced by others. Composite materials are now used instead of precious metals. Therefore, the correct disposal method would protect the environment, save lands from dumping waste, and bring benefits to the economy of the country [28].

The leading manufacturing enterprise in Russia, the "Tekhnologiya", produces up to 15 tons of components made of polymer composite materials (PCM) per year. These include components used for the tail of the promising domestic airliner MS-21, sound-absorbing structures for SAM-146, and PD-14 aircraft engines. A share of composite materials in manufacturing MS-21 and other Russian aircraft is up to 35% of the weight, while in previous generation aircrafts this segment was less than 10% [31].

The Russian government started considering composite materials as a viable material type since 2013 and, as a result, there is a steady growth in the production and consumption of various types of CFRPs [32]. Moreover, various standards and codes were introduced to ease and increase its application range [32]. Large manufacturers of carbon fiber composites (based on multilayer, single-layer nanotubes) are "Moscow Center for Nanotechnology", "Novosibirsk OCSiAl" and "Tambov Nanotechcenter LLC". There are also about 30-50 large manufacturers of composite materials and associated products in St. Petersburg and about 20-30 distributors of products and materials from other regions and countries [31].

2. Recommendations on CFRP recycling in Kazakhstan

Despite the numerous research efforts around carbon fiber waste recycling technologies, the recycling of CFRP has not been established in Kazakhstan. Nevertheless, the continuous increase of the wind turbine sector's output in the next three decades will generate thousands of tons of CFRP waste and will be sent to landfills or incinerated if not recycled. The utilization of CFRP in different sectors is becoming more popular, which will also eventually become a challenge and will need to be addressed. Hence, Kazakhstan needs to consider and integrate various recycling techniques, such as, for example, mechanical and thermal recycling. These techniques are known as the most tolerant and universal to different waste types and do not involve contaminants during chemical processes. Mechanically recycled products can be used as fillers for cement constructions, whereas pyrolysis might result in recycled fibers production which can further be reused in different non-structured elements. The potential waste from neighboring countries in substantial amounts which were described in the section above can also be beneficial as the supply chain of carbon fiber recycling is largely dependent on transportation distances. However, there are certain challenges regarding the transportation of CFRP waste. First of all, the products require initial size reduction before transportation which will have additional costs [33]. Secondly, distances from the source of waste to potential recycling site should be considered as they could impact the viability of the process. According to Li et al. [34], transportation costs constituted less than 1% of total costs for mechanical recycling of CFRP waste with 200 km of theoretical distance. Considering mechanical recycling is one of the cheapest methods of CFRP processing[35], transportation between neighboring countries should be justifiable, though optimization of routes and potential site location is a subject of further research. Manufacturers will need to commence centralized collections in their countries in order to boost economies of scale and minimize transportation costs and its environmental impact. Taking into account that Kazakhstan is located between two large countries, Kazakhstan might become a pioneer of more proactive recycling of composite materials. This can be done if necessary actions are taken at present including creating a scientific groundwork, developing commercially viable approaches, and eventually building recycling plants. Incorporating social concerns about CFRP waste in the region, economic viability, and the development of engineering solutions for recycling require a transdisciplinary approach. Further research could be the study on the viability of recycling in the region taking into account transportation, and comprehensive investigation of possible applications in a local context. Also, the findings of this work can be compared with the other countries and generalized in future.

3. Conclusion

This paper described and analyzed the current status of CFRP application and recycling in Kazakhstan and its neighboring countries such as Russia and China. The work analyzed the amount of CFRP waste from different industries including wind turbines and aeronautical sectors, including the current supply and balance sheet of CFRP products. It is found that the carbon fiber market of retail products is incomparably small in Kazakhstan. Nevertheless, the potential waste from the wind turbine manufacturing industry generated due to the plans of the government to increase wind turbine power may create certain challenges in the future. China and Russia will face significantly larger waste outputs from the end-of-life wind turbines and aircraft. This will ultimately develop a considerable CFRP waste capacity. All of these conditions might merge into an opportunity for Kazakhstan as a center for recycling CFRP waste in the region.

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References

[1] S. R. Naqvi, H. M. Prabhakara, E. A. Bramer, W. Dierkes, R. Akkerman, and G. Brem, A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy, *Resour. Conserv. Recycl.*, vol. 136, pp. 118–129, Sep. 2018.

[2] J. Wellekötter, J. Resch, S. Baz, G. T. Gresser, and C. Bonten, Insights into the Processing of Recycled Carbon Fibers via Injection Molding Compounding, *J. Compos. Sci.*, vol. 4, no. 4, p. 161, Oct. 2020.

[3] Markets and Markets, CF & CFRP Market by Source (Virgin, Recycled), Precursor (PAN, Pitch, Rayon), Resin (Thermosetting, Thermoplastic), Manufacturing Process, End-use Industry, and Region - Global Forecast to 2025, 2020.

[4] J. Zhang, V. S. Chevali, H. Wang, and C. Wang, Current status of carbon fibre and carbon fibre composites recycling, *Compos. Part B*, vol. 193, no. December 2019, p. 108053, 2020.

[5] A. K. Bledzki, H. Seidlitz, K. Goracy, M. Urbaniak, and J. J. Rösch, Recycling of Carbon Fiber Reinforced Composite Polymers—Review—Part 1: Volume of Production, Recycling Technologies, Legislative Aspects, *Polymers (Basel).*, vol. 13, no. 2, p. 300, Jan. 2021.

[6] F. Meng, E. A. Olivetti, Y. Zhao, J. C. Chang, S. J. Pickering, and J. McKechnie, Comparing Life Cycle Energy and Global Warming Potential of Carbon Fiber Composite Recycling Technologies and Waste Management Options, *ACS Sustain. Chem. Eng.*, vol. 6, no. 8, pp. 9854–9865, Aug. 2018.

[7] Carbon Conversions, 2021, *Facility*. Accessed: 10.01.2021. [Online]. Available: https://carbonconversions.com/facility/.

[8] CFK, 2010, *CFK Valley Stade Recycling GmbH & Co KG*. Accessed: 15.01.2021. [Online]. Available: https://www.cfk-recycling.de/index.php?id=57.

[9] ELG, 2018, *ELG Carbon Fibre accelerates UK expansion plans*. Accessed: 15.01.2021. [Online]. Available: https://www.elgcf.com/news/elg-carbon-fibre-accelerates-uk-expansion-plans.
[10] Karborek, 2021, *Company*. Accessed: 15.01.2021. [Online]. Available: http://www.karborekrcf.it/
[11] I. Delvere, M. Iltina, M. Shanbayev, A. Abildayeva, S. Kuzhamberdieva, and D. Blumberga, Evaluation of Polymer Matrix Composite Waste Recycling Methods, *Environ. Clim. Technol.*, vol. 23, no. 1, pp. 168–187, Jan. 2019.
[12] A. Akbar and K. M. Liew, Assessing recycling potential of carbon fiber reinforced plastic waste in production of eco-efficient cement-based materials, *J. Clean. Prod.*, vol. 274, p. 123001, Nov. 2020.
[13] IDFRK, 2021, *Leasing Of Air Transport*. Accessed: 15.01.2021. [Online]. Available: https://idfrk.kz/en/leasing/air-transport/.
[14] M. Baigarin, 2020, *План 2020 года по производству электроэнергии из возобновляемых источников выполнен*. Accessed: 15.01.2021. [Online]. Available: https://lenta.inform.kz/ru/plan-2020-goda-po-proizvodstvu-elektroenergii-iz-vozobnovlyaemyh-istochnikov-vypolnen-nurlan-nogaev_a3722534.
[15] A. Vidyanova, 2020, *Ветряные станции генерируют 45% электроэнергии ВИЭ*. Accessed: 20.01.2021 [Online].. Available: https://kapital.kz/economic/87654/vetryanyye-stantsii-generiruyut-45-elektroenergii-vie.html.
[16] Kursiv.kz, 2020, *Казахстан в 2020 году отобрал 16 проектов ВИЭ на 148 мегаватт*. Accessed: 25.01.2021. [Online]. Available: https://kursiv.kz/news/otraslevye-temy/2020-12/kazakhstan-v-2020-godu-otobral-16-proektov-vie-na-148-megavatt.
[17] Bureau of National statistics, 2021, *Carbon fibers and products of them: TNVED 6815101000*. Accessed: 20.01.2021. [Online]. Available: https://stat.gov.kz/official/industry/11/statistic/6.
[18] T. P. Sathishkumar, S. Satheeshkumar, and J. Naveen, Glass fiber-reinforced polymer composites - A review, *J. Reinf. Plast. Compos.*, vol. 33, no. 13, pp. 1258–1275, 2014.
[19] KAZTECHNOINNOVATIONS, 2021, *What Can We Do?*. Accessed: 25.01.2021 [Online]. Available: http://www.kti.kz/service/proizvodstvo-izdelij-iz-kompozitnyh-materialov.
[20] MOST&K, 2021, *MOST&K: About the company,* 2021. Accessed: 25.01.2021 [Online]. Available: https://mostandk.kz/info-about.
[21] J. Deng *et al.*, Recycling of Carbon Fibers from CFRP Waste by Microwave Thermolysis, *Processes*, vol. 7, no. 4, p. 207, Apr. 2019.
[22] L. Mishnaevsky, Sustainable End-of-Life Management of Wind Turbine Blades: Overview of Current and Coming Solutions, *Materials (Basel).*, vol. 14, no. 5, p. 1124, Feb. 2021.
[23] GWEK, 2019, "Global Wind Report 2019,". Accessed: 28.01.2021 [Online]. Available: https://gwec.net/wp-content/uploads/2020/08/Annual-Wind-Report_2019_digital_final_2r.pdf.
[24] P. Liu and C. Y. Barlow, Wind turbine blade waste in 2050, *Waste Manag.*, vol. 62, pp. 229–240, Apr. 2017.
[25] IFC, 2014, *Waste In Russia: Garbage Or Valuable Resource?*. Accessed: 25.01.2021 [Online]. Available: http://documents1.worldbank.org/curated/pt/702251549554831489/pdf/Waste-in-Russia-Garbage-or-Valuable-Resource.pdf.
[26] UMATEX, 2021, *Applications*. Accessed: 25.01.2021 [Online]. Available: https://en.umatex.com/.
[27] Rosatom, 2021, *Promising Materials and Technologies*, Accessed: 25.01.2021 [Online]. Available: https://rosatom.ru/en/rosatom-group/new-business-areas/other-products/.
[28] A. V. Petrov, M. S. Doriomedov, and S. Y. Skripachev, Recycling Technologies Of Polymer Composite Materials (Review), *Proc. VIAM*, no. 8, pp. 9–9, 2015.
[29] G. Stefan and D. Roman, 2017 *Perspectives of the wind energy market in Russia*. Accessed: 10.02.2021 [Online]. Available: https://library.fes.de/pdf-files/bueros/moskau/13474.pdf.
[30] UtilVtorProm, 2016, *Recycling and disposal of air transport*. Accessed 20.02.2021. [Online]. Available: https://xn--80ancaco1ch7azg.xn--j1amh/ru/utilizatsiya-othodov/utilizatsiya-vozdushnogo-transporta/.
[31] E. Isayeva, 2015, Промышленные композиторы, *Коммерсантъ*. Accessed 20.02.2021. [Online]. Available: https://www.kommersant.ru/doc/2825099.
[32] P. Sidorenko and I. Karpes'o, 2018, Disposal of composites: problems and promising solutions, *Basalt.Today*. Accessed 22.02.2021. [Online]. Available: https://basalt.today/ru/2018/05/15941/.
[33] S. Halliwell, End of Life Options for Composite Waste, *Natl. Compos. Network. Best Pract. Guid.*, 2006.
[34] X. Li, R. Bai, and J. Mckechnie, Environmental and fi nancial performance of mechanical recycling of carbon fi bre reinforced polymers and comparison with conventional disposal routes, *J. Clean. Prod.*, vol. 127, no. 2016, pp. 451–460, 2016.
[35] P. A. Vo Dong, C. Azzaro-pantel, and A. Cadene, Resources , Conservation & Recycling Economic and environmental assessment of recovery and disposal pathways for CFRP waste management, *Resour. Conserv. Recycl.*, vol. 133, no. August 2017, pp. 63–75, 2018.

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The Use of Generative Modelling to Automate the Design of Aerial Structural Assemblies

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Abstract. This paper presents a method of automating design that has the potential to significantly improve the design process. The intent is to develop a design automation system that is an integration of several methods in a holistic approach for use. The automation Generative Design approach allows the reuse of wing design data and parameters. For this purpose, Generative Design methodologies are discovered to enhance the system building. This example of an analyzed wing structure to develop a compatible method to automate the design is described. The model parameterization technique is used to facilitate the generative model creation based on parameters, variables, and constraints. The use of integration in SolidWorks software function is proposed as part of an approach to support designers during both the generative model-building phase of the design process and simulation verification phase. Finally, an example and validation process is presented. The aim is to quickly and cost-effectively validate analytical results from the developed process. The proposed process adopts flexibility to acquire the intended model on different sizes and purposes, likewise, it is shown how the implemented approach makes it possible to automate the generation of generative models for FEM analysis.

Keywords. Generative Model, wing design, design automation, aircraft design, simulation, transdisciplinary engineering

Introduction

Due to the existing competition in Aerospace companies, engineers in design and development departments attempt to minimize cost and time consumption for wing designs. Consequently, a need for integrated tools and methods throughout the development process has been raised. To help the design process in reducing design challenges, time, and cost. Integration of various disciplines in the wing preliminary design as one entity enables the design process to be kept intact at every step.

Automating design is a promising method to solve these problems and significantly improve the design process. During the design process, numerous variants, alternatives, and possible solutions are explored and compared iteratively, until the product is found that best suits the requirements. Moreover, changes to the design can come after the product has hit the market, as further developments, derivatives, and updates are requested. Complying with and implementing all the changes is a very time-consuming and costly activity [1]. Enabling automation of as many as possible of the repetitive

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processes during product development is a key to increasing productivity, reducing time-to-market, and cutting costs. Additionally, freeing designers from tedious work allows them to concentrate on activities that require creativity, which is hardly possible to integrate into a computer system. The intent is to develop a design automation system that is an integration of several methods in a holistic approach for use. The automation Generative Design approach allows the reuse of wing design data and parameters. For this purpose, Generative Design methodologies are discovered to enhance the system building.

Aircraft design is a multi-disciplinary and time-consuming process that involves a large number of disciplines and expertise in flight controls, structures aerodynamics, propulsion, and systems amongst others. During the initial conceptual stage of an aircraft design process, multiple aircraft configurations are studied and analyzed. Feasibility studies for various concepts and designs are carried out and the goal is to come up with a design concept that can best achieve the design objectives. One of the vital studies in any aircraft design process is the preliminary design study of an aircraft wing. The aircraft wing is a critical design component of an aircraft from a structural and aerodynamics point of view.

1. State of the art

The generative design was started by Frazer [2] in the early 1970s. It developed to some extent mostly focused on design theory, although there was no implementation method [3], due to the rising interest of engineers, this gap was filled by CAD companies [3, 4, 5, 6,], offering various generative design solutions. The current aim of generative design is best summed up by Shea; "generative design systems are aimed at creating new design processes that produce spatially novel yet efficient and buildable designs through the exploitation of current computing and manufacturing capabilities" [7].

A particular form of generative design - the Generative Design Method (GDM) [8] derived from Knowledge-Based Engineering [9], is defined here as - a designer driven, parametrically constrained design exploration process, operating on top of history-based parametric CAD systems that are unstructured in terms of design development and supportive of emergence [10]. A wide range of methods and modeling techniques were developed till now: Constraint-Based Evolutionary Decision Support System [11], GENE_ARCH [12], Intelligent Genetic Design Tool [13], Genetic Algorithm Designer (GADES) [14], Shape Grammar [15]

The Generative Modeling (GM) method belongs to the group of generative methods, ie the Generative Design Method (GDM). There is also one of the methods of Knowledge-Based Engineering (KBE) and due to the intensive use of geometric modeling, it is one of the methods of Geometry-Based Design Automation (GBDA) [16] Such systems are particularly suitable for design families of highly similar structures [8, 17, 18] or modular systems [19] but it can be used in other more sophisticated applications from aerospace [16] automotive [20, 21] or a manufacturing industry [22]. Advanced applications of Generative Modeling in optimization, in particular in Multidisciplinary Design Optimization (MDO), are found more and more often [16, 23].

The Generative Design Method (GDM) is an inclusive CAD-based generative design study method designed suitable at all stages of the design development process – starting from conceptual to detailed design. The GDM comprises six key components: [8, 17]

1. Genotype – is composed of a generic parametric CAD model, a list of design parameters and their initial value, and an initial exploration envelope.
2. Phenotype – generated CAD files (that may include build history, built-in relationships, and built-in equations).
3. Exploration envelope (Constraints) – a list of minimum and maximum values of the driving parameters specifying the limits of the design space to be explored.
4. Design Table - a data table that stores the driving design parameters, their initial values, and the limits, and other data that may be required, and the generated design values preferable in an accessible spreadsheet format.
5. Design Generation Macro – a macro or a spreadsheet function that operates on the design table. It generates random variations of the driving parameters within limits set by the initial design envelope.
6. CAD system - is a parametric CAD engine with a transparent and editable build history, preferably with a 3D geometric kernel with capabilities to manage geometric relationships, engineering equations and connect to external design tables.
7. Performance filters – A pass/fail software filter, that can evaluate the performance of generated designs based on data from the design table, CAD system or associated analytical packages.

2. Generative modeling methodology

2.1. Structure

The knowledge-based method combined structural design and Generative Model designing system are used thoroughly including several sub-systems to optimize the whole process.

The generative models building approach started by establishing an inter-related discipline and sub-systems vary from data acquisition, design calculation, design automation, CAD, and FEA.

The development started in specifying the wing conceptual design criteria and parameters. Basic wing structural analyses are performed on strength and aerodynamic perspective. Few parameters of wing component geometries are linked to sizing analysis results through the design table. Any updates in the level of the parameter will affect the CAD model, likewise, the initial design criteria are linked with the generative model building approach. The approach uses both parameters and analysis to implement in CAD model building. Moreover, Wing structure assembly is made in relation to wing structural configurations analysis and result through the developed generative model building approach. The system will allow a generation of different types of wing configurations as required directly from given parameters.

Then, the testing of the generic model was done to ensure that the generic aircraft wing model can cater to different types of aircraft wing configurations and planform shapes. The next step included the use of generic model components assembly and making structural mesh generation and making FEA of the generic aircraft wing model. Eventually, FEA can be performed at any part or assembly configuration that was made by a generative model. The application of the model follows a new design paradigm with a generative model (Figure 1). The problem with the new approach is the integration of the results of the following analyzes in the design process, and thus in the set of rules controlling the construction of Generative Models. Distribution of aerodynamic loads on the parameter resulting from flow analysis, an envelope of loads resulting from operational states of the airplane. Strength analyzes resulting from the general issues of the strength of materials as well as specific ones related to, for example, the design of composite material, the installation layout resulting from the structure and construction of various specialized installations on the plane, specialized rules, and good aviation practices (aeroelasticity, handling), the technology of manufacturing basic aircraft structures. These are various fields and the ongoing integration of the analysis results guarantees a transdisciplinary approach. The tasks to be performed and the relevant parameters that are the input to the next steps are described below.

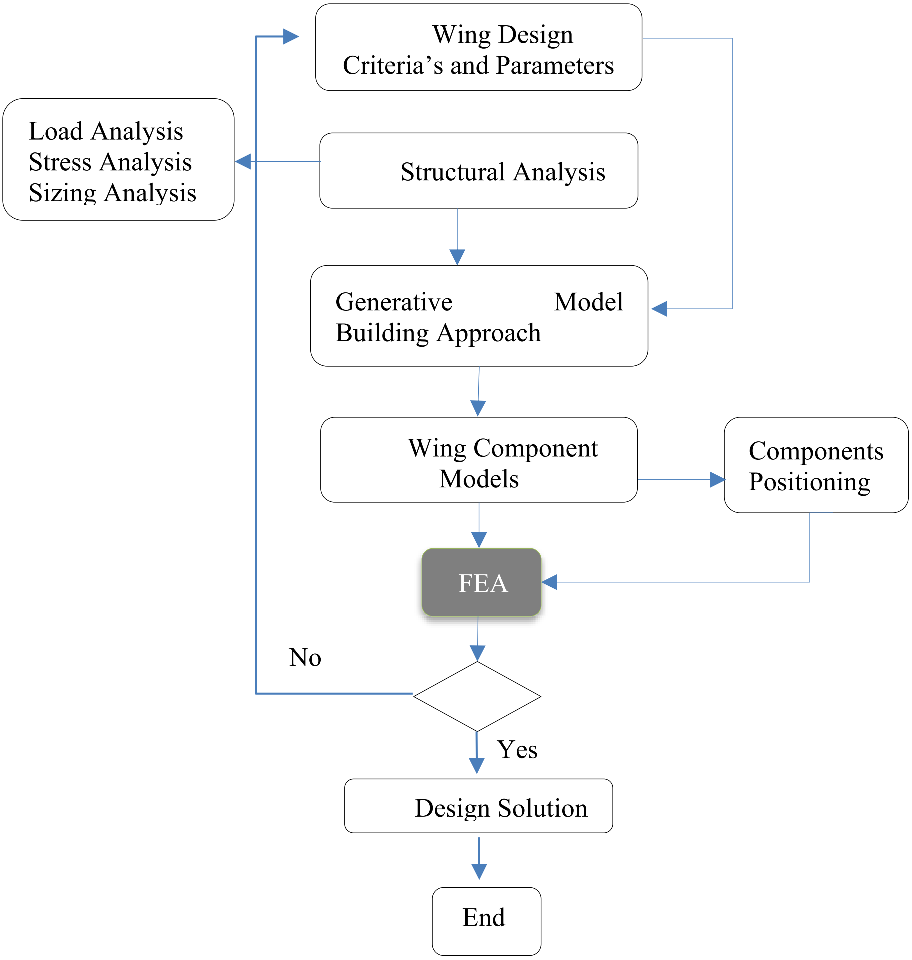

Figure 1. The paradigm of Automation of Wing Design using Generative Modeling Method.

2.1.1. Wing Design Parameters

This wing design analysis began with choosing the aircraft application. The geometrical and aerodynamical parameters of the chosen aircraft are specified for structural analysis.

According to these assumptions, the basic features of the wing are selected according to which the conceptual structure of the wing can be proposed (Figure 2, Figure 3).

Aspect Ratio- is defined as the wingspan squared divided by the wing area.

Taper ratio- defined as the ratio between the tip chord of the wing and the root chord of the wing.

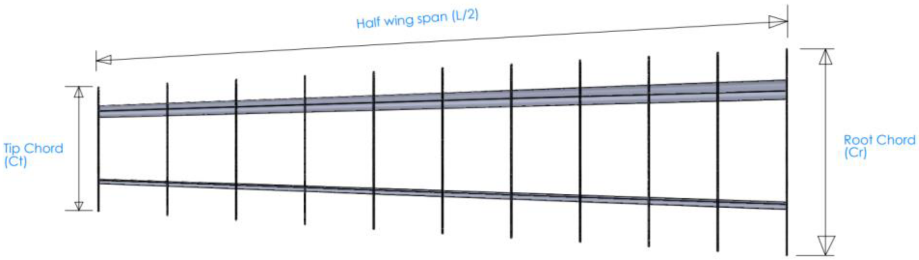

Figure 2. Swept wing geometrical parameters.

Mean Aerodynamic Chord- is the average chord length of a tapered or swept wing.

Airfoil Shape- is defined as coordinates that form the shape of an airfoil and wing ribs.

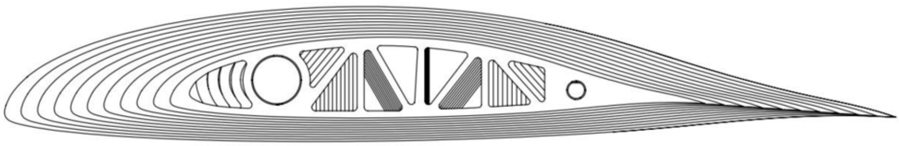

Figure 3. Wing rib shape.

2.1.2. Wing Load Analysis

Wing load analyses are a very crucial beginning. Wing geometrical parameters are used to analyze three major load analyses of aircraft wings. Obtaining different results are possible by changing geometrical parameters, which later influences sizing analysis of spar or rib.

2.1.3. Sizing and Stress Analysis

Sizing analysis is dedicated to determining wing components thickness based on calculation results, which are simultaneously linked to CAD through the generative modeling system. Thus, various sizes are obtained at different initial design criteria and loads.

2.1.4. Generative Modeling Approach

Later wing structural analysis, various wing component sizing is calculated hence become one of the major roles in determining generic models. The concept of the wing components generic model was then developed in the generative method approach.

Spar positioning and ribs spacing concepts are developed similarly as wing components to generate an assembly generic model.

The theoretical outlines for the proposed generative model design method alongside methods of implementation are presented in Figure 4.

The methods of building a generative model process involve relations of various software and techniques. Wing geometrical parameters are considered as the initial step to build fixed geometries, while each parameter are interrelated with SolidWorks function, such as formulas and constraints. The thickness of components and wing structural assemblies are regulated by a design table where these parameters are linked to excel calculation. Thus, the whole approach allows a generation of different wing model configurations that can also be automatically updated in FEA.

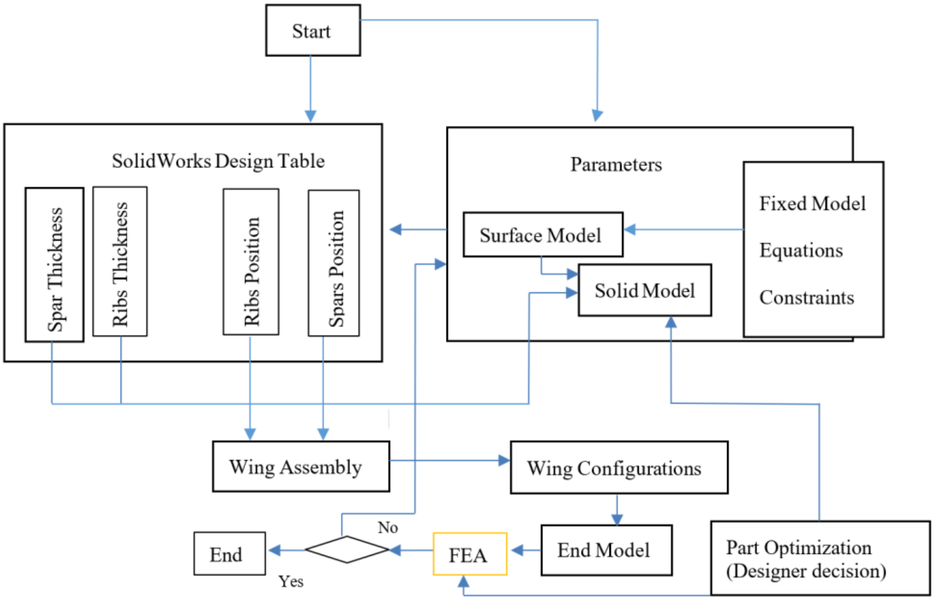

Figure 4. The paradigm of Generative Model Building.

2.1.5. Concept of Wing components Generative Model Building

The spar building method has contained few constraints, formulas, and equation relations which are mostly geometrical and thickness as shown in Table 1. Furthermore, geometrical parameters are directly linked to the calculation analysis, hence iteration is achievable in the calculation spreadsheet directly affects the thickness.

Ribs parameters include airfoil coordinates, shape and chord length, Web length, flange width, diameter for circular section thickness, material, and color. Thickness is directly driven from a spreadsheet calculation result, as a result, different CAD model outputs are obtained in an iteration.

Table 1. Spar geometrical parameters and constraints.

Spar Types	*Parameters*					
	Large Diameter (mm)	**Small Diameter (mm)**	**Web Height (mm)**	**Upper Flange Thickness**	**Circular Hollow Thickness**	**Web Thickness**
I	--	--	120	--	--	--
Circular Hollow	140	130	--	--	--	--
			Constraints			
I	5.7	--	110<h<120	Ut <10 < 20	--	--
Circular Hollow	140<D< 120	100>d>70	--	--	10<Ct<15	10<Wt<15

2.1.6. Concept of Assembly Generative Modeling approach

The geometric reference for modeling includes the spar-positioning plane, the spar-starting plane, the spar termination plane, the upper and the lower wing skin surfaces. The geometric reference elements are shown in Figure 5. The spar-positioning plane is used to determine the position of the spar in the wing assembly model. The starting and termination plane of the spar is used to determine the beginning and end of the spar along the spanwise direction.

2.1.7. Wing Components positioning

Using SolidWorks design table capabilities, designers can define any number of ribs, spars, and span length. The number, position, and orientation of each element are assigned using lists of parameters published in the input file together with the parameters defining the aircraft outer surfaces. The constraints for wing components assembly confiugrations are relative to wing span and geometry. Table 2 shows constraints of assembly configurations,and Figure 6 shows an example of a generic wing assembly generated by the GM and component positioning.

Table 2. Wing structural assembly constaints.

Location number	**Front Spar**	**Rear spar**
Location 1	X*25%	X*70%
Location 2	*X*30%*	*X*70%*
Location 3	X*35%	X*70%-75%
Location 4	X*40%	X*70%-80%

Where, X is chord length and spar locus measures from leading edge.

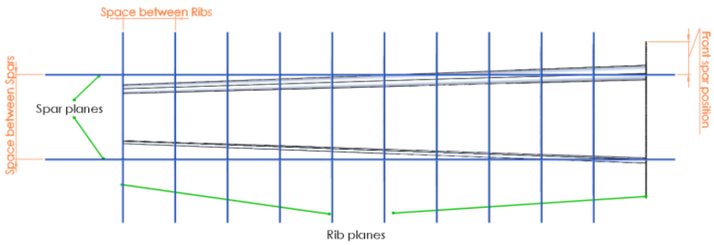

Figure 5. Wing assembly skeleton view and input parameters used to define assembly configurations.

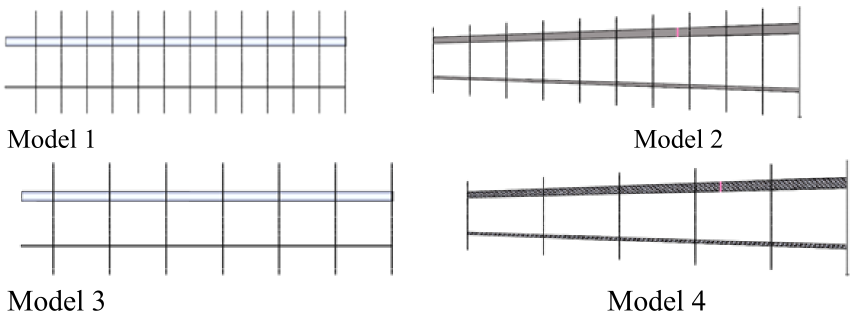

Figure 6. Example of generated wing structure configuration.

2.2. FEA

The system set up a FE model, starting from a finished CAD model, as produced by the generic design model environment. In this section, a seamless approach is developed that linked the generic model and the FEA environment as shown in Figure 7.

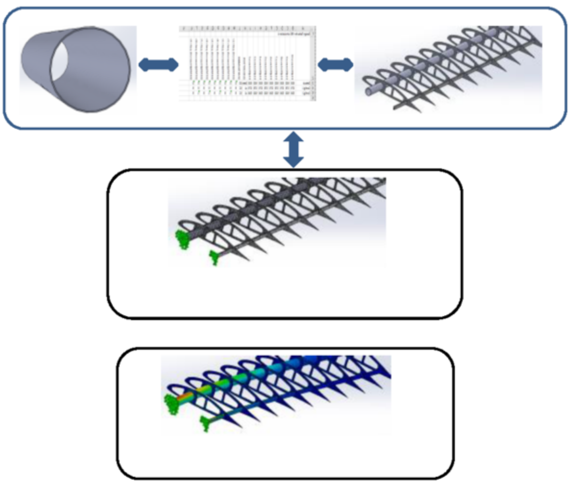

Figure 7. Seamless link between the Generic Model environment and the FEA environment

Geometrical change depends on the configuration in the generic model environment, any selected configuration CAD will be ready to make mesh generation. Before mesh generation dedicated materials are assigned, boundary conditions and forces are applied. Practically, any change that is made in the design table SolidWorks allows the simulation without a need to export the CAD format to another software. In the resulting environment, likely related to two previous environments, mesh update as 3D model changes.

3. Discussion

Through the adoption of the automation of generative building systems a designer is able to create a generative model of wing components and wing structural assembly configurations, as per parameters and constraints. Assembly model constraints are set to be relative to wing chord length and span, thus a designer can not exceed a logical positioning and quantity of components under given constraints.

The time to make a change in components and assembly model is one way closer and quickly done by creating several sample models in the design table solution,thus substantially shorter lead-time was achieved to do in repetitive design.

The developed approach system has the capability of automating both CAD models and FE Analysis in the same software without a need of exporting models for further FEM analysis.

When a different design needs to be attempt, the design parameter can be changed and these changes are automatically propagated to the linked models. Hence, a designer is capable to obtain both analytical and simulation results at the same time, likewise, it allows designers to compare models based on design goals and ultimately to make the optimal decision.

4. Conclusions

The established system is the first of its kind to use design calculation data acquisition in order to generate both CAD and FEM analysis in similar software.
Some of the significant achievements by the developed system are,

1. Simplistic version of generative modeling for wing components and structure at the preliminary design phase
2. Parametrized CAD model generation
3. Generative finite element mesh generation
4. Faster start-up time for modeling & FE analysis
5. Easy manipulation of design parameters and constraints

The automating approach entails design calculations and knowledgebase relation to create a CAD model for wing components and assembly. Similarily, capable of automating both CAD models and FE Analysis in the same software without a need of exporting models for further FEM analysis.

When a different design needs to be done, the design parameter can be changed and these changes are automatically propagated to the linked models. Hence, a designer is capable to obtain both analytical and simulation results at the same time, likewise, it allows designers to compare models based on design goals and ultimately to make the optimal decision. This dramatically speeds up the process of geometry generation of different wing planform or configurations so that the designer focuses more on the design of the aircraft wing rather than worrying about the creation of the geometry.

References

[1] J.H. McMasters, R.M. Cummings, Rethinking the Airplane Design Process – An Early 21st Century Perspective, AIAA 2004-693, *42nd AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, USA, Jan. 2004.
[2] J.H. Frazer, Creative design, and the generative evolutionary paradigm, in D.a.B. Corne, Peter, (eds.) *Creative evolutionary systems*, Morgan Kaufmann Publishers Inc. (Elsevier): California, San Francisco, 2002, pp. 253-274.
[3] N.N., Generative Components, Bentley Systems, 2010; Available from: http://www.bentley.com/enUS/Promo/Generative+Design
[4] N.N., Grasshopper. McNeel Corp. 2010; Available from http://www.grasshopper3d.com/.
[5] N.N., Genometri, Genoform. 2002, Genometri Pte Ltd.: Singapore.
[6] N.N., Para Cloud GEM. 2010; Available from: http://www.paracloud.com/.
[7] K. Shea, R. Aish, and M. Gourtovaia, Towards integrated performance-driven generative Design tools. *Automation in Construction*, 2005, Vol. 14, Issue 2, March 2005, pp. 253-264.
[8] K. Sivam, A practical generative design method. *Computer-Aided Design*, 2011, Vol. 43, pp. 88-100.
[9] W.J.C. Verhagen, P. Bermell-Garcia, R.E.C. van Dijk, R. Curran, A Critical Review of Knowledge Based Engineering: An Identification of Research Challenges, *Advanced Engineering Informatics*, 2012, Vol. 26, Issue 1, pp. 5-15.
[10] E.R. Oxman, Theory, and design in the first digital age. *Design Studies*, Vol. 27, Issue 3, May 2006, pp. 229-265.
[11] Y. Guoyan, W. Xianozhen and L. Peng, A constrained based evolutionary decision support system for product design, *2009 Chinese Control and Decision Conference*, DOI: 10.1109/CCDC.2009.5191831, pp. 2585-2590.
[12] L. Caladas, GENE_ARCH: An evolution-based generative design system for sustainable architecture. In: Smith I.F.C. (eds) *Intelligent Computing in Engineering and Architecture. EG-ICE 2006. Lecture Notes in Computer Science*, vol 4200. Springer, Berlin, Heidelberg. https://doi.org/10.1007/11888598_12.
[13] P.V. Buelov, Using Evolutionarry algorithms to aid designers of architectural structures. In: Creative Evolutionary Systems, P.J.Bentley, Editor. 2002, Morgan Kaufmann San francisco, CA. pp. 315-336
[14] P.J. Bentley, From coffee tables to hospitals: generic evolutionary design, in P.J. Bentley (ed.) *Evolutionary Design by Computers*, Morgan Kaufmann San Francisco, CA, 1999, pp. 405-423.
[15] J. Huang, A. Pytel, C. Zhang, S. Mann, E. Fourquert, M. Hahn, K. Kinnear, M. Lam and W. Cowan, *An Evolution of Shape/Split Grammars for Architecture*, Technical Report CS-2009-23. 2009, David R. Cheriton School of Computer Science, University of Waterloo.
[16] K. Amadori, *Geometry Based Design Automation - Applied to Aircraft Modelling and Optimization*, Linköping Studies in Science and Technology. Dissertations, No. 1418.
[17] S. Thajudeen, M. Lennartsson, F. Elgh, P.J. Persson, Parametric modelling of steel connectors in a glulam based post and beam building system - Towards a flexible product platform approach, *Advances in Transdisciplinary Engineering*, 2020, Vol. 12, pp. 564-573.
[18] W. Skarka, Application of MOKA methodology in generative model creation using CATIA. *Engineering Application of Artificial Intelligence*, 2007, Vol. 20, Issue 5, pp. 677-690.
[19] W. Skarka, Using Knowledge-Based Engineering Methods in Designing with Modular Components of Assembly Systems, *11th International Design Conference (Design 2010)*, May 17-20, 2010, Vol. 1-3, pp. 1837-1846 .
[20] A. Jałowiecki, W. Skarka, Generative modeling in ultra-efficient vehicle design, *Advances in Transdisciplinary Engineering*, 2016, Vol. 4, pp. 999-1008.
[21] C.B. Chapman, M. Pinfold, The application of knowledge-based engineering approach to the rapid design and analysis of an automotive structure, *Journal of Advances in Engineering Software*, 2001, Vol. 32, Issue 12, pp. 903-912 .
[22] W. Skarka, T. Neumann, New methods of designing stamping dies assemblies by using generative models. In: Transdisciplinary engineering: a paradigm shift. *Advances in Transdisciplinary Engineering*, 2017, Vol. 5, pp. 456-463.
[23] J. Andersson and P. Krus, Metamodel Representations for Robustness Assessment in Multiobjective Optimization, *ICED01 International Conference On Engineering Design*, Glasgow, UK, Aug. 2001.

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Design of the Power Supply System for Vertical Take-Off and Landing Unmanned Aerial Vehicle

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Abstract. The article presents an analysis of the possibilities of supporting the Vertical Take off and Landing Unmanned Aerial Vehicle electric power systems by using photovoltaic cells. A typical commercial VTOL class drone with electric power was selected for analysis. Concepts of power supply supported by photovoltaic cells have been developed. Analysis of the potential change in performance through the use of such support are presented on the basis of the UAV simulation model and the model-based design. The simulation model takes into account not only the flight parameters of the drone, but also the drive system with the power supply system and the assumed variable lighting parameters. Such a multidisciplinary model was used to analyse the functional parameters. The analysis also includes hypothetical changes in the performance parameters of photovoltaic cells and their impact on the change in UAV performance as well as the impact of changes in the airframe geometry on the profitability of using such a solution.

Keywords. VTOL UAV, photovoltaic cells. Model-Based Design, simulation model, power supply, aircraft design

Introduction

Nowadays, the electric drives are displacing the internal combustion drives, due to its flexibility, resistance to thermal changes, and possibility of using renewable energy sources. Thanks to that we can reduce exhaust fumes and pollution, which are harmful to environment. Taking into account advantages of photovoltaics cells e.g. its durability, increasing efficiency and easy connection to others devices (batteries, capacitors) solar cells shows great potential in application for autonomous vehicles. In this specific case some extraordinary factors must be considered (e.g. cloudy, temperature, irradiance). Various aspects are touched upon in this work beginning with UAV design, by analyzing weather conditions, all the way to electrical engineering and its issues such as converters and elements of the electrical circuit. Main goal of this work is to give an answer to question whether solar-powered UAV is reasonable.

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1. Division of vertical take-off and landing vehicles

To begin the conceptual process formation of UAV VTOL we must first consider which structure will bring the optimal ratio of hovering and surface to place their solar cells, with possibly the best mounting angle to reach the highest energy yield. Figure 1 presents the general division of vertical take-off and landing vehicles.

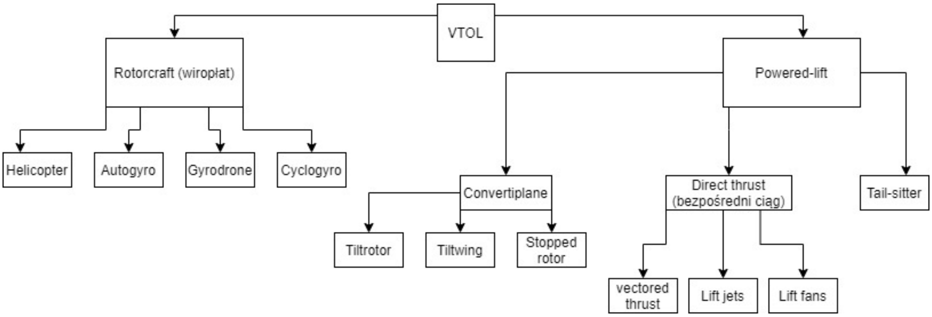

Figure 1. General division of vertical take-off and landing vehicles due to design and the type of drive

Due to the high complexity of the construction process the load-bearing structure (UAV VTOL tailsitter structure) was adopted from the "Sky X" project - its geometric dimensions. All calculations in this document are based on these assumptions. Sky-X structure and basic dimensions are shown in Figure 2. [1]

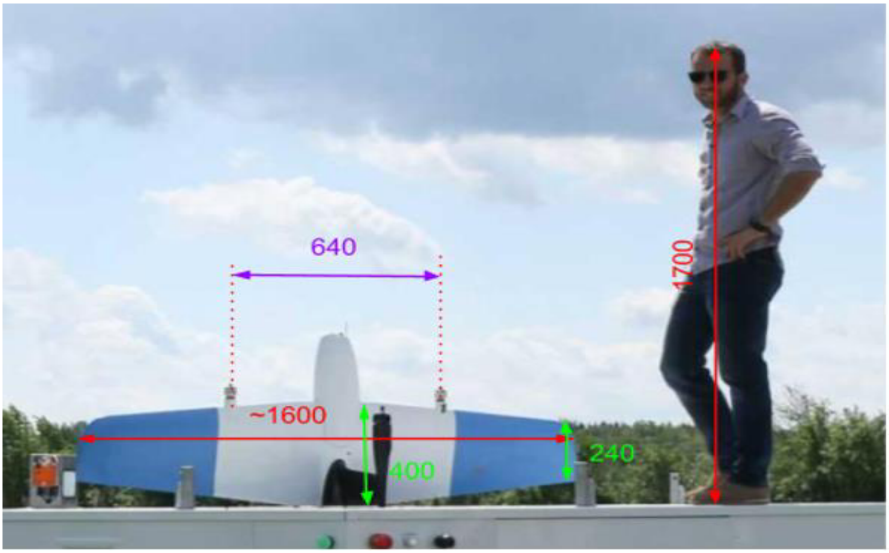

Figure 2. Sky X basic dimensions in reference to human adult.

In order to provide the best possible power, MPPT devices are used to adjust the voltage from photovoltaic cells. These are high-performance DC-DC converters with adjustable gain between the input voltage (PV cells) and the output voltage (batteries). Such a converter can also change the input voltage for other devices such as servo motors, radio, GPS or speed controllers. The figure shows a diagram of the operation of a system with PV cells, MPPT converter, batteries and other devices. Figure 3 presents concept of the power supply system, together with the UAV VTOL control system. [2][3]

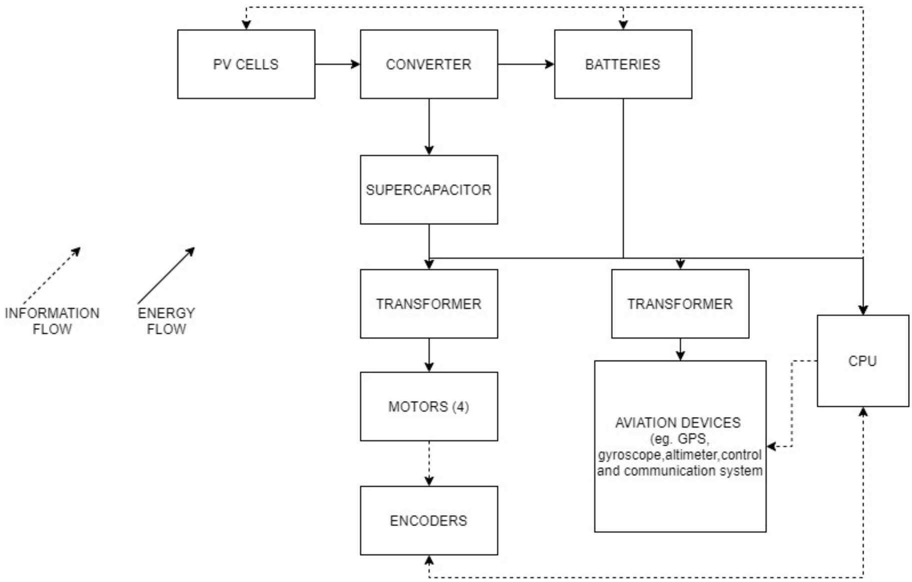

Figure 3. Power supply and control systems of vertical take-off and landing unmanned aerial vehicle taking into account both the flow of energy and information, with necessary equipment.

2. Criteria for the selection of photovoltaic cells in terms of geometric configuration and efficiency.

As it has been written the entire system will be powered by solar cells. It should also be remembered to appropriate selection of batteries and accumulators that will accumulate the energy generated by PV panels so that the VTOL can also fly at night (when no solar energy is available). The basic criterion that will be set for PV cells will be flexibility - the goal of their highest efficiency, an equally important factor will be their weight, efficiency and the influence of temperature. After evaluation to the further calculations were chosen GaAs solar cells. Due to the conceptual nature of the work, the financial aspect may be omitted. [4]

3. The influence of the clouds on energy performance.

Cloud cover has a direct impact on the amount of radiation hitting the solar cell, thus determining the power that the cell can generate. Clouds may have a different structure, sky coverage, degree of water, or density and thickness, so their behaviour towards solar radiation will change. Figure 4 shows the dependence of solar radiation reaching the Earth's surface on the types of clouds and the height of the Sun.

Cloud cover has a direct impact on the amount of radiation hitting the solar cell, thus determining the power that the cell can generate. In this paper calculations were made based on publications, and then modelled with octane scale, which distinguishes 10 degrees of cloud cover from 0/8 (clear sky) to 9/8 (sky invisible). Thanks to that sky coverage can be easily divided into 10% steps. Octane scale was better descripted in bibliography sources.[5][6]

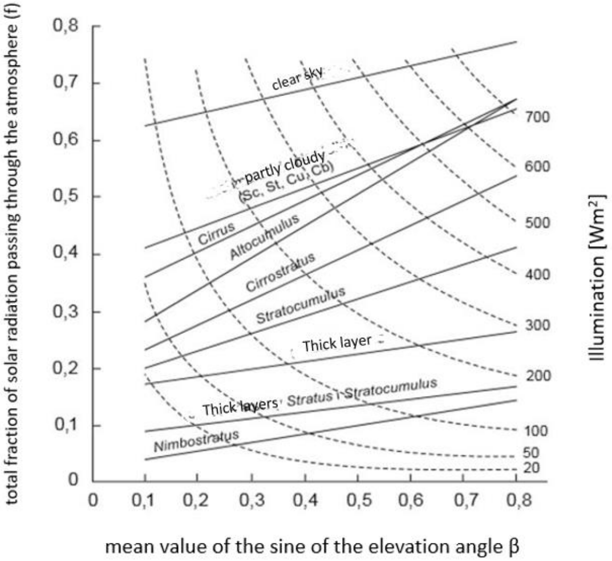

Figure 4. Dependence of solar radiation reaching the Earth's surface on the types of clouds and the height of the Sun

4. Solar energy availability

The amount of solar radiation available depends on several factors, the main ones being latitude, as well as the position of the sun in the sky. We can assume that during the flight UAV VTOL maintains a horizontal flight trajectory, parallel to the Earth's surface, then the intensity of solar radiation can be defined as the sum of scattered, reflected and direct components of solar radiation intensity. Availability of solar radiation was expressed in article of D. Matuszko [5] and also on paper. [9]

5. Model-based design methods assumptions

In order to verify the photovoltaic power supply system and its validity, specific functional tests should be carried out.

After verifying the load capacity of the UAV VTOL, the following functional tests should be performed:

- UAV vertical take-off and landing with photovoltaic panels and a battery,
- UAV vertical take-off and landing with greater battery capacity (greater number of cells).

Next step, which has to be done is to check whether the use of photovoltaic cells for a given technological problem is justified. Tests should be performed at:

- variable irradiance value (e.g. cloudiness, fog, night),
- variable temperature,
- the optimal inclination of the solar cell must be taken into account for the best possible results.

6. Developed calculation model

In the MATLAB R2019 computing environment, specifically its Simulink software, a model of the power system was developed, consisting of a photovoltaic cell, a battery, a supercapacitor and a converter [7][8]. Calculation model is presented in figure 5.

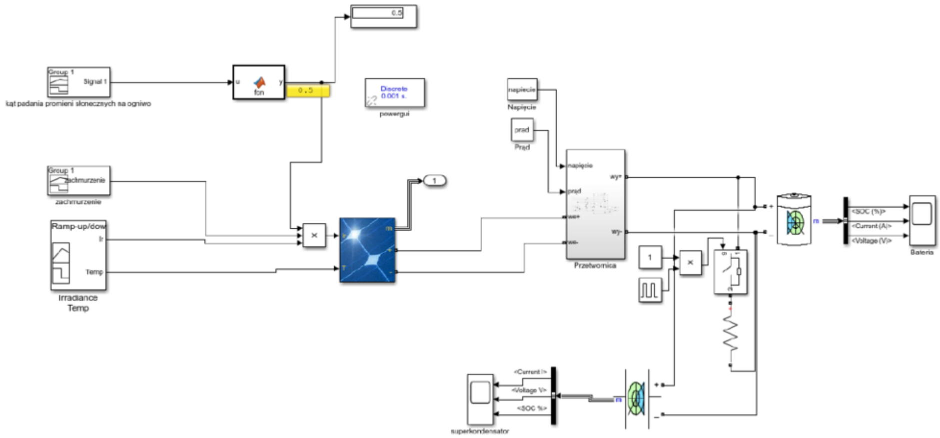

Figure 5. The entire power supply system with a photovoltaic cell and a supercapacitor.

The models available in the Simulink software library were used to develop the model shown in Figure 7. These models are mathematical representation of physical devices available on the market. With the photovoltaic cell, in order to obtain more real power yields, the following were additionally modelled:

- temperature change,
- change of insolation value,
- cloud cover,
- the angle of incidence of sunlight on the cell.

Changing the angle of incidence of sunlight on the cell affects the output power of the solar cell - in accordance with the Lambert's law. [9]

Signal, which represents the angle of sun's elevation, is featured as a triangular time function as is it often proposed in scientific studies. This angle will vary depending on the latitude or the day of the year.

The cloud cover value on a scale of 0-1 (where 0 - cloudless sky, 1 - sky fully covered with clouds) was also modelled using a signal. Irradiance and temperatures were also modelled as a signals of value in time. [5]

The developed computational model uses the block of the photovoltaic cell function built into the Simulink environment. It was decided to use it because of a better representation of the work of a real photovoltaic cell.

The converter is an important element of the system. The electricity generated by the solar cell is supplied further (including to the battery) via a DC-DC converter of the CC-CV type (Constant Current - Constant Voltage). Figure 6 shows the converter block with the set values of operation - voltage and current, and Figure 7 shows the inside of the converter block - its proper model which were elaborated based on the thoughts and experiences of the authors and the results of similar works. Creation and development of DC-DC converters is a frequently discussed engineering topic, which was described in many studies that inspired this work In the context of general assumpions [10], converters [11], lithium battery modelling [12] PV – battery – supercapacitors configurations [13] charging and discharging of supercapacitors [14] models of PV cells [15]

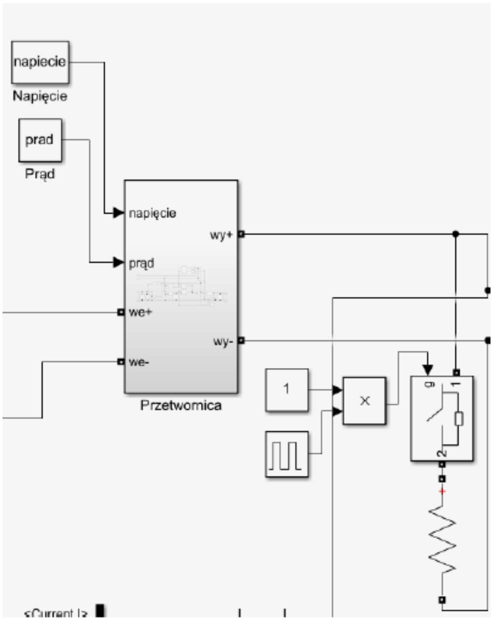

Figure 6. Blocks, which determine converter's proper work. Consist of input values of variables, which are necessary to proper work of converter so as: input voltage and current.

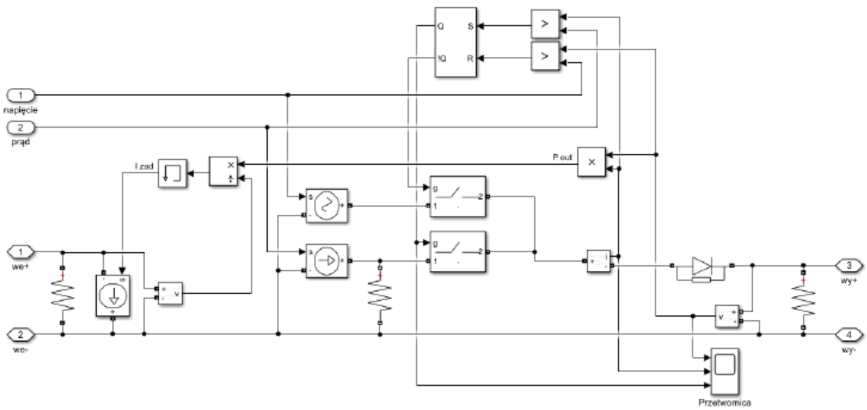

Figure 7. Modelled DC-DC converter – modelled as CC-CV converter (constant current- constant voltage). Developed model is mean value converter.

In the developed calculation model, the li-ion battery model existing in the libraries of the MATLAB 2019R Simulink same as supercapacitor.

7. Calculation and assumpitons of VTOL energy requirements

Calculations were made using equations which can be found in additional scientific papers. Table consists of input values serving, together with the output results resulting from their substitution into the formulas. Calculations were prepared for 2 cases:

- Without solar panels (take-off mass)
- With solar panels (take-off mass)

Table 1 presents energy requirements for VTOL without mass of solar panels and comparatively after re-evaluation.

Table 1. VTOL energy requirements before and after re-evaluation.

Parameter name	Symbol	Value before re-evaluation	Value after re-evaluation	Unit
Take-off mass	Wto	20	20,72	kg
Air density	ρ	1,2	1,2	kg/m3
Climb velocity	Vc	6	6	m/s
Power coefficient	k	1,2	1,2	-
Coefficient	KT	1,15	1,15	-
Maximum established thrust	Tmax	23	23,83	N
Propeller radius	Rp	0,2	0,2	m
Propeller area	A	0,1256	0,1256	m2
Propeller power	P	1176,3	1238,8	W
zero wing factor	CD0	0,008	0,008	-
Wing area	S	0,36	0,36	m2
Thrust in climb	Tc	20,0622	20,7822	N
Maximum admissible climb velocity	Vmax	24,5235	24,7413	m/s
Battery discharge efficiency	ηb	0,95	0,95	-
ESC efficiency	ηe	0,95	0,95	-
BLDC motors efficiency	ηm	0,9	0,9	-
Propeller power in climb	Pc	963,4	1014,3	W
Altitude (established)	Hm	1000	1000	m
Total energy consumption in climb	Ec	395378,2	416262,3	Wh
Velocity in horizontal flight	Vr	33,7	34,3	m/s
Velocity in horizontal flight	Ve	25,6	26,0	m/s

Parameter name	Symbol	Value before re-evaluation	Value after re-evaluation	Unit
Thrust in horizontal flight	Tr	3,9	4,1	N
Thrust in horizontal flight	Te	4,5	4,7	N
Propeller power	Pr	160,2	168,9	W
Propeller power	Pe	142,1	149,8	W
Energy consumption	Ecr	11711,4	12133,1	Wh
Energy consumption	Ece	13671,4	14163,6	Wh

8. Analysis of energy yields

Two cases were taken into account: the first - the longest day of the year and the second - the shortest. For both described cases it was assumed that there is no cloud cover - the sky is clear and the entire solar radiation intensity falls on the surface of the photovoltaic panels. Only the decrease in energy yields is taken into account, in line with Lambert's law. The value of solar radiation intensity is taken into account, similarly to other calculation models, for similar technological solutions as the value of solar intensity occurring for the equator at solar noon, i.e. 1200 W / m2. The area of the wings (including the area of solar panels located on them) is 0.72 m2. GaAs cells parameters (made of gallium arsenic) were used for the calculations. Such cells are characterized by a low weight (100 mg / cm2 = 1 kg / m2), as well as a high efficiency of 28% (in some studies, a higher value is given, but most studies indicate the value of 28%). Then, the values presented in Table 1 were revalued, taking into account the increased weight of the entire structure due to the presence of photovoltaic panels. Table 2 presents input values, used in calculations and table 1 presents energy requirements for VTOL with solar panels (column value after re-evaluation).

Table 2. Input values.

Irradiance value [W/m2]	Solar panels area [m2]	Panels efficiency [%]
1200	0,72	28

Then, the possible energy yields (Table 3) resulting from the use of GaAs photovoltaic cells on the ship's surface on the longest and the shortest day of the year, respectively, were calculated. No cloudiness was assumed, as well as a constant value of solar radiation intensity, similar to other studies, such as on the equator at solar noon (1200 W/m2).

Table 3. Possible solar yields.

Season	Solar yields [W]
For the longest day of the year	1862,784 W
For the shortest day of the year	895,104 W

The increased WTO take-off weight is of particular importance in the vertical flight phase. Increasing this mass by 0.72 kg resulted in an increase in energy consumption by as much as 20,884.11 Wh, and in the horizontal flight phase by 421.61 and 492.17 [Wh] respectively. [17][18]

9. Conclusions

Due to the gradual withdrawal from conventional energy sources known to mankind, such as coal or fossil fuels, alternative sources of electricity should be sought, preferably renewable, obtained from natural sources and not affecting the natural environment. The paper analyses the possibility of developing a power supply system for vertical take-off and landing unmanned aerial vehicles. For such a technical solution, the cells are required to exhibit appropriate parameters, such as:

- appropriate weight,
- flexibility,
- high efficiency.

After analysing the photovoltaic cells available in scientific studies, it was decided to accept cells made of gallium arsenic (GaAs) for further analysis. Such cells have the best weight-to-efficiency ratio among the currently developed and analysed photovoltaic cells. Their weight is 100 g / cm2, and the efficiency reaches even 28%, which suggested that the use of this type of cells would be completely justified. Due to the conceptual nature of the work, the financial value of such a solution was omitted.

In further analysis, calculations were made to estimate the energy requirements of UAS. It was found that the best type of such vessel that could be powered by solar energy would be a tail sitter, which carries out the ascent and landing process vertically, and then, after reaching the assumed cruising altitude, goes to level flight. The dimensions of the "SKY X" aircraft, which is a commercial tail sitter solution, were adopted for the calculations. Then, with the assumed dimensions, calculations were carried out with the use of MS Office Excel environment, thanks to which the energy consumption values were calculated in the phase of vertical and horizontal flight. In the next step, the same values were calculated for the increased initial weight of the WTO, which was increased by the weight of the photovoltaic cells used. Possible energy yields resulting from the use of photovoltaic cells with 28% efficiency on days with the longest and the shortest number of sunny hours were also calculated. After comparing these values, we can conclude that the use of currently available technologies photovoltaics in aircraft that carry out missions on a surface not exceeding the stratosphere are unjustified, because the yields from such cells will not be able to compensate for the energy expenditure that is necessary for the performance of cruise missions by aircraft of vertical take-off and landing. Although the values of the yields were approximate, the analysis assumed that there was no cloud cover (thus the solar radiation intensity was not dispersed), and the effect of the wind force was not taken into account, which could also affect the resulting power. It was also assumed that the panels are arranged on the surface in such a way as to maximize the energy yield that the PV panel can provide. The analysis includes the variable efficiency of cells resulting from the occurrence of Lambert's law, which concerns the efficiency of the resulting panels.

In order to use solar cells in such a technical issue as an unmanned aerial vehicle for vertical take-off and landing, it would be necessary to develop photovoltaic panels, the efficiency of which would be significantly improved compared to those available so far.

A lot of hope are perovskites - naturally occurring minerals that can absorb sunlight (e.g. calcium titanium), but the naturally occurring ones do not conduct electricity. However, modified in the laboratory, they gain new features, such as current conductivity. At the moment, the perovskites are efficient at the level of 20-25%. However, in the future they can feature in many energy-renewable solutions.

References

[1] https://skyx.com/ Accessed: 01.03.2021

[2] J. G. Leishman, *Principles of Helicopter Aerodynamics*, Cambridge University Press, New York, 2006.

[3] J. D. Anderson, *Aircraft Performance and Design*, WCB/ McGraw-Hill, Bethesda, 1999.

[4] W. Zientarski, R. Figura, Analysis of the operating parameters of the photovoltaic module, *Buses* (in polish: Analiza parametrów pracy modułu fotowoltaicznego, Autobusy) 12/2016, s.602-611, 2016.

[5] D. Matuszko, *The influence of cloudiness on insolation and total solar radiation*, (in polish:Wpływ zachmurzenia na usłonecznienie i całkowite promieniowanie słoneczne), Wydawnictwo Uniwersytetu Jagiellońskiego, Kraków, 2009.

[6] J.R.L. Monteith, *Physics of the biological environment* (in polish: Fizyka środowiska biologicznego), PWN, Warszawa 1979.

[7] K. Mateja, W. Skarka, Towards energetic autonomy of UAV. *Advances in Transdisciplinary Engineering*, Vol. 12, pp. 423-432.

[8] R. Niestrój, T. Rogala, W. Skarka, An Energy Consumption Model for Designing an AGV Energy Storage System with a PEMFC Stack, *Energies*, 2020, 13(13), 3435.

[9] S. Chukwuebuka Arum, D. Grace, P.D. Mitchell, M.D. Zakaria, N. Morozs, Energy Management of Solar-Powered Aircraft-Based High Altitude Platform for Wireless Communications, *Electronics*, 2020, 9(1), 179.

[10] H. Zhongxi, W. Bo, L. Zhaowei, C. Qingyang, Z. Xiongfeng, Preliminary Design of a Small Unmanned Battery Powered Tailsitter, *International Journal of Aerospace Engineering*, 2016, 3570581.

[11] N. Hinlov, Generalized Models of Basic DC-DC Converters, *AIP Conference Proceedings*, 2018, 2048, 060021.

[12] M. Benes, R. Fucik, V. Havlena, V. Klement, M. Kolar, O. Polivka, J. Solovsky, P. Strachota, An Efficient and Robust Numerical Solution of the Full-Order Multiscale Model of Lithium-Ion Battery, *Mathematical Problems in Engineering*, 2018, 3530975.

[13] M.E. Sahin, F. Blaabjerg, A Hybrid PV-Battery/Supercapacitor System and a Basic Active Power Control Proposal in MATLAB/Simulink, *Electronics*, 2020, 9(1), 129.

[14] S. Allu, B. Velamur Asokan, W.A. Shelton, B. Philip, S. Pannala, A generalized multi-dimensional mathematical model for charging and discharging processes in a supercapacitor, *Journal of Power Sources*, 2014, Vol. 256, pp. 369-382.

[15] W. Abd El-Basit, A.M. Abd El-Maskood, F.A. Soliman, Mathematical Model for Photovoltaic Cells, *Leonardo Journal of Sciences*, 2013, Issue 23, pp. 13-28.

[16] R.H. Stone, The T-wing tail-sitter unmanned air vehicle: from design concept to research flight vehicle, *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2004, Vol. 218, No. 6, pp. 417–433.

[17] U. Ozdemir, Y.O. Aktas, A. Vuruskan, Y. Dereli, A.F. Tarhan, K. Demirbag, A. Erdem, G.D. Kalaycioglu, I. Ozkol, G. Inalhan, Design of a commercial hybrid VTOL UAV system, *Journal of Intelligent & Robotic Systems*, 2014, Vol. 74, pp. 371–393.

[18] R. Mozo Ordóñez, *Diseño de las alas de un vehículo aéreo no tripulado (UAV)*, Universidad De Valladoid Escudela De Ingenierias Industriales, Valladoid, 2017.

[19] A.V. Welles, *Hybrid Electric Distributed Propulsion for Vertical Takeoff and Landing Aircraft*, Syracuse University, 2018.

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GPU-Enabled Physics-Based Floor Plan Optimization Based on Work Place Analytical Data

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Abstract. This paper presents an approach for optimizing floor plans using data collected from workplaces and a physics-based planning algorithm utilizing GPU-acceleration. The approach is compared to two approaches based on Genetic Algorithms and Particle Swarm Optimization. Common objectives, such as minimizing distance between related departments and daylight usage are optimized using the physics-based method in a case study of an actual plot and company. The results show that the physics-based approach is very efficient at handling large amounts of rooms compared to the other methods tested.

Keywords. Floor planning, architecture, particle swarm optimization, genetic algorithm, physics-based.

Introduction

Designing a residential or office building is a complex task, with many constraints and objectives that need to be fulfilled. The requirements come from technical regulations, economical considerations, and workplace efficiency and experience. As regulations and budgetary concerns are often prioritized, the human factors in floor planning are frequently overlooked. To solve this, and to handle the complexity of the design task, computational tools may help. This paper presents a method for efficiently designing a workplace floor plan based on collected data from employees, and constraints such as the outer boundary of each floor.

Generating and optimizing floor plans has been studied at least since the 1970s [1], however, there have been few, if any, attempts to generate them using a physics-based approach. Physics-based form finding has previously been successful in other areas [2], which is why the approach may be interesting for floor planning as well. Rigid body physics and spring based constraints have many properties that make them interesting from a layout point of view as they deal naturally with the interaction of two and three dimensional objects. First, they efficiently prevent overlapping geometry in two and three dimensions. Second, they efficiently handle location-based objectives, such as preferred locations and preferred neighboring objects/rooms. Third, they can efficiently be run on modern graphical processing units (GPUs) using highly parallelized algorithms.

In this paper, a floor planning approach is presented that is based on Nvidias PhysX Flex platform for particle-based rigid and soft body physics through the Flexhopper plug-in for Grasshopper and Rhinoceros. The optimization is based on actual data collected on workplace efficiency and experience, such as area and adjacency requirements. This requirement data is handled by the physics-based method, resulting in a time-efficient way of positioning large amounts of offices in parallel on the GPU. The method is compared to two popular algorithms for design exploration: the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The physics-based method is then applied to a case-study based on actual requirements and building envelopes.

1. Related works

1.1. Floor plan generation

Floor planning has been an interesting optimization and generation problem since at least the 1970s when Eastman [1] did early work on automating floor planning through a rule-based approach for sequentially filling the floor plan. More recent examples include Das et al [3] who use a tree-based partitioning of the boundary to fill grid-based outlines. Flack and Ross [4] use GA and a graph-based approach to evolve rectilinear floor plans. Rodrigues, Gaspar and Gomes [5] study energy efficiency of the floor plan using a two-step approach, where a floor plan is first generated, and then optimized for energy efficiency. Among the approaches that utilize Grasshopper and GA is the work of Boon et al. [6] who use Grasshopper and the plug-in Galapagos to optimize floor plans. They generate floor plans in three dimensions and minimize the distance between the functional areas of the plan.

Within computer graphics, there are also a number of publications that attack the problem, such as Merrel, Schkufza and Koltun [7] and Lopes et al. [8] who use graph-based approaches to plan rectilinear boundaries and Tutenel et al. [9] who use a rule-based algorithm for procedural generation of interiors.

However, none of the above presented works applies a physics-based solver to the floor-planning problem, and none looks at completely arbitrary floor boundaries. While some works discretize an arbitrary boundary using a grid-based system [7][4], the methods do not work directly on the actual outline. Moreover, none of the works utilizes the GPU in finding solutions.

1.2. Genetic Algorithm

First presented by Holland and Goldberg [10][11], GA has been applied to a wide range of applications within building design [12], and has, as mentioned above, been used before in generating floor plans. The genetic algorithm emulates natural evolution by gradually improving the fitness of individuals in a population over several generations. Each individual represents one point in the search space, and is assigned a fitness based on how well it conforms to constraints and objectives. The most fit individuals are then selected to breed the next generation through cross-over and mutation operators. The specific GA implementation used in this paper is Galapagos, which is a Rhino/Grasshopper plug-in.

1.3. Particle Swarm Optimization

PSO has been used for a large number of applications [13][14] including floor planning [15]. PSO is inspired by the motion of, for instance, birds, bees or fish and their ability to work intelligently as a swarm, even though each individual may only be acting according to simple rules. In PSO, each individual, or agent, adapts its motion through the search space according to its history, fitness and neighboring agents. By attractive forces to more optimal regions of the search space, the agents collectively move towards a global optimum. The specific PSO implementation used in this paper is Silvereye, which is a Rhino/Grasshopper plug-in.

2. Description of the implementation

2.1. Workplace efficiency and experience

In order for the results of the floor plan generator to be meaningful, real-life objectives and constraints are required. One way of collecting these is by analyzing an existing workplace through interviews, surveys, location based trackers, video recording, etc. Such data can be analyzed and converted into physical requirements, such as number, size and type of rooms, which functions need to be close to each other, etc. Other requirements in terms of building codes, such as minimum daylight intake and accessibility can also be added. In this paper, the following requirements have been implemented and are taken into account by the algorithms presented:

- Area of room
- Type of room
- Number of rooms of a certain type
- Distance to daylight
- Distance to preferred neighboring functions
- Accessibility
- No overlapping rooms
- No rooms outside the perimeter of the floor

2.2. Physics-based requirements

Some requirements can be fulfilled simply through generating rigid bodies with the correct geometry. However, other requirements need to be represented as forces to enable a physics-based optimization algorithm. Forces include, but are not limited to, user-defined force fields such as point sources, wind, gravity; contact forces between moving and static objects; frictional forces; and forces generated by springs. A summary of how the different requirements were represented is shown in **Table 1**.

Table 1. List of requirements and their physics-based representation

Requirement	Representation
Area of room	Geometry
Type of room	Geometry
Number of rooms of a certain type	Geometry
Distance to daylight	Force field
Distance to preferred neighboring functions	Springs

Accessibility	Contact forces and force field
No overlapping rooms	Contact forces
No rooms outside the perimeter of the floor	Contact forces

2.3. Time-dependent constraints

As applying all force-based requirements at once would result in a sub-optimal solution, where objects do not have enough time to find their optimal positions before being entangled or forced into sub-optimal positions by other objects, a time-dependent approach is needed. The time-dependent approach applies physics-based requirements one at a time. For instance, during the initial stage the rooms are allowed to move freely on the floor plan and are only constrained by the neighboring springs, the floor surface and gravity. This enables the rooms to find their neighbors without any pre-positioning, other than a random scatter at the beginning. The time-line of the approach is shown in Table 2. After a requirement has been activated, it remains active throughout the time-line.

Table 2. Time-line of the requirements

Requirement	Sequence
Area of room	0
Type of room	0
Number of rooms of a certain type	0
Distance to preferred neighboring functions	1
No overlapping rooms	1
Distance to daylight	2
No rooms outside the perimeter of the floor	2
Accessibility	3

2.4. Platform

The rigid body physics simulation is implemented through the Nvidia PhysX Flex software library, which enables rigid body physics to be simulated on Nvidia GPUs. This approach enables massive parallelization of the simulation and orders of magnitude faster simulation times compared to CPUs at a comparable price point. The PhysX library was interfaced through the Flexhopper plug-in for Grasshopper, which, in turn, is a scripting plug-in for the CAD-tool Rhinoceros by McNeel. This enables the definition of geometry such as floor perimeter and office rooms in Rhinoceros' standard CAD interface, and the algorithmic scripting of Flexhopper through Grasshopper. As Rhino provides a familiar CAD interface, this platform is intuitive to use for an Architect.

2.5. Set-up

The scale of the model is in meters, to better work with the default physics settings and numerical limits of the calculations. An artificially high gravity of 350 m/s^2 was used to ensure that the blocks representing the rooms remained in contact with the floor during the simulation. A particle radius of 0.4 m was used. The same radius was used for the Solid Rest Distance and Collision Distance setting, which determines the minimum distance between solids. A Particle and Shape collision margin of 0.5 m was used. A maximum speed of 3.4028e38 m/s and a maximum acceleration of 1000 m/s^2. All the remaining rigid body physics settings were set to 0, except Relaxation Mode, which was left at the default value of True, and Relaxation Factor, which was left at the default value of 1.

The springs between the rooms were connected to the center of gravity for each room and had a spring stiffness of 0.05 and a rest length of 0 m.

The force field that attracts bodies to the outside perimeter was represented as a number of point attractors spread out at equal distances along the perimeter with a strength linearly changing from 100 to -100 throughout the simulation time-line, with a positive value indicating a repulsive force and a negative an attractive force.

To ensure accessibility, a wall offset from the outside perimeter by the width of the rooms and with the thickness of the required corridor was introduced at the last stage of the simulation to force the rooms to leave a void. The corridor was introduced from below the floor to lift up and displace the offending rooms. The corridor initially had a repulsive force field attached to it to force rooms away from it. During the last stage of the simulation, the repulsive force was replaced with an attractive force to pull the rooms to it.

3. Benchmark

The physics-based method was benchmarked against two commonly used methods for design optimization, GA and PSO. The benchmark consisted of a simple outer boundary and a number of rooms to be placed. The objectives were to keep rooms inside the outer boundary, to avoid overlapping rooms, and to place the rooms as closely to each other as possible. To compare how the methods perform with the complexity of the problem, two configurations were run: one with 10 rooms, and one with 100 rooms.

3.1. Set up

The rooms are set up as rectangles with random widths and lengths between 1 and 2 m. Each room is given a random initial position, but within the outer boundary.

The parameters for the GA and PSO methods are the *x*/*y* offsets from the initial position, represented as floating point numbers. The initial value for each parameter is set to 0 m. The parameter intervals are set to -30 m to 30 m, which allows the rooms to be moved just outside the perimeter.

All methods were constrained to a run-time of 1.5 minutes for the 10-room benchmark, and 15 minutes for the 100-room benchmark. While this does not ensure convergence of the result, the difference in efficiency between the methods should be possible to determine.

As Silvereye and Galapagos do not support separate constraints or multiple objectives, the goal functions are weighted into a single objective function that is to be minimized.

Rooms outside of the outer boundary are penalized by adding the number of rooms that are outside the outer boundary, $n_{outside}$, and normalizing the value by dividing by the total number of rooms, n, as described by Eq. 1.

$$f_1 = \frac{n_{outside}}{n} \qquad \text{Eq. 1}$$

The number of overlapping rooms is penalized by counting the number of overlapping rooms, $n_{overlapping}$, and normalizing the value by dividing it by the total number of rooms, as described by Eq. 2.

$$f_2 = \frac{n_{overlapping}}{n} \quad \text{Eq. 2}$$

The objective to bring the rooms as close together as possible is measured by the total distance between the rooms and normalizing the value by dividing it by a reasonable estimate of the maximum possible distance between the rooms and the number of distance comparisons, as described by Eq. 3.

$$f_3 = \frac{\sum_{i=1}^{n} \sum_{j=i+1}^{n} \sqrt{\left(X_j - X_i\right)^2 + \left(Y_j - Y_i\right)^2}}{\sqrt{(X_{max} - X_{min})^2 + (Y_{max} - Y_{min})^2}\, n(n-1)/2} \quad \text{Eq. 3}$$

The weighted objective value used by the GA and PSO methods, $f_{weighted}$, is simply the sum of all objective functions divided by the number of them, as described by Eq. 4.

$$f_{weighted} = \frac{f_1 + f_2 + f_3}{3} \quad \text{Eq. 4}$$

PSO settings: Iterations 100, max velocity 0.200, swarm size 20.

GA settings: Max stagnant 50, Population 50, Initial boost 2, Maintain 5%, Inbreeding 75%.

3.2. Results

The results for the benchmark run with 10 and 100 rooms are presented in **Figure 1** and **Figure 2** respectively. The fitness reported in the figures is based on $f_{weighted}$ from Eq. 4. A visual representation of the results for the methods is presented in **Figure 4**. It is evident that the physics-based method converges on a result very quickly compared to the two other methods. The difference in convergence rate is even more evident in the 100-room benchmark. The PSO method seems to be more suited to this particular problem than GA.

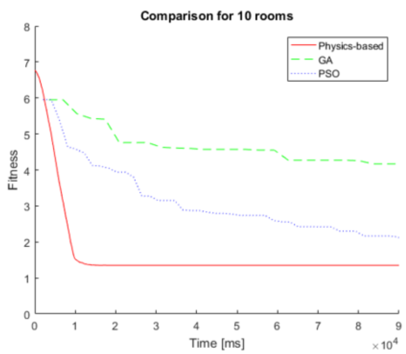

Figure 1. Fitness over time for the three methods while optimizing the placement of 10 rooms.

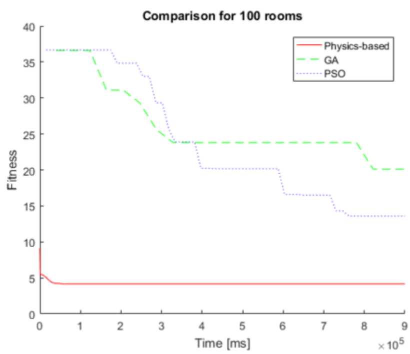

Figure 2. Fitness over time for the three methods while optimizing the placement of 100 rooms.

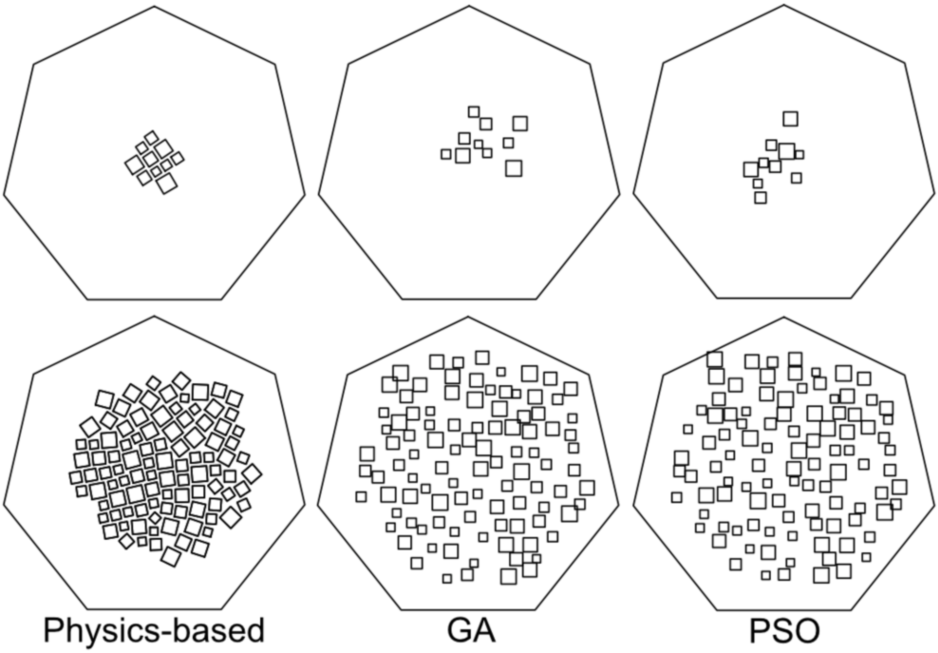

Figure 3. A visual representation of the optimization results for the three methods.

4. Case study

A floor plan for an office space in the H+ area of Helsingborg, Sweden was used as the starting point, see Figure 4. Workplace data from WPA for an anonymous company was used as a basis for the requirements. Based on this data, geometries for the different rooms and their preferred neighboring functions were input.

Figure 4. Plan for the area specified for the case study, with the building footprint marked in red (courtesy of Helsingborg Stad and Superlab)

Enabling requirements one after another, the results shown in **Figure 5** are achieved. Initially, only the accessibility, perimeter and no overlap requirements are enabled, as shown in **Figure 5**a. In the **Figure 5**b, the proximity requirements are enabled, resulting in the two groups of rooms to cluster together. In **Figure 5**c, the proximity to the outer perimeter requirement is enabled. The algorithm was then applied to several floors of the building, with the results presented in **Figure 6**.

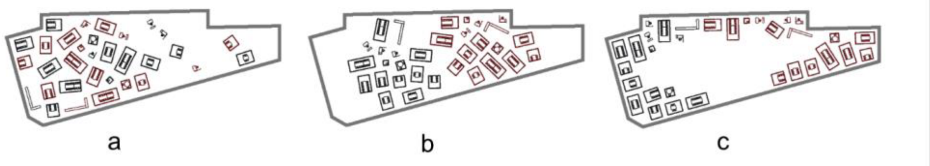

Figure 5. Rooms placed within the boundary. The rooms are color-coded based on the department they belong to.

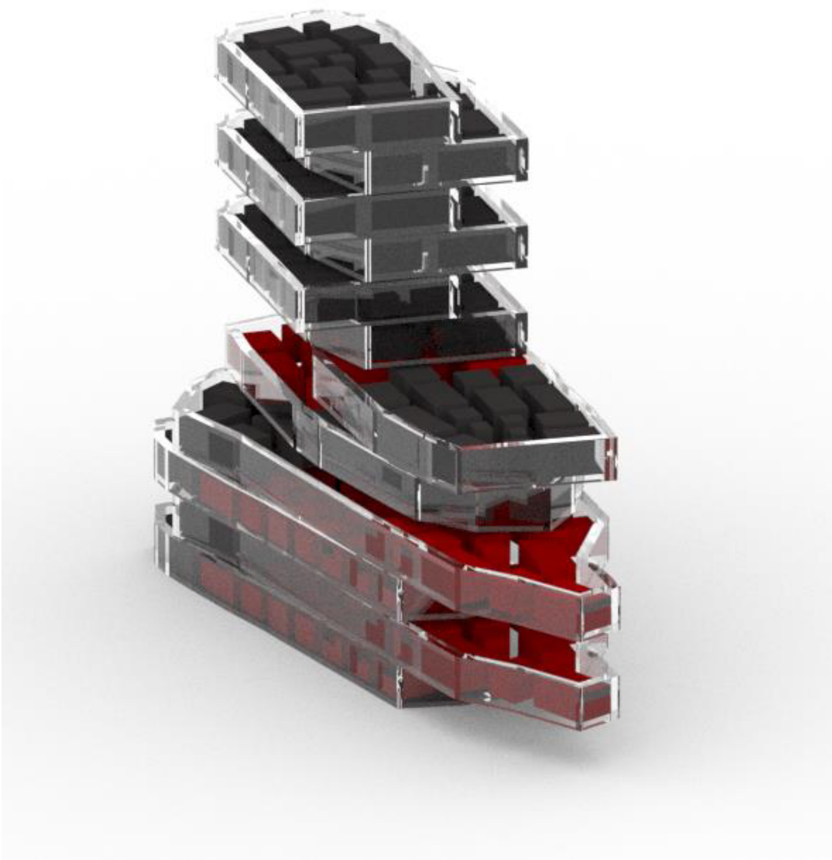

Figure 6. The physics-based algorithm applied to several floors in a building.

5. Conclusions

This paper has demonstrated that physics-based floor planning is a viable method for quickly and efficiently determining the optimal position of rooms within an outer boundary. With the given constraints and objectives described in this paper, the physics-based method outperformed popular methods such as GA and PSO. It should be noted, however, that the convergence rate of stochastic methods like GA and PSO will vary slightly depending on the initial random seed and more independent runs would be needed to statistically compare the methods.

While physics-based optimization is promising in its efficiency, there are limitations to its usability. Mainly, the challenge lies in being able to represent objectives and constraints as physical forces.

Acknowledgements

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References

[1] C.M. Eastman, Automated Space Planning, *Artificial Intelligence*, 1973, 4 (1): 41–64.
[2] D. Piker, Kangaroo: Form Finding with Computational Physics, Architectural Design, 2013, Vol. 83 (2): 136–37. https://doi.org/10.1002/ad.1569.
[3] S. Das, C. Day, A. Hauck, J. Haymaker, and D. Davis, Space Plan Generator: Rapid Generation & Evaluation of Floor Plan Design Options to Inform Decision Making, *Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*, 2016, 106–15.
[4] R.W.J. Flack and B.J. Ross.. Evolution of Architectural Floor Plans, *Lecture Notes in Computer Science*, 6625 LNCS, 2011, pp. 313–322.
[5] E. Rodrigues, A. Rodrigues Gaspar and Á. Gomes. Improving Thermal Performance of Automatically Generated Floor Plans Using a Geometric Variable Sequential Optimization Procedure, 2014, *Applied Energy*, Vol. 132, pp. 200–215.
[6] C. Boon, G. Corey, N. Papaefthimious, J. Ross, and K. Storey, Optimizing Spatial Adjacencies Using Evolutionary Parametric Tools: Using Grasshopper and Galapagos. *Perkins + Will ResearcH JournaL* 2015, 07 (02): 25–37
[7] P. Merrell, E. Schkufza and V. Koltun. Computer-Generated Residential Building Layouts, *ACM Transactions on Graphics*, 2010, 29:1, https://doi.org/10.1145/1866158.1866203.
[8] R. Lopes, T. Tutenel, R.M. Smelik, K.J. de Kraker and R. Bidarra, A Constrained Growth Method for Procedural Floor Plan Generation, *11th International Conference on Intelligent Games and Simulation, GAME-ON 2010*, pp. 13–20.
[9] T. Tutenel, R. Bidarra, R.M. Smelik and K.J. De Kraker. Rule-Based Layout Solving and Its Application to Procedural Interior Generation. *Proceedings of the CASA Workshop on 3D Advanced Media in Gaming and Simulation (3AMIGAS)*, 2009, https://graphics.tudelft.nl/Publications-new/2009/TSBD09a/TBSD09aRB.pdf, Accessed July 1, 2021.
[10] J.H. Holland, *Adaptation in Natural and Artificial Systems*. The University of Michigan Press, Ann Arbor, 1975.
[11] D.E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison-Wesley, Reading, 1988.
[12] A.T. Nguyen, S. Reiter and P. Rigo, A Review on Simulation-Based Optimization Methods Applied to Building Performance Analysis, *Applied Energy*, 2014, Vol. 113, pp. 1043-1058.
[13] R. Poli, Analysis of the Publications on the Applications of Particle Swarm Optimisation, *Journal of Artificial Evolution and Applications*, 2008, pp. 1–10. https://doi.org/10.1155/2008/685175.

[14] J. Kennedy and R.C. Eberhart, Swarm Intelligence, *IEEE Technology and Society Magazine*. 2002, Vol. 21, Issue 1, pp. 9, https://doi.org/10.1109/MTAS.2002.993594.

[15] T.Y. Sun, S.T. Hsieh, H.M. Wang and C.W. Lin, Floorplanning Based on Particle Swarm Optimization, *Proceedings - IEEE Computer Society Annual Symposium on Emerging VLSI Technologies and Architectures 2006*, 2006, pp. 7–11. https://doi.org/10.1109/ISVLSI.2006.46.

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Analysis and Optimization of the Propeller Shape for a Stratospheric Drone Research Platform

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Abstract. Fix-wings small aircraft or drones, for flight, must be equipped with a source of thrust. In most cases, it will be propulsion systems including engine and propeller that generate the necessary thrust force. Regardless of whether the system includes an electric motor, combustion, or hydrogen engine of torque moment, the most important element of the system is the propeller. It is the element responsible for generating thrust, which is the force necessary for the flight in each of its stages. The article presents all stages of the analysis and optimization of the propeller for the considered highly flexible structure stratospheric drone. Analysis, after integration with CAD software, allows for the preparation of a comprehensive generative model. The basic propeller parameters were selected on the basis of flight altitude, considered structure, flight time, flight speed, the weight of the structure, assumed location of the engine and propeller. These assumptions made it possible to conduct a preliminary analysis of loads, propeller blade pressure distribution, thrust, and the total level of vibrations. The goal of the research is to develop a methodology of designing and preliminary analysis of propeller, which can be integrated into the generative model.

Keywords. Propeller, transdisciplinary, generative model, aircraft design, stratospheric drones.

Introduction

There are many types of propulsion used in aviation. The most common drive in civil aviation, modeling, and the drone industry is a system consisting of internal combustion or electric motor and a propeller that converts rotational energy into thrust. A very big problem is the proper selection of propeller parameters for the designed aircraft structure. This is usually a long process that requires a lot of testing. This article presents the optimization of the propeller blades used in the "Twin Stratos" UAV HALE designed by SkyTech eLab in cooperation with the Silesian University of Technology. All parameters adopted for the calculations were based on the data provided by the main designer.

The performance of the designed structure depends mainly on the quality of the selected propeller and the optimization carried out. The propeller is responsible for the greatest loss of energy supplied to the drive system due to its transformation. The main assumption of the designed HALE UAV is to use two engines whose propellers will rotate counter-rotating for stability. Maneuvering will be accomplished in part by the

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difference in engine thrust. It follows that one propeller should provide the thrust necessary for the flight of the entire designed aircraft. Another assumption is the use of a propeller with folding blades. This is the reason that the efficiency of the central part of the propeller will be reduced.

The main research problem described in the article is the optimization of the propeller blade shape, taking into account the assumptions described above. This is an unusual case due to the high flexibility of the supporting structure and, consequently, the low allowable frequency of vibrations generated by the drive system. This problem was solved with the use of mathematical sciences and fluid mechanics, with the use of motion equations, into which the assumed input data were introduced, the procedure was also introduced in the further part of the article. The obtained results constitute comparative data for further analysis. Another scientific discipline used to solve the problem is computer science, which uses modern CAD software. The last discipline is mechanics, electrical engineering, and mechatronics based on laboratory analysis carried out in a specially designed measuring platform. The results of the analyzes were compared, and the relationships between the input data, calculated values, and measured data allowed for the creation of the propeller optimization methodology. Due to the necessity to conduct a practical analysis, a design of a measuring platform was developed, the purpose of which is to conduct comparative practical tests. The results of the practical test will be compared with the results obtained by numerical analysis.

1. Basic propeller information

Aviation propellers are designed to convert the rotational energy of the engine shaft to the force of thrust. The thrust is the force generated by the rotating propeller, and the axis of rotation is the direction of the force. In simplified terms, it can be assumed that the propeller is a specific gear, the efficiency, and optimization of which is the problem discussed in this article. The propeller considered and optimized is the so-called slow-speed propeller, the rotational speed of which does not exceed 6000 [rpm]. It is characterized by wide, elliptical blades.[1]

The main dimension of the propeller is its radius R. It is the diameter of the circle made at the ends of the blades. Propeller pitch H, as shown in Figure 1. This is the distance the propeller would travel in one revolution (from point 0 to point 1) if it could screw into the air without slip, like a bolt into a nut [2]. The actual pitch of the propeller depends on the ratio of the flight speed to the rotational speed of the propeller. When there is no propeller thrust because the speed is very high (e.g. diving) or there is no slip because the propulsion is stationary (e.g. the start of take-off), no has high efficiency of the propeller, because at take-off it should have a small angle of attack, and as speed increases, it should increase [3]. Therefore, a fixed-

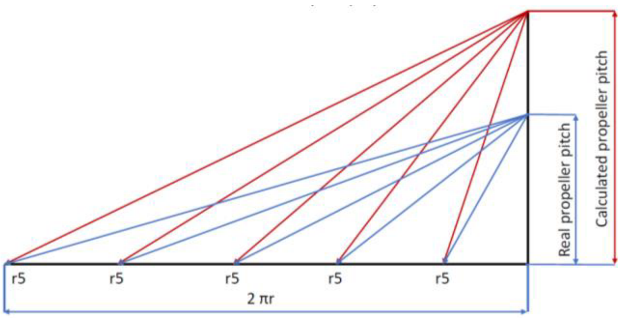


Figure 1. Fixed pitch propeller

pitch propeller achieves maximum efficiency at a certain airspeed, i.e. it is operational within a narrow speed range.

2. Methodology of propeller optimization

There are many ways to optimize the pitch of the propeller blades. The article presents the main methods of propeller optimization. Nowadays the most common are numerical optimization of the shape of the blades. As shown in Figure 2, this type of optimization is the easiest way to get the best results. The results are obtained using FEM analyzes that can be performed after the appropriate interference of the numerical model and, as in the case of the presented work, with the use of modern technologies enabling the production of physical elements and the analysis of their parameters for measurement platforms. Figure 3, presents the optimization process used in the analysis of the presented propeller design. Due to the time of conducting practical tests and the time of making models, the first optimization is usually performed based on the virtual environment and FEM tools. The optimization must be based on preliminary calculations that give information about the initial diameter of the propeller, the initial position of the blade at the different radius. Table 1 shows the possible ways of analyzing the designed propeller.

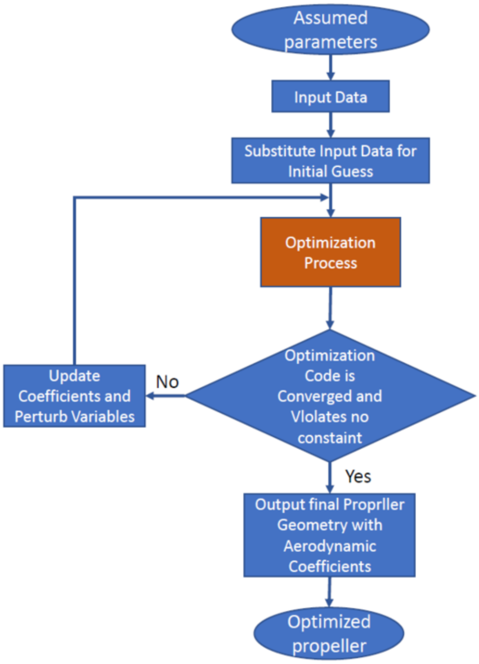


Figure 2. Propeller mathematical model optimization process chart

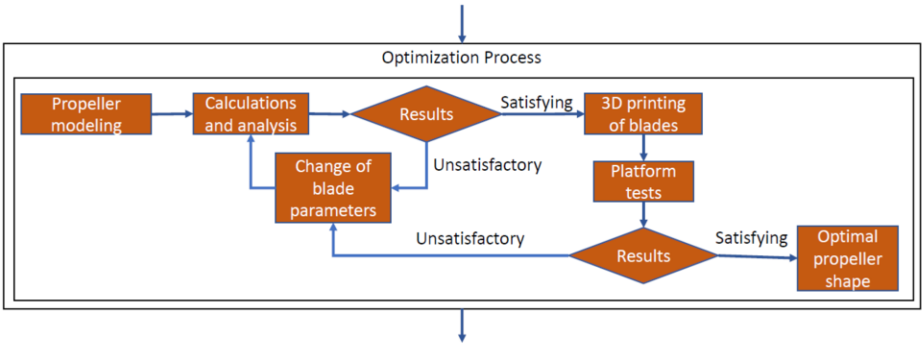


Figure 3. Propeller optimization process chart

Table 1. Propeller optimization methods

Method	Description of the method
Empirical method	This empirical method is based mainly on two parts namely nomographs – Cluton (1990), and is a combination of graphics with lines marked with scales representing parameters like power, airspeed, engine speed, propeller diameter and reference lines. For design a new blade, lines are drawn (manually) connecting three input parameters: engine power, engine speed and flight speed. As outputs, the method provides the propeller diameter, pitch and efficiency. [4]
Vortex Lattice Method (VLM)	To improve the efficiency of propellers using the Vortex Lattice Method, CP is kept as an equality constraint and CT became an objective function. Using the VLM, the twist angle distribution can be optimized. [5]
Chord length distribution optimization	As before, CT is an objective function to be maximized and CP and AF, an activity factor, are equality constraints. The activity factor is defined and it represents the power absorbed by a propeller. Here, an activity factor is added as another equality constraint, since the chord length distribution can be optimized under the same activity factor and advance ratio.
3-D panel method	The 3-D panel method used in this study is a lifting surface theory developed by Cho and Williams [7,8] and it is based on unsteady, linear aerodynamics. The method is brie¯y explained in the following subsections and more details on the method can be found in [8].
Xrotor	Xrotor [9] is an interactive program for the design and analysis of propellers and channel and free-drive fans. Xrotor was created by Mark Drela and Hal Youngren, who are also the creators of the well-known Xfoil [9]. Xrotor is Fortran-based software; therefore requires the Fortran compiler to create a command-line based work environment.[10]
CAD modeling method	Preparation for numerical optimization begins with the definition of some variables and parameters that defines the problem, its possible solution domain and constraints.[11] In this analysis were used SolidWorks software in which optymization were made in the basis of aerodynamic thrust and moment of inertia analysis results.

3. Propeller appropriate profile selection for the considered aircraft

A properly selected and optimized propeller made in the appropriate technology determines how the entire propeller will behave during take-off, flight at maximum speed, and flight with cruising speed. These parameters are best presented by a full, three-dimensional Navier-Stokes solution. Unfortunately, Navier-Stokes solutions of most rotating wing devices are traditionally limited by the tendency for non-physical dissipation of vorticity and the substantial computational resource requirements [12]. There is a possibility to simulate turbulent fluid motions, Reynolds decomposed the flow quantities into its average and fluctuating components. The new quantities were substituted to the Navier-Stokes equations and as a result, Reynolds Averaged Equations (RANS) were obtained. The fluctuating components in the transport equations are unknown and cause the system of the equation not to be closed. Additional equations, which enable solving the new terms, are defined as turbulence models [13].

Based on the research carried out by Woelke [14], it can be concluded that the numerical analysis may be applicable only in the initial design stages and the physically obtained flows may have significant differences with the calculated values even when assuming the appropriate initial values and additional parameters. These differences result from parameters not included in the calculations.

The selection of the propeller is a very important element - we want to get as much thrust from the drive unit as possible. The larger the propeller, the greater the thrust, the greater the pitch for the same diameter, the greater the speed of the demonstrator. An important factor is also the type of the model under consideration - the aerobatic model uses propellers with a larger pitch (they fly at higher speeds), slow-rotating RC models should have a propeller with a smaller pitch (definitely slower), and models flying very slowly with the largest possible diameter for a given engine with the shortest possible stroke. Another important factor is choosing the right propeller diameter for a given engine. Too little causes the engine to run at maximum revolutions, too much overloads the engine without achieving the maximum possible thrust. The propellers with small diameter and narrow blades require very high rotational speeds - in the order of a dozen or even twenty thousand revolutions per minute, in order to generate the appropriate thrust.

Folding propellers work best in low-speed models, i.e. motor gliders. When the engine is turned on, the propeller blades unfold as a result of the centrifugal force, and when the engine is turned off - they fold along the fuselage, creating little aerodynamic drag. The motor is electrically braked, otherwise, the propeller will continue to rotate acting as a brake.

4. Optimization based on initial calculations and aircraft parameters

Flight parameters for the designed aircraft are a set of assumptions that allow the initial calculation of the aircraft parameters. They define the maximum flight altitude, cruising speed, or other main values. The main flight parameters necessary to do the calculations of the designed aircraft are presented in the table Table 2.

Table 2. Optimal flight parameters for propeller

Parameter	Signature	Value	Unit
Air speed	Va	50	[km/h]
Rotational speed	ω	2100	[rpm]
Wing area of the aircraft	A	0,53	[m2]
Mass of aircraft	m	7,1	[kg]
Number of motors	Nm	2	[-]

A mathematical analysis was performed based on the existing propeller data based on the CLARK-Y profile. The equations presented by Romander [12] were used, these are the basic calculations used in the design of the propeller blades. This allowed for the initial determination of the value of the propeller size, generated thrust at a given flight speed and efficiency. Those parameters are presented in Table 3.

Table 3. Initial parameters of propeller.

Parameter	Signature	Value	Unit
Tip diameter	D	0,37	[m]
Number of blades	NB	2	[-]
Disc Area Ratio	DAR	0,10752	[m2]
Hub Diameter	HD	5	[mm]
Hub Area	HA	19,635	[mm2]

Obtaining these data allowed to analyze the potential linear displacement of the propeller assuming perfect incompressibility of the surrounding center, i.e. the theoretical pitch. After taking into account the efficiency from CAD analysis of the propeller, this parameter allows determining the actual thrust.

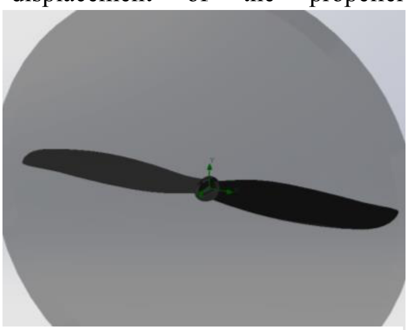


Figure 4. Standard propeller for RC airplane models

Table 4. Calculated blade angles

Station	Radius [mm]	Pitch [mm]	Blade Angle	Mach number
1	5	174.68	79.80	0.017

2	15	165.23	60.30	0.019
3	25	164.37	46.30	0.023
4	35	164.64	36.82	0.028
5	45	165.28	30.31	0.033
6	55	166.09	25.67	0.039
7	65	166.98	22.24	0.045
8	75	167.93	19.61	0.051
9	85	168.91	17.55	0.057
10	95	169.92	15.89	0.063
11	105	170.93	14.53	0.069
12	115	171.96	13.39	0.075
13	125	173.00	12.42	0.082
14	135	174.04	11.60	0.088
15	145	175.09	10.88	0.094
16	155	176.14	10.25	0.101
17	165	177.19	9.70	0.107
18	175	178.25	9.21	0.113

Pitch p, is the theoretical axial displacement in one turn as if a reference blad section was moving without any slip Table 4, shows the initial calculations of the propeller blade and on the basis of that calculations, the first model of the propeller was designed and analyzed in CAD tool.

5. Optimization based on an detailed virtual 3D model

Analysis of generated thrust for two types of propellers was performed using the SolidWorks software. For this purpose, a standard propeller was used, used in modeling as a drive for model aircraft. The visualization of the analyzed propeller is presented in Figure 4. This propeller was treated as a reference point for the designed and optimized propellers.

A propeller was designed, the diameter of which did not exceed the value previously calculated based on the power method. The optimization aim to obtain the thrust necessary for flight at the maximum allowable engine speed. This parameter was obtained by changing two parameters influencing its value. These are the propeller pitch and the length of the profile chord on different propeller diameters. The main limitations are the diameter of the propeller and the amount of drag generated by the propeller. Due to the use of two propellers, the diameter must be selected in such a way as not to cause mutual losses in the thrust value. The resistance of the rotating propeller, however, cannot be too high for the previously selected electric motor.

The optimization was based on previously calculated angles of attack of the propeller in profiles on individual cross-sectional diameters. The results of the first propeller made in this way did not meet the design requirements due to the insufficient value of the thrust generated at the key rotational speeds for the designed structure. Results are presented in Table 6.

The SolidWorks FEM analysis required the creation of a virtual wind tunnel, the internal conditions of which will be strictly defined and constant. Thanks to this procedure, it was ensured that all changes in speed, pressure, and temperature were caused by the rotating tested propeller [15]. This wind tunnel is shown in Figure 5.

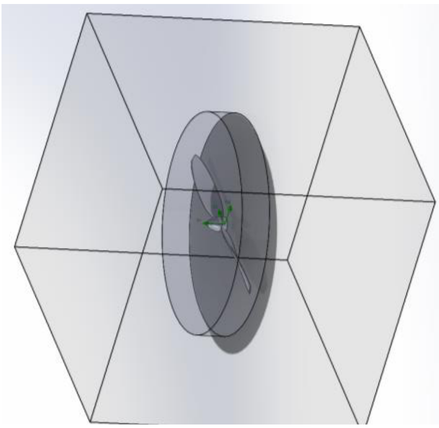
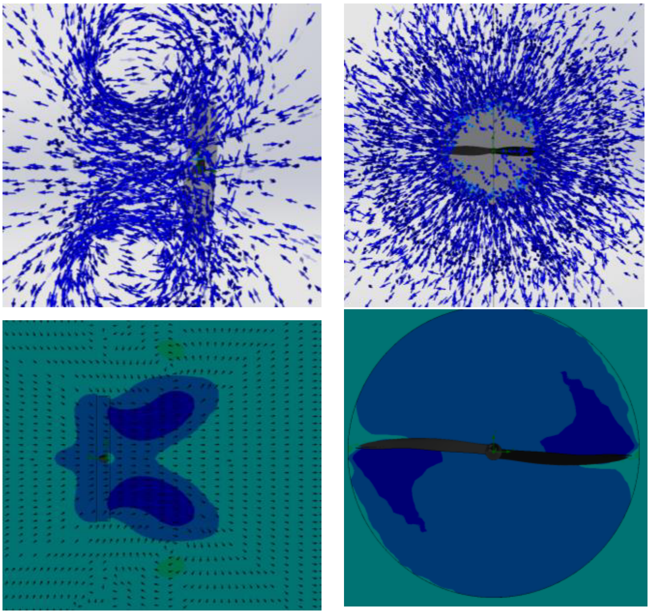


Figure 5. Virtual wind tunel with designed propeller inside

The figures below show the research based on of which the optimization of the blade shape, the angles of attack of individual sections, and the length of the chords used in these sections was carried out. Figures in table Table 5, show views of the air flowing while the engine is running. This is important because it is easy to see where and at what rotational speed the airflow starts to become unstable (turbulent).

Table5. Pressure and flow distribution during CAD analysis



Turbulent airflow changes the performance of the propeller in the area where it occurs. The pressure changes generated by the rotating propeller shown in Table 5, define the places where the air stream hitting the wing would have a destructive effect on the aircraft, causing the vibrations in the structure. Results of analyzing the optimized type of propeller are presented in table Table 6.

Table 6. Analysis results for propeller design

Data	Standard drone propeller 15”	Manually calculated propeller first design	SolidWorks first optymized propeller	SolidWorks final optymized propeller	Units
Propeller design	Ready model	Design I	Design II	Design III	
Diameter of propeller	~332	330	330	330	[mm]
Average thrust for 100 [rad/s]	0,217	0,291	0,387	0,337	[N]
Average thrust for 140 [rad/s]	0,388	0,597	0,753	0,738	[N]
Average thrust for 180 [rad/s]	0,703	0,984	1,275	1,211	[N]
Average thrust for 220 [rad/s]	1,061	1,509	1,816	1,792	[N]
Average thrust for 260 [rad/s]	1,464	1,978	2,723	2,568	[N]
Average thrust for 300 [rad/s]	1,964	2,817	3,559	3,296	[N]

As a result of the research, the shape of the propeller was created, which was selected to make a prototype in the form of a 3D printout. The model of a specific propeller will be rebuilt so that it is possible to fold the propeller. This is one of the main assumptions of the project and the work related to it will be presented in the next scientific publication. The final shape of the designed propeller is shown in Figure 6.

Due to the limitations imposed by the achievable engine power and optimal rotational speeds. The profile that generated the highest thrust was not selected as the optimal shape. The optimal profile was defined as the generated thrust was the highest for the resistance to rotation.

Figure 6. Final optymized propeller blade shape

6. Presentation of the design of measuring system

To analyze the obtained results in laboratory conditions, a measuring platform was constructed and built to measure the thrust value of the drive set in the form of an electric motor and a propeller. See Figure 7. The platform was equipped with a trolley attached to a strain gauge beam measuring the pressure force, the other end of which was attached to the mainframe of the test platform. The motor mount and the motor itself are placed on the trolley. See Figure 8. The generated thrust will be measured by a change of electrical resistance generated by the deformation of potentiometric beam. See Figure 9.

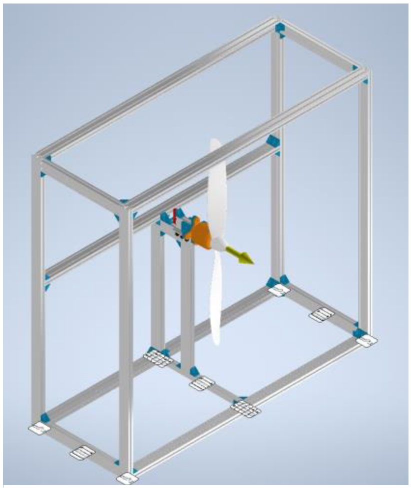


Figure 7. View of measuring system frame

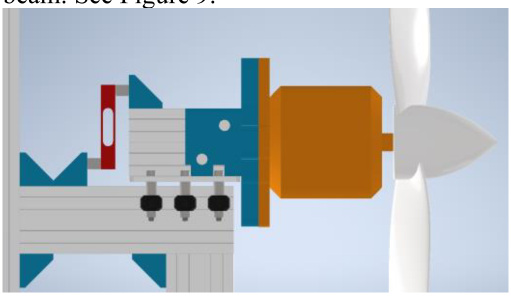


Figure 8. View of motor and propeler month in measuring system

Carrying out the test requires placing a linearly movable trolley on which an electric motor equipped with a speed controller will be mounted. It will allow determining the actual rotational speed of the propeller. The measurement obtained from the strain gauge beam combined with the engine rotational speeds will allow generating thrust diagrams, which will be a comparative value for each of the considered propellers.

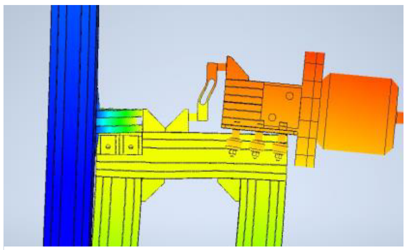


Figure 9. View of displacement during measurement

7. Discussion and conclusions

Parameters based on which the preliminary calculations were made, the calculation of the necessary engine power, and the optimal propeller size and rotational speed were used to make preliminary calculations for the propeller. It should be noted that the calculations were made based on the demonstrator on a smaller scale. This model has been optimized for a specific type of mission.

Pre-determined mathematically optimal propeller sizes, mean chords and angles of attack at different reference diameters were used to generate a preliminary CAD model using SolidWorks. In this program, the first analysis of the thrust generated by the mathematically calculated propeller was also performed. The results of the analysis showed suboptimal thrust values and a significant amount of power necessary to turn the propeller.

The first shape optimization was carried out by operating the angle and chord lengths for individual reference diameters of the propeller. Many types of propellers were created and were subjected to the same virtual aerodynamic tests as the initial propeller. As a result of this test, a propeller was selected, the parameters of which correspond to the required engine rotational speed and the predetermined diameter.

The next stage of work was to develop a methodology for testing propellers that will allow determining the thrust of the analyzed propellers. In order to develop this methodology, a measuring platform has been designed on which the necessary thrust tests will be carried out. The final stage of the works will be the transformation of the developed propeller into a folded propeller. Another optimization of the blade shape for the folded propeller. Printout of optimized propeller blades and their assembly on the head with the possibility of folding the blades. Tests carried out on an estimated stand will confirm the effectiveness of the methodology for developing foldable propellers for low-speed propulsion systems of HALE UAV aircraft.

The experience gained during the analysis for the given demonstrator, based on which the above article was written, will allow for easier determination of thrust parameters, rotational speeds, and assumed propeller profiles for the TwinStratos aircraft in the 1:1 scale. The data on the calculations used for the propeller was also used to create a calculation methodology and analysis for similar HALE UAV aircraft.

Acknowledgement

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References

[1] P. Yu, J. Peng, J. Bai, X. Han, X. Song, Aeroacoustic and aerodynamic optimization of propeller blades. *Chinese Journal of Aeronautics*, 2020, Vol. 33, pp. 826-839.

[2] M. Rostami, A. Farajollahi. Aerodynamic performance of mutual interaction tandem propellers with ducted UAV, *Aerospace Science and Technology*, 2021, Vol. 108, 106399.

[3] K. Wang, Z. Zhou, X. Zhu, Z. Xu, Aerodynamic design of multi-propeller/wing integration at low Reynolds numbers, *Aerospace Science and Technology*, 2019, Vol. 84, pp. 1-17.

[4] O. de Almeida, F.C. de Miranda, O.F. Neto, A Comparative Study for Propeller Blade Design, *Engenharia Térmica (Thermal Engineering)*, 2016, Vol. 15, pp. 30-37.
[5] J. Cho, S. Lee, Propeller Blade Shape Optimization for Efficiency Improvement, *Computers & Fluids*, 1998, Vol. 27, pp. 407-419,
[6] R.S.A. Turner, *Design and Optimisation of a Propeller for a Micro Air Vehicle Using Computational Fluid Dynamics*, OFFCDT, School of Engineering & Information Technology. ZEIT 4500 Aeronautical Thesis & Practical Experience, Final Thesis Report 2010
[7] J. Cho and M.H. Williams, Propeller-wing interaction using a frequency domain panel method, *Journal of Aircraft*, 1990, Vol. 27(3), pp. 196-203.
[8] M.H. Williams, *An unsteady lifting surface theory for single rotation propellers*, Purdue University Report, W. Lafayette, IN, 1985.
[9] M. Drela, *Xfoil: An interactive program for the design and analysis of subsonic isolated airfoils*, http: //web.mit.edu/drela/Public/web/xfoil/. Accessed Februar, 2016.
[10] P. C. Klein, *Parametric modeling and optimization of advanced propellers for next-generation aircraft*, Delft University of Technology, Thursday August 31, 2017
[11] M. Lis, *Numerical analysis and optimization of motoglider's propeller structure*, Institute of aviation, al. Krakowska 110/114, 02-256 Warsaw, Poland
[12] E.A. Romander and M. Field, Computational simulation of propellers in cruise, *Proceedings of the 23rd Congress of International Council of the aeronautical Sciences*, Toronto, 2002, Canada, pp.212.1-212.10.
[13] Woelke, M., Viscosity turbulence Models employed by Computational Fluid Dynamic, *Transactions of the Institute of Aviation*, 2007, 191, pp. 92-113.
[14] K.Szafran, O. Shcherbonos, and D. Jemocki, Effects of Duct Shape on Ducted Propeller thrust Performance, *Transactions of the Institute of aviation*, 2014, 237, pp. 84-91.
[15] Solid Works aerodynamic analysis tutorial from: https://www.engineersrule.com/tutorial-performing-flow-simulation-aerofoil/ , 2021.

Part 6

Individual and Teams

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Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Virtual Tours to Promote the Remote Customer Experience

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Abstract. Today, virtual reality and augmented reality can allow people to interact with products and places in a very realistic way. In this direction, the use of immersive virtual tours (VTs) can improve the users' experience, their perceptions, attitudes and even intended behaviours as potential or actual consumers. The paper focuses on a traditional Italian cheese product and defines a transdisciplinary, multimodal approach where VT helps the remote customer experience based on a VT application to virtually visit a Parmigiano Reggiano cheese dairy, using cutting-edge virtual reality set-up. The paper describes how to create a virtual tour of industrial plants by mapping the main actions, from the storytelling definition, to the plant digitization, until the creation of the virtual, immersive and multimodal application using Unity3D. The VT combines visual experience with gesture recognition and audio stimulation, adding also olfactory cues, in order to create an interactive and realistic experience.

Keywords. Virtual Reality, Virtual Tours, Customer Experience, user-centered design, multimodal approach

Introduction

Virtual Reality (VR) technologies are able to create interactive, digital environments to give users the illusion of displacement to another location, also simulating different tasks [1]. To achieve this result, a set of technologies (e.g. head-mounted display, input devices, motion capture) are used to interact with an artificial scenario, digitally simulated with a high-performance computer, reproducing a real world or creating an imaginary environment. Nowadays, VR applications are increasingly widespread due to the reduced cost of devices and the development of robust platforms that can limit the programming effort [2]. VR applications can range from design to manufacturing, comfort assessment and training, from medicine [3] to industry [4], museum [5] and marketing [6]. However, even though VR promises to be validly used for consumer marketing, its potential impacts are currently not well understood [7]. In particular, the combination of VR and 360° videos to create some novel marketing experiences has not been exploited in a meaningful way yet [8], although is actually not exploited. Moreover, the Covid-19 pandemic situation emphasized the need of new marketing solutions in

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order to promote remote experience of products and places. In the last year, VR offered a risk-free way to escape the destination and travel in a safe and comfortable way [9]. In this context, VR could be used to ensure the creation of an interactive and engaging tours with the scope to emotionally affect the user and raise his/her awareness about the culture of a typical product and its origin, encouraging consumers from all over the world to visit physical dairies and to buy products. Companies can share with their customers an immersive, realistic experience with the product and the production process. From literature review, it emerged that VTs are already used for retail purposes, mainly based on 360 images and videos [10], but customers are barely involved in the process of production to raise their interest in the product. The aim of the research is using VR to replicate the customer experience lived by users inside the production site, choosing one of the main Italian well-known agri-food products, the Parmigiano Reggiano (PR) cheese. The adopted approach was defined transdisciplinary as it integrated computer sciences, engineering disciplines and user-centered design approach together with marketing issues, dissolving the boundaries between them, and promoting learning-by-doing. It was possible by applying technical virtual simulations with a novel marketing scope. This work describes how to use VTs to create a remote customer experience and validate this approach on the mentioned case.

1. Research background

In recent decades, the ever-increasing technological innovation, the world interconnection and the lower cost of technological devices have grown a strong motivation towards the digital world, especially in the retail context [11]. The application of immersive virtual technologies is aimed at supporting experience simulation, as well as training [12], in a variety of different application areas, ranging from therapy [13], marketing [14,15], gaming [16], film industries [17], education [18,19], art and museums [20], sales al retail [21], tourism [22], until to wine tourism gastronomic [23]. VR tools are able to digitally reconstruct the real world, including spaces and objects, that can be explored through appropriate devices, interacting with production sites and products. Focusing on the marketing sector, virtual simulation can lead a consequently positive impact on the user's purchasing decisions by showing remotely the product and/or production process features [24]. For instance, companies can give an immersive virtual tour to potential customers, able to simulate an actual interaction with the product and the production site even from considerable distances, practically all over the world.

Moreover, the last pandemic scenario due to COVID-19 accelerated the need to create VTs as a real opportunity to effectively bring people in places they cannot visit. Indeed, VTs can easily give access to a specific location in a remote way [25,26], a museum [27], a process or a product production for marketing purposes [28] or a specific tourist attraction [29,30]. In addition, VTs could be also used for educational scopes, for students' learning [31] or tourists' education [19]. The majority of VTs are "static" considering the user in a fixed position viewing a 360° image [32] or experiencing an engaging 360° video [33]. On the contrary, a VT is more immersive and interactive, and enables the user to freely move into the scene, being involved in specific tasks thanks to a responsive scenario.

2. Methodology

This paper proposes a methodology to effectively build interactive VTs to empower local products marketing and sales. For this purpose, the new proposed methodology aims at creating a remote customer experience with the final goal to improve the number of people visiting the production site and improve the product sales, also in different geographical areas, using a user-centered approach, starting from the user research and user needs' definition. The method uses several VR technologies to create an interactive simulation by combining 360° videos with interactive virtual scenes to stimulate the users' multi-sensorial involvement and provide a valuable customer experience in a remote way.

The methodology exploits a set of software and hardware devices as shown in Figure 1. First of all, Unity3D is the main development platform for generating virtual and immersive contents to create a true-to-life simulation. Moreover, a specific VR platform (SteamVR) is used to enjoy the VR space wearing a head mounted display (HMD), managing specific camera settings to adjust the correct user's point of view. Video editing software tools (Insta360 Studio 2020 and Premiere Pro) are used for video recording and post-processing. In addition, Blender is adopted for 3D modelling and high-quality rendering. Finally, Reaper was useful for audio editing and recording correction about the audio storytelling by the narrative voice.

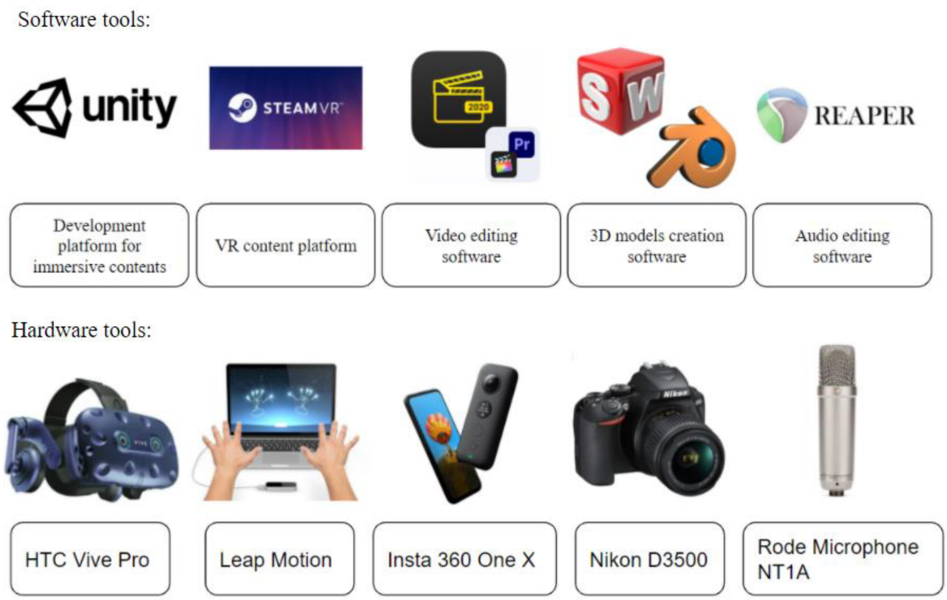

Figure 1. Adopted software and hardware tools.

About hardware devices, the HTC Vive pro eye is used as HMD; it is equipped with 32 infrared sensors for 360-degree tracking, a gyroscope, an accelerometer, and a laser position sensor. The Leap Motion controller allowed hand tracking and gesture recognition to make users interact with its bare hands. Hands position, even the fingers, are tracked with high-precision infrared camera system and digitalized by complex

mathematical algorithms. For shooting immersive contents and digitizing real sites, a 360 camera (Insta 360 One X) is used together; a reflex camera (Nikon D3500) is used then for texture gathering. A smartphone is adopted for the One X camera remote control, for streaming in real time the camera point of view and light-effect settings. At last, a high-quality recorder (Roe Microphone NT1A) is used for audio recording.
Using the proposed set-up, five phases are defined to create a VT simulation as shown in Figure 2, according to a user-centered approach.

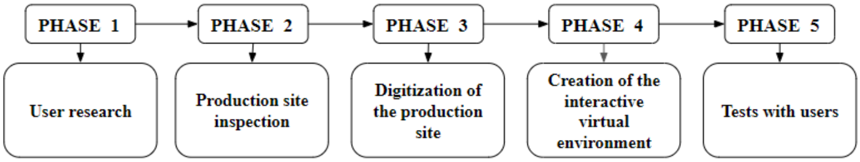

Figure 2. Step by step methodology.

The first step for the VT creation is the *User research*. It allows analysing the main consumer users, understanding their habits, needs and motivations. A sample of potential customers is usually interviewed and asked to fill a questionnaire to define their profile. In order to achieve this target, *personas* could be an effective way to define different profiles. *Personas* are 'fictitious, specific, concrete representations of target users' [34]. The *personas* are investigated during the pre-work studying. The answer is: *What are the potential clients to whom it may concern?*
The second phase is the *Production site inspection*. After visiting different production sites, we choose the best location for video shooting. After that, the production process is analysed in order to identify the main steps and narrated by marketing-oriented storytelling [35]. During the inspection, we need also define the type of digitalization to apply, between a) capturing the physical scenario with a digital 360° camera, or b) digitally creating the scenario by CAD models and materials with real textures. The choice mainly depends on specific location characteristics and level of interaction of the final VT. The advantage of recording 360° videos is high-fidelity with the real production site, while 3D model reconstruction permits user's interaction with objects.
After that, the *Digitization of the production site* is realized by both 360° video recording and 3D CAD models creation, as decided in the previous phase. In the former case, the main challenges are: positioning the camera in the best place (avoiding principal character in stitching area, the fish-eye effect, and keeping a certain distance from walls, people, and objects), and controlling video framing to capture every detail throughout the surrounding space. If objects require a high-level of detail, it is desirable to use a specific software in order to reproduce the true-to-life textures in the virtual environment.
Subsequently, the attention is dedicated to the *Creation of the virtual interactive environment*. VR devices must be firstly settled and integrated, depending of the VT creation needs. The stereoscopic reproduction of 360° videos need to map the video into a sphere to project the recording in the virtual world, while the creation of interactive scenes starts modelling the virtual scenario, represented by walls, ceiling, ground and setting of light condition, and importing 3D models of virtual objects. Moreover, objects' behaviours must be settled to create the desired interaction with users. Usually, also audio feedback must be added for a realistic experience. All scenes are then grouped within a customized script to allow the user to navigate the VT.

Finally, *Tests with users* are organized to validate the VT effectiveness and impressions. It is based on the analysis of the users' subjective impression and behaviours during the virtual experience. Users are asked to compile a pre-test questionnaire about demographic data, familiarity and level of expertise with VR tools, and knowledge on the specific product. After testing, users are asked to compile a post-test questionnaire about personal judgement and impressions about the quality of the experience during the VT simulation (e.g. engagement, easy to use, level of interest, sickness).

3. Case study

The case study refers to the visit to a dairy of a typical Italian product, the Parmigiano Reggiano cheese. The main scope is creating an immersive and interactive VT able to make users experiencing the main phases of cheese production and recreate the most relevant sensory aspects in a remote way. In this way, the virtual visit can be offered to a huge variety of potential customers who cannot physically go to the specific territory. It will open main opportunities for the producing companies to extend their market reaching a wider public with respect to the current physical visits.

Phase 1 focused on user research and aimed at understanding the target users and defining their features. Several personas were defined in the research; an example is represented in Figure 3.

Phase 2, about the production site inspection, involved different production sites in the Emilian territory, more specifically in the Modena area. Among all dairies, the "4 Madonne" cheese factory was chosen for video shooting (https://www.caseificio4madonne.it/). Different areas inside the dairy were selected, representing the main steps of the production process. A storytelling was defined as described in Figure 4.

Phase 3 was about the digitization of physical scenarios, using the Unity3D platform. The VT was structured in five different scenes, properly linked one after the other, as follows:

1. Welcome virtual scenario;
2. 360-videos of the entire PR production (from milk preparation to ageing);
3. Beating virtual scenario;
4. Fire branding virtual scenario;
5. Virtual tasting.

The first scene reproduces an entrance hall, in which the visitor meets the avatar (in this case, a dairyman) that guides him during the VT and provides useful information about the production process. When the simulation starts, an avatar tour guide begins to narrate the product origins. Different information panels were introduced in the scene in order to enrich the experience of the visitor: a territory map showing the cheese production area, infographic about the production process, and an interactive panel to listen to additional information by pushing one of the panel buttons like in a tablet interface (e.g. in-depth history, biodiversity, territory, consortium, counterfeiting, list of dairies).

In the second scene, 360-videos of the real production process were edited and mounted in order to highlight the main phases of production, paying attention to avoid image distortion and stitching issues. To increase the level of immersion, the narrating voice is balanced with the environmental noise of the production area. In this case, the scene is automatically changed at the end of the videos.

Figure 3. Example of personas from User research

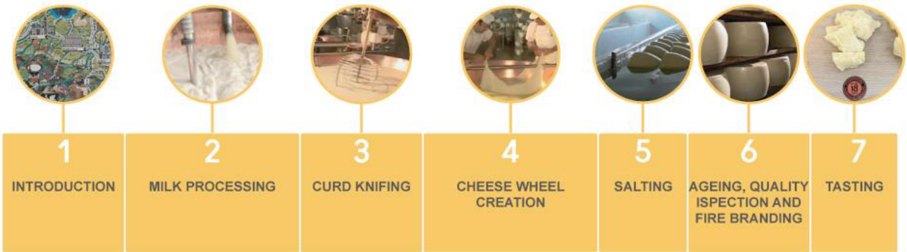

Figure 4. Storytelling for the Parmigiano Reggiano production process.

The third scene referred to the beating of cheese wheels, which takes place in the seasoning warehouse. It is an interactive scene since the user is invited to carry out a beating task on his own, exploiting VR devices. The user can use a particular gavel and beat a cheese wheel in specific points of the surface, looking at an expert. When the gavel hit the cheese wheel, the visitor hears the typical sounds, that vary depending on the specific point of the wheel.

The fourth scene is probably the most impressive one and referred to the cheese wheel branding. This phase takes place in the seasoning warehouse where the user is invited to pick up the marker and engrave the consortium stamp on the lateral side of the cheese wheel. In order to improve the realism of the scene, a flame animation was implemented and when the marker collides with the cheese surface, a small column of smoke rises from emulating the real effect.

The last scene is about cheese tasting and aims to involve the consumer to finally buy the product. The avatar tour guide describes the tasty peculiarity and the aftertaste sensations that characterizes each cheese ageing (e.g. 12, 18, 24 and over 36 months). Every ageing is also described by the ingredients individuated as aftertaste to be combined with the tasting, to create the proper desire to taste. Figure 5 shows examples of the implemented scenes in the VT.

Figure 5. Examples of VT scenes: welcome virtual scenario (up-left), the beating PR scenario (up-right), the fire branding virtual scenario (down-left), the virtual tasting (down-right).

4. Results

The proposed VT was qualitatively evaluated by a preliminary test carried out in Lab environment involving 8 users recruited from university employees. Users range from 20 to 40 years old, 75% male and 25% female. The sample of users is made of 50% VR experts or middle-experts, and 50% completely inexperienced. The VT lasted approximately 20 minutes for each user, excluding the calibration device phase before each session. A set of metrics was defined to assess the quality of the virtual experience as summed up in Figure 6. Each user was asked to judge the quality of the lived experience according to a 5-point Likert scale using the post-test questionnaire. Table 1 shows the collected results. Results were also presented by a bar graph in order to better show the main significant metrics, as reported in Table 1. A low average value for *Sickness* (2,0) indicates a good quality of the virtual simulation and comfort of the overall experience. This is due to the high refresh rate and a high- quality rendering offered by the selected devices. The high score values obtained for *Immersion level* (4,5) and

Realism (4,1) demonstrate the effectiveness of this type of simulation. Thanks to the high-quality rendering reconstruction, an effective life-like reproduction of the entire production process is achieved. Also, *Level of interest* (4,4) and *Engagement* (3,9) reported high scores, highlighting the good user involvement and the high emotional involvement of the users, demonstrating the potential success of the proposed marketing strategy. Moreover, the scenes' structure was settled up with an intuitive interface, as demonstrated by *Ease to use* score (4,3). Although these final scores don't have statistical significance, they can provide useful information on the perception of the user's experience about the proposed VT.

Table 1. Users' test values from evaluation questionnaires.

	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	Aver.
Engagement	4	5	3	5	4	4	4	2	3,9
Level of interest	5	4	5	5	5	4	4	3	4,4
Ease to use	4	4	5	5	4	5	3	4	4,3
Immersion level	4	5	5	5	4	5	5	3	4,5
Realism	3	4	5	5	4	4	5	3	4,1
Sickness	2	1	2	4	2	1	1	3	2,0

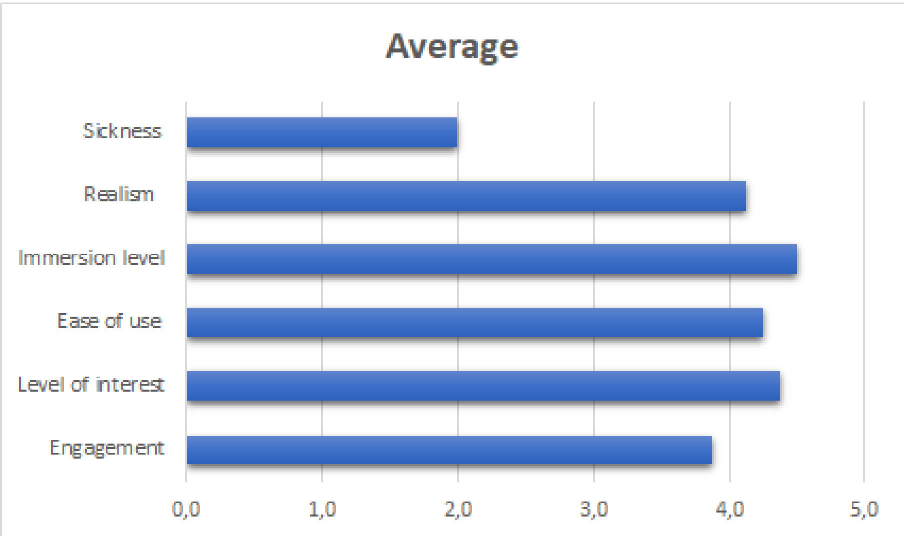

Figure 6. Average scores from qualitative users' assessment.

5. Conclusion

The study highlighted the strengths of the new digital technologies and their important role in the development of remote user experience. Indeed, VR tools could replace the static experience of e-commerce sites by offering the possibility to virtually visit a production site thanks to an interactive experience. Results obtained from preliminary tests showed a general positive evaluation of the VT: thanks to the transdisciplinary approach, users can live an immersive tour that simulates the user interaction, improving the user knowledge about the production process, and further augmenting what users usually live during the traditional visit. Moreover, the VT was able to overcome the geographical barriers, making a visit feasible also when it is not possible. This aspect assumes a particular importance in the recent Covid-19 scenario, when social distancing is affecting on-site visits and consequently sales. As a result, the remote experience by VTs can relaunch local companies promoting their products worldwide. Future works will focus on the comparison between the experience lived by the proposed VT and by the classical physical tour, using a larger statistical sample of users, in order to validate the effectiveness of this tool and the impact on sales intention. Moreover, feedback from users during and after testing will be investigated also by adopting wearable devices (e.g. heart-band, smartwatch) to collect physiological data to quantify the users emotional state, and extending the user sample. In addition, also intention to buy will be investigated.

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References

[1] S. R. Ellis, What are virtual environments?, *IEEE Comput. Graph. Appl.*, 1994, Vol. 14, no. 1, pp. 17–22.

[2] R. Manseur, Virtual reality in science and engineering education, *Proceedings Frontiers in Education 35th Annual Conference*, 2005, pp. F2E-8.

[3] R. Aggarwal *et al.*, An evidence-based virtual reality training program for novice laparoscopic surgeons, *Ann. Surg.* , 2006, Vol. 244, No. 2, pp. 310-314.

[4] M. Peruzzini, F. Grandi, S. Cavallaro, and M. Pellicciari, Using virtual manufacturing to design human-centric factories: an industrial case, *Int. J. Adv. Manuf. Technol.*, 2021, Vol. 115, pp. 873–7.

[5] A. Fineschi and A. Pozzebon, A 3D virtual tour of the Santa Maria della Scala Museum Complex in Siena, Italy, based on the use of Oculus Rift HMD, *2015 International Conference on 3D Imaging (IC3D)*, 2015, pp. 1-5.

[6] T. Griffin, J. Giberson, S. H. M. Lee, D. Guttentag, M. Kandaurova, K. Sergueeva and F. Dimanche, *Virtual reality and implications for destination marketing*, Travel and Tourism Research Association: Advancing Tourism Research Globally, 2017.

[7] S. Barnes, "Understanding virtual reality in marketing: Nature, implications and potential," *Implic. Potential (November 3, 2016)*, 2016, http://dx.doi.org/10.2139/ssrn.2909100.

[8] H. Stuart, *Virtual Reality Marketing: Using VR to Grow a Brand and Create Impact*. Kogan Page Publishers, London, 2018.

[9] D. Streimikiene and E. Korneeva, Economic impacts of innovations in tourism marketing, *Terra Econ.*, 2020, Vol. 18, No. 3, pp. 182–193.

[10] E. Baek, H. J. Choo, X. Wei, and S. Y. Yoon, Understanding the virtual tours of retail stores: how can store brand experience promote visit intentions?, *International Journal of Retail & Distribution Management,* 2020, Vol. 48, No. 7, pp. 649-666.

[11] J. Hagberg, M. Sundstrom, and N. Egels-Zandén, The digitalization of retailing: an exploratory framework, *International Journal of Retail & Distribution Management*, 2016, Vol. 44 No. 7, pp.

694-712.
[12] R. Lohre, A. J. Bois, G. S. Athwal, and D. P. Goel, Improved complex skill acquisition by immersive virtual reality training: a randomized controlled trial, *JBJS*, 2020, Vol. 102, No. 6, p. e26.
[13] A. Rizzo *et al.*, Development of a VR therapy application for Iraq war military personnel with PTSD, *Stud. Health Technol. Inform.*, 2005, Vol. 111, pp. 407–413.
[14] L. Montagna, *Realtà virtuale e realtà aumentata: nuovi media per nuovi scenari di business*. Hoepli Editore, Milano, 2018.
[15] D. Fontana, Realtà Virtuale e Aumentata: scenari applicativi per il marketing, Hoepli Editore, Milano, 2019.
[16] C. Yildirim, Cybersickness during VR gaming undermines game enjoyment: A mediation model, *Displays*, 2019, Vol. 59, pp. 35–43.
[17] M. Gödde, F. Gabler, D. Siegmund, and A. Braun, Cinematic narration in VR–Rethinking Film conventions for 360 degrees, *International Conference on Virtual, Augmented and Mixed Reality*, 2018, pp. 184–201.
[18] Z. Merchant, E. T. Goetz, L. Cifuentes, W. Keeney-Kennicutt, and T. J. Davis, Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis, *Comput. Educ.*, 2014, Vol. 70, pp. 29–40.
[19] H.-M. Chiao, Y.-L. Chen, and W.-H. Huang, Examining the usability of an online virtual tour-guiding platform for cultural tourism education, *J. Hosp. Leis. Sport Tour. Educ.*, 2018, Vol. 23, pp. 29–38.
[20] M. C. tom Dieck, T. H. Jung, and D. tom Dieck, Enhancing art gallery visitors' learning experience using wearable augmented reality: generic learning outcomes perspective, *Curr. Issues Tour.* , 2018, Vol. 21, no. 17, pp. 2014–2034.
[21] H. Van Kerrebroeck, M. Brengman, and K. Willems, When brands come to life: experimental research on the vividness effect of Virtual Reality in transformational marketing communications, *Virtual Real.*, 2017, Vol. 21, No. 4, pp. 177–191.
[22] G. Zeng, X. Cao, Z. Lin, and S. H. Xiao, When online reviews meet virtual reality: Effects on consumer hotel booking, *Ann. Tour. Res.* , 2020, Vol. 81, p. 102860.
[23] J. C. Henderson, Food tourism reviewed, *British Food Journal*, 2009, Vol. 111, 317–326.
[24] C. Hartmann, and M. Siegrist, Virtual reality and immersive approaches to contextual food testing. *Context: The Effects of Environment on Product Design and Evaluation*, 2019, pp. 323-338.
[25] R. K. Napolitano, G. Scherer, and B. Glisic, Virtual tours and informational modeling for conservation of cultural heritage sites, *J. Cult. Herit.*, 2018, Vol. 29, pp. 123–129.
[26] O. B. P. Mah *et al.*, Generating a virtual tour for the preservation of the (in) tangible cultural heritage of Tampines Chinese Temple in Singapore, *J. Cult. Herit.*, 2019, Vol. 39, pp. 202–211.
[27] D. A. L. Carvajal, M. M. Morita, and G. M. Bilmes, Virtual museums. Captured reality and 3D modeling, *J. Cult. Herit.*, 2020, Vol. 45, pp. 234–239.
[28] A. Marasco, P. Buonincontri, M. van Niekerk, M. Orlowski, and F. Okumus, Exploring the role of next-generation virtual technologies in destination marketing, *J. Destin. Mark. Manag.*, 2018, Vol. 9, pp. 138–148.
[29] Y.-C. Huang, S. J. Backman, K. F. Backman, and D. Moore, Exploring user acceptance of 3D virtual worlds in travel and tourism marketing, *Tour. Manag.*, 2013, Vol. 36, pp. 490–501.
[30] D.-I. D. Han, J. Weber, M. Bastiaansen, O. Mitas, and X. Lub, Virtual and augmented reality technologies to enhance the visitor experience in cultural tourism, M. C. tom Dieck and. T. Jung (eds.) *Augmented reality and virtual reality*, Springer Nature Switzerland, 2019, pp. 113–128.
[31] J. A. Bennett and C. P. Saunders, A virtual tour of the cell: Impact of virtual reality on student learning and engagement in the STEM classroom, *J. Microbiol. Biol. Educ.*, 2019, 26;20(2):20.2.37.
[32] O. B. P. Mah, ... and C. C. Feng, Generating a virtual tour for the preservation of the (in)tangible cultural heritage of Tampines Chinese Temple in Singapore. *Journal of Cultural Heritage*, 2019, Vol. 39, pp. 202-211.
[33] L. Argyriou, D. Economou and V. Bouki, Design methodology for 360 immersive video applications: the case study of a cultural heritage virtual tour, *Pers. Ubiquitous Comput.*, 2020, pp. 1–17.
[34] J. Pruitt and T. Adlin, *The persona lifecycle: keeping people in mind throughout product design*. Elsevier, San Francisco, 2006.
[35] J. Pulizzi, The rise of storytelling as the new marketing, *Publ. Res. Q.*, 2012, Vol. 28, No. 2, pp. 116–123.

Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Conceptual Design Study of a High-Altitude Mountain Rescue Rotorcraft

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Abstract. While there is a market for trekkers venturing into isolated environments, there will also be a market for specialized vehicles to rescue trekkers waylaid by unfortunate circumstance. This paper presents a conceptual design study of a helicopter specifically for rescue operations in extremely high altitude and mountainous terrain. Mt. Everest suffers from overcrowding and a high fluctuation of inexperienced climbers who pose a risk to themselves and other climbers around them. Rescue by fellow climbers when incapacitated is risky and difficult. There is a need for a rescue helicopter capable of hovering and extracting climbers as high up as the summit. However, there are many challenges from multiple disciplines that limit potential solutions. Helicopter sizing, economics, medical treatment, and socio-legislative policies all impact the major decision-making processes. This paper proposes a design that best addresses these issues using currently available technology. Turboshaft engines, contrary to electric motors, loose power with increasing altitude which means that for high-altitude operations it must be overpowered. The novelty of this design concept is the application of a compact coaxial helicopter with a hybrid-electric turboshaft propulsion system which balances the power required in high-altitude hover and cruise. The feasibility of this design is then compared to a traditional helicopter using a theoretically sized turboshaft engine. Many components from the Airbus H135 are integrated to reduce cost.

Keywords. High mountain rescue, rotorcraft, helicopter design, hybrid propulsion, transdisciplinary engineering

Introduction

Scaling Mt. Everest is one of the greatest challenges humankind can accomplish. Even though climbing equipment has significantly improved and most hazards are removed, many climbers are still unable to complete the journey. This is due to the shift in experience; since the climb has become commercialized, inexperienced climbers are flocking to the mountain in large numbers [1]. A bottleneck caused from inexperienced climbers can be seen in Figure 1. Although legislative action has been taken to reduce the number of unfit climbers, the Nepalese economy relies heavily on the revenue generated from these tourist expeditions. The safety of all those scaling Everest will continue to be at risk until a new search and rescue (SAR) platform is designed for climbers who are lost, fatigued, or incapacitated.

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Figure 1. Bottleneck at the peak of Mt. Everest [1].

Extraction at the peak of Mt. Everest is an niche mission. In 2005, helicopter test pilot Didier Delsalle made a 3-min touch down on the top of Mt. Everest using an Airbus AS350 Squirrel B3 with 2 Arriel 2D turboshaft engines at 700 kW each. The helicopter was lightened for this attempt and had only the pilot onboard. Although current helicopters might reach the peak by shedding excess weight and using updrafts to their advantage, no helicopter can sustain a hover necessary for high-altitude recovery. Considering the effects of the operational environment and requirements, a top-down design process was adopted. The design requirements are summarised as:

1. Must complete the prescribed mission profile within 3 hours.
2. Must be capable of extracting injured or unconscious climbers.
3. Must include a hoist system rated for 300 kg.
4. Must include systems capable of surveying the ground and locating the climber.
5. Must be capable of maintaining heading in winds up to 74 km/h from any direction.
6. Shall adhere to all FAA regulations and be certified for day and night IFR flight.
7. All crew members must be capable of communicating with each other at all times.

The concept of operations (CONOPS) and performance details of the final design are presented in Figure 2. The CONOPS is representative of the infrastructure currently available for high-altitude mounteneer recovery in Nepal. Current SAR practices and medical treatment for common mountaineering distress are expanded in Section 1. Rotor selection and propulsion selection are discussed in Section 2. The performance and feasibility of the complete design are covered in Section 3.

The sizing methodology is based on Prouty [2], with additional corrections based on updated empirical data. This methodology requires an initial weight estimate determined from similar helicopters. An analytical evaluation of current platforms based on design requirements determined our concept should have a maximum take-off weight (MTOW) similar to the HAL Light Utility Helicopter, the AugustaWestland AW109, Bell 407, Airbus H135, and Kamov Ka-226. Through iteration, the final MTOW was estimated to be 2741.5 kg (Sea Level @ ISA+20°C).

REFUEL	Leg 3				END
20 mins	2 min hover	Descent	Cruise	2 min hover	
13	14	15	16	17	18
3780	3780	3780-1402	1402	1402	1402
20	2	2.25	35.41	2	178.2533968
0	0	5392.29	129607.71	0	0
0	~	2378	0	~	0
0	0	40	61	0	0
0	0	-17.64	0	0	0
0	90	23.8	0	90	0
1939.37	1939.37	1939.37	1939.37	1939.37	1939.37
840.5	840.5	840.5	1134	1134	1134
494	494	494	494	494	494
0	720.5	504.7	971.4	673.3	0
0	0	0	0	0	0
210	203.28	197.99	37.46	31.18	31.18
575	575	575	575	575	150
2724.37	2717.65	2712.36	2551.83	2545.55	2545.55

REFUEL	leg 2						
20 mins	2 min hover	Climb	Cruise	30 min hover	Descent	Cruise	2 min hover
5	6	7	8	9	10	11	12
3780	3780	3780-8870	8870	8870	8870-3780	3780	3780
20	2	5.75	4.69	30	3.03	6.9	2
0	0	14483.74	13516.26	0	2728.73	25271.27	0
0	~	5090	0	~	5090	0	~
0	0	42	48	0	15	61	0
0	0	14.76	0	0	-27.98	0	0
0	90	19.36	0	0	61.8	0	90
1939.37	1939.37	1939.37	1939.37	1939.37	1939.37	1939.37	1939.37
840.5	840.5	415.3	415.3	415.3	415.3	840.5	840.5
494	494	494	494	494	494	494	494
0	720.5	415.3	415.3	415.3	423.785	812.8	720.5
0	0	494	108.2	476.8	328.815	0	0
210	203.28	192.14	183.04	124.9	118.9	92.71	85.99
405	405	405	405	575	575	575	575
2554.37	2547.65	2536.51	2527.41	2639.27	2633.27	2607.08	2600.36

	START	Leg 1			
		2 min hover	Climb	Cruise	2 min hover
Phase Number	0	1	2	3	4
Altitude	1402	1402	1402-3780	3780	3780
Time [min]	0	2	2.62	35.6	2
Δx [m]	0	0	4718.25	130281.75	0
Δy [m]	0	~	2378	0	~
V_x [m/s]	0	0	30	61	0
V_y [m/s]	0	0	15.12	0	0
Angle of attack [degrees]	0	90	26.75	0	90
Empty Weight	1939.37	1939.37	1939.37	1939.37	1939.37
Power Available Turboshaft [kW]	1343	1134	840.5	840.5	840.5
Power Available Electric Engine [kW]	494	494	494	494	494
Power Required Turboshaft [kW]	0	673.3	840.5	812.8	720.5
Power Required Electric Engine [kW]	0	0	0	0	0
Fuel Weight [kg]	210	203.72	193.44	58.42	51.7
Payload Weight [kg]	405	405	405	405	405
Current Weight	2554.37	2548.09	2537.81	2402.79	2396.07

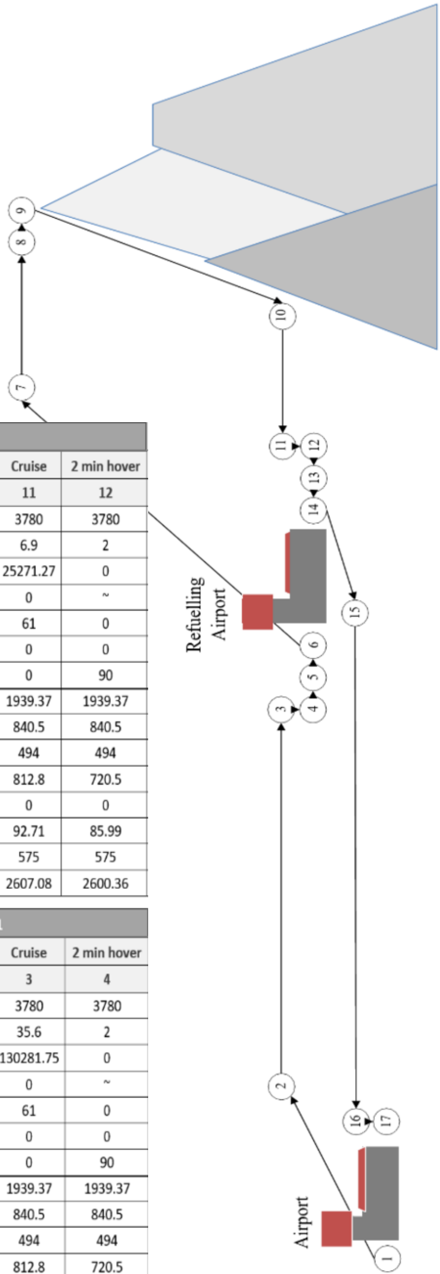


Figure 2. Mission Profile and Flight Path.

1. Operational Procedures

A common misconception of search and rescue operations is that patients are treated on site. However, this is not the case since most search and rescue operations occur in conditions considered too hazardous for medical treatment. Instead, operators follow a three-step rescue procedure: Identify, Diagnose, and Stabilize. Each step has a highly detailed explanation justifying each action; however, only a few items are discussed for the sake of brevity.

Identification relates to locating the distressed patient and reviewing the surrounding area to determine the best extraction method. The safest extraction method is a ground-based extraction, where crew members are dropped off close to the distressed patient, where they are then brought to a helicopter rendezvous point. Although the CONOPS assumes a long-winch extraction at the peak, the design focus for this concept prioritizes ground-based extraction for use in other mountain search and rescue operations. Other considerations specific to Mt. Everest are whiteout, where powdered snow impairs visibility and introduced unwanted moisture in the propulsion system. A Forward Looking Infrared (FLIR) camera and search light are included as critical mission systems.

Diagnosis follows a rigorous flowchart of assessments needed to identify what trauma the patient is undergoing. A detailed breakdown of these assessments can be found in any SAR or medical response procedure guide. For mountaineering, trauma is commonly presented as a physical injury or altitude-sickness related. Both traumas can result in unconsciousness, which is considered a worst-case scenario since diagnosis becomes increasingly difficult. The patient must be rushed to a medical facility to receive a more in-depth diagnosis.

Stabilization relates to monitoring the patient's vitals until they are admitted into a medical facility. The helicopter must store a large selection of first-aid supplies, including drugs, bandages and braces, and intubation equipment. However, since space is limited, priority should be given to common trauma specific to the CONOPS. Priority treatment for altitude-related trauma is supplemental oxygen and exposure to sea level pressure. A barometric pressure chamber was considered as a critical mission system. However, it was later replaced with supplemental oxygen and rapid descent to lower altitudes since the chamber hindered access around the cabin.

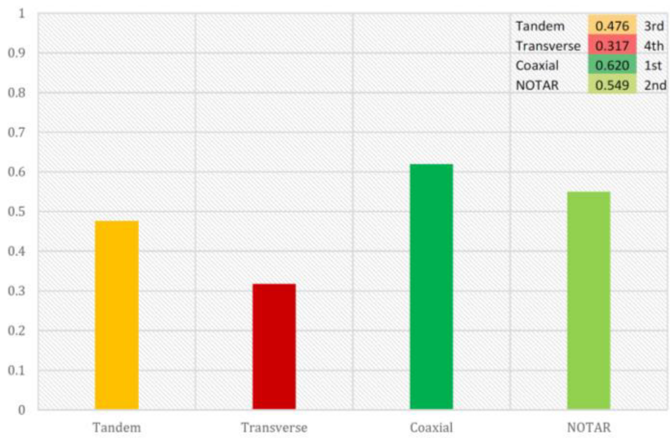
Keeping in mind the SAR operational procedures during the sizing process ensures the concept has retained all critical elements necessary for practical use. Many compromises were made to reduce the weight as much as possible due to how difficult sizing became.

2. Sizing

Altitude density is the dominant factor for all sizing decisions. Decreased air density affects the helicopter by 1) lowering the total thrust produced by the rotors and 2) lowering the maximum continuous thrust and increasing the thrust-specific fuel consumption (TSFC) of conventional turboshaft engines.

The first sizing issue is especially important for the anti-torque rotor. Johnson's research documents that conventional tails become less efficient anti-torque devices with higher altitudes and require considerable sizing to overcome this issue [3]. To avoid this problem, dual rotor configurations with a zero-net torque or configurations with unconventional anti-torque control such as the NOTAR were considered. Intermeshing rotors were not considered due to blade clearance over the main cabin doors. Even if sizing the rotors for sufficient clearance, there is an unnecessary psychological hesitancy when operating near rotors angled downwards and conflicts with SAR procedure.

Four rotor configurations were considered: Tandem, Transverse, Coaxial, and NOTAR. Figure 3 shows the results of the rotor configuration trade study with weighting factors selected. Data were sourced from Jane's, so proven configurations were chosen [4]. The parameter weights prioritize hover characteristics since this is the most critical design requirement. 17.5% weighting factor was given to hover ceiling and hover stability. Other parameters considered include vibration, weight, and performance characteristics.



Weighting factors used:

Weight	8%
Useful load	5%
Range	7.5%
Endurance	6.25%
Cruise Speed @ SL	5%
Cruise Speed @ alt	0.5%
Hover ceiling	17.5%
Hover stability	17.5%
Vibration	15%
Year of production	6.25%
Number of aircraft	4%
Cost	7.5%

Figure 3. Rotor type selection.

Prioritizing hover, coaxial rotors present the best choice for the given mission profile [5,6]. Nonetheless, the other configurations were still investigated independently. After evaluating rotor configurations, the design team split into two subgroups for sizing the helicopter. The first subgroup focused on the coaxial rotor design, while the second subgroup sized their design using the same requirements but for tandem and transverse rotors. Investigation for the NOTAR configuration ended quickly since further research into the concept showed it was also heavily density dependant.

The tandem and transverse rotor sizing confirmed the choice for using coaxial rotors. The primary issue with these configurations was the structural weight penalty needed to support both rotors. Additionally, when sizing the fuselage, it became apparent that having a cabin stretching the length of the rotor support structure was more desirable but did not address specific design requirements and was therefore unnecessary.

The second sizing issue led to the development of two propulsion packages. For hover at the summit, the required power output for a 2,800 kg helicopter is about 920 kW. For pure turboshaft configurations, this scales up to roughly 3000 kW of power available at sea level with a power loss of 69% at altitude. 2 Safran RTM 322 turboshafts were used in the traditional sizing approach.

Instead of sizing large and powerful turboshafts, a hybrid package incorporating lighter engines combined with electric engines can be used. 2 Safran Arriel 2N turboshafts, as well as 2 Siemens SP260D electric motors, are used in the hybrid sizing approach. Although the hybrid propulsion system has an increased empty weight due to the significant battery weight, it will reduce the overall fuel weight since electric propulsion does not suffer any altitude losses. A diagram of the hybrid propulsion system is shown in Figure 4.

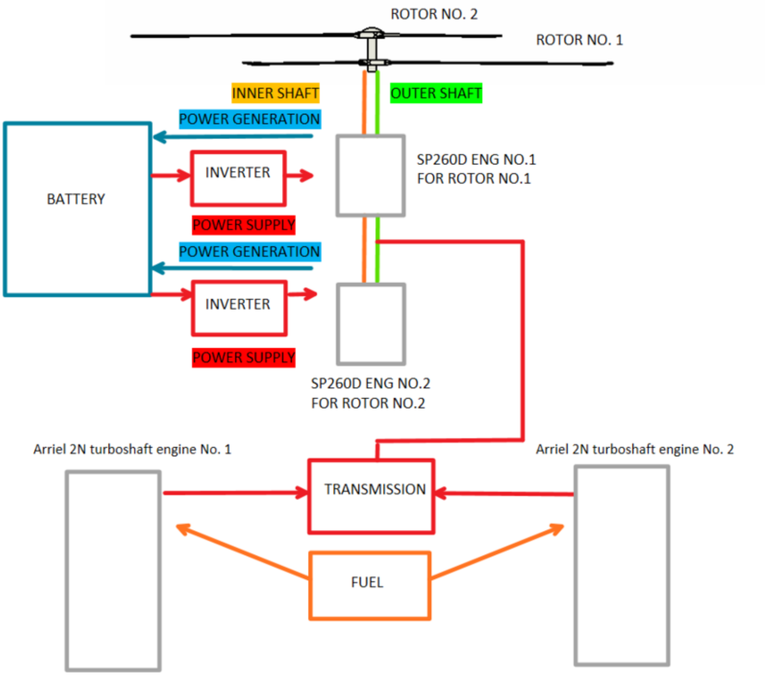


Figure 4. Hybrid propulsion system configuration diagram.

For the electric engines, the SP260D was selected since it was the only suitable electric engine currently available with the required power output. Although not in service yet, legacy models have already been implemented in small fixed-wing aircraft such as the LE300. The engine has a current TRL of 8. More information about the SP260D is shown in Table 1. A battery margin of 10% has been incorporated during sizing.

Table 1. Electric powerplant specifications.

2 Siemens SP260D Electric Engines		Manganese-Titanium (Lithium) Battery	
Engine Weight	$100\ kg$	Battery Weight	$150\ kg$
Power Output (ideal)	$520\ kW$	Specific Energy	$140\ Wh/kg$
Motor Efficiency	95%	Battery Energy	$75.6\ MJ$
Power Output (real)	$494\ kW$	Battery Volume	$0.11\ m^3$
Maximum RPM	2500	Minimum Temperature	$-20°C$

Battery technology is expected to improve in performance and affordability within the next few years. The design uses a Manganese-Titanium rechargeable battery. This battery is expensive but has a high specific energy. There is also a minimum operating temperature requirement; however, this can be offset with insulation and integration with the electric de-icing system.

Additionally, batteries can complicate the readiness and availability of the helicopter due to their slow charging times. In this design, the batteries are installed near the undercarriage as an interchangeable pack, where they can be easily removed and replaced. Fully charged batteries can be installed with every landing if necessary, while the depleted batteries are charged at the offsite. Since the batteries can be easily removed, the helicopter can change to a light, turboshaft helicopter like what is currently used for search and rescue. The SP260D can also recharge batteries using excess turboshaft power in flight.

After iterating both packages' design, the hybrid propulsion package is revealed as the only feasible option. The turboshaft package quickly diverged; the power requirements increased due to increasing fuel from a high TSFC. The engine required to follow the traditional sizing approach currently does not exist. On the other hand, the hybrid package converges appropriately. At design altitude, the power loss is about 50%, a 20% improvement compared to the turboshaft package.

Additionally, the drive system needed for the turboshaft package is burdensome. A gear reduction ratio of 10:1 is needed for the larger turboshaft engines instead of the 3:1 gear reduction ratio required for the turboshafts in the hybrid package. The Siemens SP260D does not require a transmission system since it can be installed directly onto the driveshaft. Having a smaller gear reduction ratio results in a smaller overall transmission and reduced aircraft vibrations which is the main discomfort for search and rescue patients.

All engine data used in the evaluation process is sourced from their respective EASA type datasheet. Engines were evaluated based on power to weight ratio, power density and required gear reduction ratio. Separate trade studies were carried out for small and large turboshafts. The last aspect of sizing is the cabin layout. The interior is designed to keep all varying loads close to the centre of gravity while maximizing available space. The internal layout is shown in Figure 5.

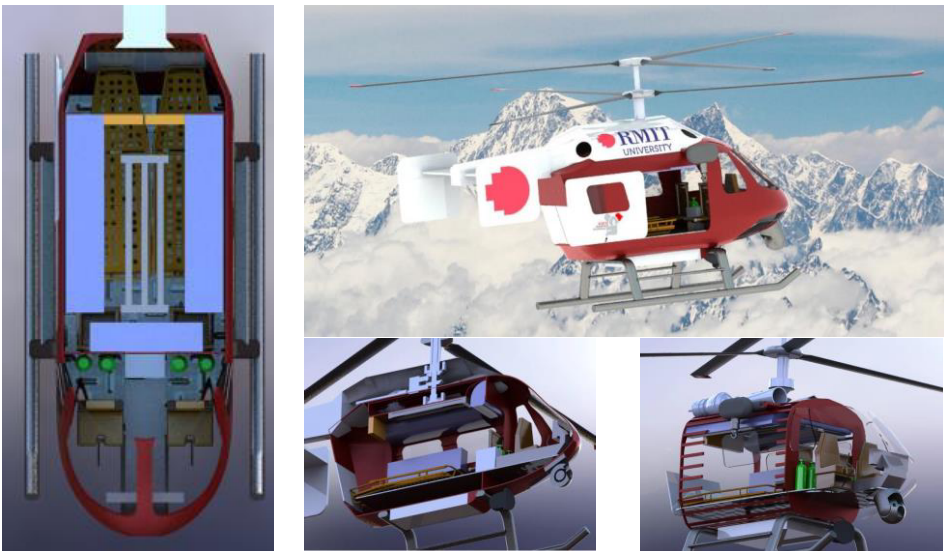


Figure 5. Final helicopter design configuration and layout.

All subsystems and instruments are placed concerning the patient. Crew seats are positioned at the patient's head to allow for easy monitoring with fold-up seats for improved accessibility. Additional roof mounted monitors are positioned above the patient stretchers which are used to display patient vital signs or give mission information to the crew before extraction.

Clamshell doors at the back of the fuselage allow for easy egress allowing for rapid transfer from the helicopter landing site to the medical centre. Medical equipment is stored overhead by the crew members. Mountaineering equipment is stored in both the centre console and in rucksacks, which can be found behind the cabin seats alongside the supplemental oxygen tanks. The cabin must remain unpressurized since a pressurization system is too heavy and will be depressurized once the main cabin doors are open for operation. Pressurized suits were considered for the crew but, like the barometric pressure chambers, conflicted with SAR practices since they reduced mobility and limited cabin space.

3. Performance and Feasibility

The introduction of a hybrid propulsion system creates optional performance metrics depending on the SP260D motors required for the mission. The power available at designated altitudes is summarised in Table 2. Table 3 shows the major design and performance characteristics.

Table 2. Power available vs altitude.

Altitude (m)	Turboshaft Power (kW)	Electric Power (kW)	Power Available (kW)
Sea level	1,342.6	494	1,836.6
1,402	1,133.9	494	1,627.9
3,780	840.5	494	1,334.5
8,870	415.3	494	909.3

The power required to hover and for forward flight is derived from Prouty, with corrections made based on the statistical analysis provided by Leishman and Syal [7]. There is a minor power penalty for using coaxial rotors. The power requirements for forward flight and climb are shown in Figures 6 and 7, respectively.

Since the rate of climb depends on excess power available, the helicopter design has two possible climb charts, depending on which power sources are used. Due to the electrical engines, the rate of climb increases significantly, allowing for a much faster climb to the summit. The electrical power also makes the helicopter extremely responsive, with a maximum rate of climb of 52 m/s.

Table 3. Helicopter Design Summary.

MTOW	2,741 kg
Empty Weight	1,956 kg
Useful load	785 kg
Max. cruise speed at SL	273.6 km/h
Hover ceiling	9,327 m
Max. range at SL	309 km
Max. endurance at SL	2.5 hrs

Range and endurance were approximated using McCormick [8]. Power and speed for best range were approximated as power and velocity at half fuel weight. Specific fuel consumption for the Arriel 2N is approximately 0.28 kg/kWh. For the proposed design, the maximum range is 309 km at 25 m/s and 407 kW, and maximum endurance is 2.5 hours at 38 m/s and 491 kW. The battery power provides 32.4% of the total range and

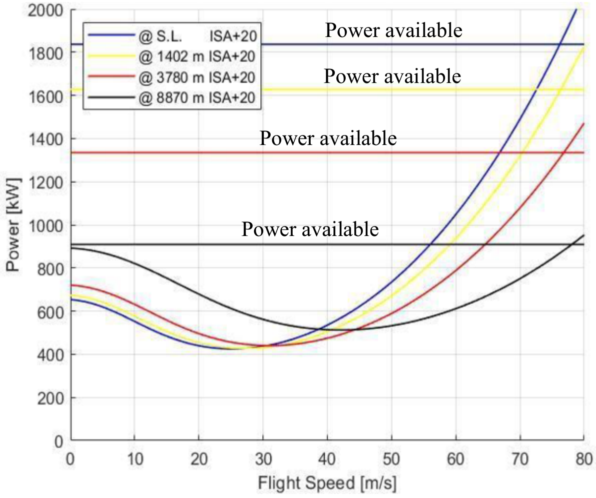


Figure 6. Power required for forward flight.

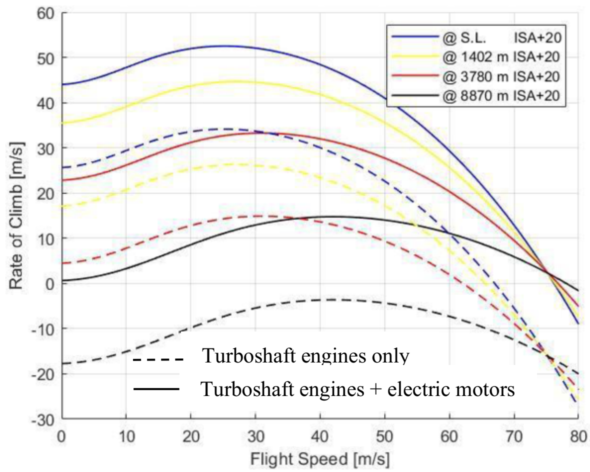


Figure 7. Maximum rate of climb vs flight speed.

27% of the total endurance. The absolute hover ceiling for the helicopter is at 9,327 m (ISA+20°C).

The hybrid-solution design is unlikely to be manufactured due to socio-economic reasons. Although there is a need for high-altitude recovery, there is insufficient demand for high-altitude vehicles to justify the development costs. An cost estimate using the Johnson Space Centre Advanced Mission Cost Model (AMCM) for development costs and a cost estimate relationship function based on empirical data is shown in Table 4. To reduce development cost, the concept integrates existing components from the Airbus H135. An aircraft manufacturer might be tempted into producing this design if there were other in-demand operation at Everest-level altitudes to increase production size. In the world, there are 14 mountains higher than 8,000m ("eight-thousanders").

Table 4. Cost breakdown vs. Manufacturer experience

Cost (FY2019)	Airbus (2nd Gen. model)	Experienced Manufacturer	New Manufacturer
Development	$327.57 Million	$420.65 Million	$1014.9 Million
Unit	$5.73 Million	$5.73 Million	$5.73 Million

Mt. Everest is only open for a few months per year seeing roughly 4 to 16 deaths per year. During the off-peak months, the design concept will have the same mission capabilities as a commercially available helicopter but with reduced range and endurance capabilities, making it an unattractive alternative. This design would be more commercially viable if engine weight and TSFC is reduced, which is likely in the next few years. Designing a greater than 3000 kW utility helicopter and creating a low weight variant for high-altitude recovery is more practical from an aircraft manufacturer's perspective.

4. Conclusion

This paper presents a summary of a conceptual design project for a high-altitude rescue helicopter. Although some helicopters can reach the summit of Mt. Everest, sustained hovering at that extreme altitude extracting an injured mountaineer is a significant design challenge. In 2005, an Airbus EC135 B3 without payload and one pilot made a 3-min touch down on the summit of Mt. Everest. It would not have been capable of sustained hover with payload sufficent for a rescue mission.

The proposed design overcomes this problem by installing a hybrid propulsion system that consists of a combination of a turboshaft engine and electric motor. The electric motor power output is not affected by altitude and provides extra power while hovering at altitude. The hybrid concept has an advantage in hover ceiling, rate of climb, vibration, noise, and environmental pollution but has a penalty on range and endurance. The selected turboshaft engines, Arriel 2N, are similar to engines on the Airbus EC135 but the additional electric motors give it superior high-altitude performance. They are switched off for standard cruise operations. The likelihood of the concept being manufactured is low due to the low demand for high hover ceilings. A traditional helicopter design will likely be manufactured instead once the appropriate engine is designed with the necessary access power. Alternatively, the concept of add-on electric motors can be considered to modify conventional helicopters into extremely high-altitude rescue vehicles.

Acknowledgement

This paper summarises the final design of a high-altitude rescue helicopter in response to the 2018 – 2019 VFS Student Design Competition. The RMIT University student team included: Dylan Lynch, Jonathan Lakkis, Marianne Celestial, Tharushi Bopage, Yansen Ongko and Nurul Ibrahim.

References

[1] J.G. Kai Schultz, Mujib Mashal and Bhadra Sharma, 'It Was Like a Zoo': Death on an Unruly, Overcrowded Everest, in *New York Times*, ed: New York Times Company, May, 26 2019.
[2] R.W. Prouty, *Helicopter performance, stability, and control*. Krieger, Malabar, Florida, 2002.
[3] W. Johnson, *Helicopter theory*. Courier Corporation, New Jersey, 2012.
[4] N.N., *Information Handling Services Jane's all the world's aircraft. Development & production*, IHS Global Limited, Coulsdon, 2015.
[5] J. Leishman and M. Syal, Figure of Merit Definition for Coaxial Rotors, *Journal of the American Helicopter Society,* 2008, Vol. 53, No. 3, pp. 290-300.
[6] L.I. Garipova, A. S. Batrakov, A. N. Kusyumov, S. A. Mikhaylov, and G. Barakos, Aerodynamic and acoustic analysis of helicopter main rotor blade tips in hover, *International Journal of Numerical Methods for Heat & Fluid Flow*, 2016, Vol. 26, No. 7, pp. 2101-2118.
[7] J.G. Leishman, *Principles of helicopter aerodynamics*, 2nd ed., Cambridge University Press, New York, 2005.
[8] B.W. McCormick, *Aerodynamics, aeronautics, and flight mechanics*, 2nd ed., Wiley, New York, 1995.

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Human Interaction in a Virtual Reality Environment

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Abstract. Virtual Reality (VR) and Augmented Reality (AR) are becoming useful tools to provide a visual representation of a product, a design or environment without the cost of building a prototype. Other applications include maintenance support, procedures development and workstation design. Currently, VR and AR systems can only display visual and audio cues. For example, in workstation design, i.e., a ship's bridge, aircraft flight deck, command centre, maintenance facility, etc., it is important to for design engineering to determine if the human operator can reach the gauges, switches and controls. To meet the ergonomic and human factor design criteria, the human operator must easily interact with all the displays, instruments, equipment, and controls. This impacts the design and location of seats, instrument panels and windows. VR and AR devices, such as the controllers and gloves, can track the position of the human hand and fingers in a virtual environment but are not able to detect realistic distance or interference with a virtual object. This paper presents a new VR prototype to allow an operator in a fully immersive environment to reach and touch any object in the virtual world. As a case, study the environment was applied to the cabin design of a medical helicopter. Feedback and suggestions from the medical personnel were obtained and are presented.

Keywords. Virtual/Augmented reality, workstation design, transdisciplinary design, helicopter cabin design, air mobile stroke unit

Introduction

Environments where people operate or interact with each other are difficult to design with traditional CAD tools as these do not capture or represent human ergonomic features and behaviours such as interference, human-machine and inter-human interaction, etc. Interactive and immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) are becoming useful tools to provide a visual representation of a product, design, or environment without the relative expensive cost of fabricating a prototype. Other VR/AR applications include maintenance support, procedures development and workstation design. Even with some limitations such as computational cost or motion sickness, VR/AR have become useful tools in the design of workspace and architectural projects.

In workspace design, e.g. a ship's bridge, command centre, maintenance centre, etc., it is important to determine if a human operator can reach the gauges, switches, and controls. The ergonomic design of a workspace requires an understanding of the variability in human bodies, their personal preferences, and the environment they interact

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with. All these will impact the design and location of seats, instrument panels and windows, and influence an operator's interaction with all the displays, instruments, and controls. For this reason, reach and touch capability in VR and AR is essential to understand the ergonomic and human factor when designing a workstation.

In this project, we use VR and AR technologies to facilitate human-workspace interactions and to improve the overall efficacy and effectiveness of such interactions. The tracking sensors and novel software algorithm was developed to detect the distance of a human hand to any point in the virtual world, and to provide feedback to the VR operator that contact has been made. The VR environment was used as part of the design process of the Air Mobile Stroke Unit (Air MSU), which is an ambulance helicopter to be used as response to emergencies in regional and remote areas [1].

1. Background

1.1 VR Applied to Workstation Design

Different studies have showed that VR can be used as a tool in the design of workstations and for training purposes [2]. More specifically, it can be used in the ergonomic design of workstations, where a virtual environment can be easily tested and modified than a physical prototype [3, 4].

Additionally, workplaces can be simulated for training purposes, in particular those with manual tasks and procedures that must be executed on a regular basis. VR presents a useful tool to reproduce a virtual representation of the workplace where the user can refine their skills before executing the task in the real world [5 - 8]. In the aerospace industry, some studies have been conducted to evaluate the design of luxury cabins using VR for business flights [10].

1.2 Interaction in VR Environments

At the current state of VR technology, one of the most challenging problems is to create a realistic environment in which the user can have the ability to reach and touch the objects in virtual environment [11,12]. Haptic technology, also known as kinaesthetic communication or 3D touch, refers to any technology that can create an experience of touch by applying forces, vibrations, or motions to the user [13]. Most advanced forms of haptic feedback are gloves that allow the user to *grab* an object and move it. Force-feedback option can be added by using actuators or air pressure in the fingers. This type of advanced haptic technology is still in development and current gloves are typically large and heavy (Figure 1). However, the type of haptic feedback needed depends on the application. For some applications, it is sufficient to be able to *touch* the object. Infrared hand tracking devices can detect the position of the user's hands relative to external tracking sensors.

Figure 1. Haptic gloves (www.haptx.com).

The position of the hands in the real world can then be translated to a position in the virtual world [11]. The next development is to implement a technique get the desired interaction between the virtual hands and the components of the VR environment [12,14].

This paper describes a technique for determining the distance between the hands and any part of the virtual world and to detect if the hands are *touching* the object. When an object is touched it is highlighted (visual cue) and the hand-held controllers vibrate (sensory cue). This capability is very useful and sufficient in the design of workspaces where the ability to easily reach and touch instruments, controls and other objects must be verified.

1.3 Determining Perceived Distance

In the past decade, many design engineers have used VR to design immersive environments, particularly in large scale projects, because VR provides them the ability to create a low-cost iterative design tool for testing and prototyping true scale 3D products or systems.

In commercial product developments, VR is being used as a tool not just for visualization but also for develop the manufacturing workflows and ergonomic production workstations. However, one of the challenges to develop high fidelity VR environment is to reproduce a true to scale perception for the users. Some studies have suggested that distances appear to be compressed in immersive virtual environments when compared to the real world. Hence, many studies have been conducted to understand the depth, distance perception, and the visual characteristics of the virtual representation of the real world. For example, Loomis et al. have investigated, through experimental study of perceived space and motor action, the process of mapping between real space with its corresponding virtual space [15,16]. However, the reason for this disagreement in the perception is yet unidentified [5,17].

1.4 Transdisciplinary Design

This project is transdisciplinary in the sense that the key concepts, expertise, and methods are drawn from multiple disciplines, such as engineering, technology, human factor, computer science and information visualization. In line with this, we utilize the engineering knowledge to develop the 3D models, the emergent VR technology (HTC Vive) to manipulate the 3D virtual object, the human factor approach to evaluate the interactions between real and virtual environment, and the 3D modelling software to visualize and evaluated results.

2. VR Equipment and Application Development Tools

For the development of the virtual Reality environment the game engine Unity (www.unity.com) was used due to its embedded tools and libraries that make the implementation of VR functions a straightforward process. A process diagram of the development is described in Figure 2.

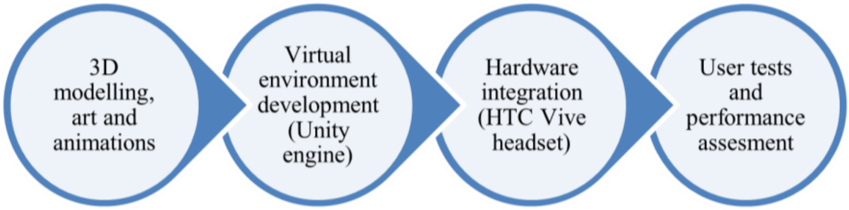

Figure 2. Development process diagram.

The work on the VR application has been focused on two fronts, first to implement interactions with 3D models in a virtual environment, and second to use these functions in an ambulance helicopter virtual model, in which a user could interact with the aircraft model and its parts.

2.1. 3D Modelling

All the 3D objects were modelled using the computer-aided design software, i.e. 3DEXPERIENCE as shown in Figures 3-5. The virtual models consisted of an ambulance helicopter, a stretcher, a human mannequin, crew seats, and a CT-scanner unit.

Figure 3. Helicopter CAD model.

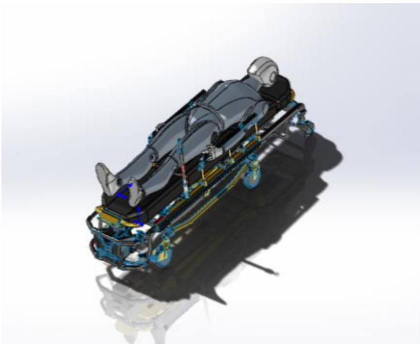

Figure 4. Patient + stretcher 3D model.

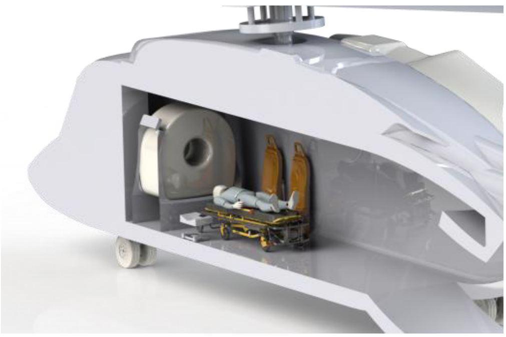

Figure 5. Ambulance Helicopter Virtual Assembly

3. VR environment development

One of the main goals for the development of the VR application was to create a *reach and touch* capability in the virtual environment. This will contribute to the human-centered design of an efficient and ergonomic workspace, such as a ship's bridge, aircraft flight deck, operator station, medical unit, etc.

The team was composed of a transdisciplinary group of medical professionals, biomedical, mechanical, and aerospace engineers that met regularly to identify requirements and discuss progress. The virtual reality application was developed so the user can experience and evaluate the layout of equipment and interact with different components inside and outside the aircraft.

This paper is reporting on the conceptual phase of the study, which included the simplified models of the aircraft and its components. We intend to use the results collected during the pilot experiment to refine and further develop specific components to fulfil the user requirements.

The pilot experiment was conducted with a professional health worker to seek her feedback through semi-structured interview session. We sought to understand the subjective measurements of performance, usability, and comfort of the VR application.

3.1. VR Equipment

An HTC Vive PRO headset and controllers were used in the development of the virtual reality application (Figure 6). This headset uses *room scale* tracking technology, which allows the user to operate in a 5m x 5m area. The user uses two hand-held controllers to interact with the virtual environment. The position is determined using a minimum of two fixed infra-red tracking stations.

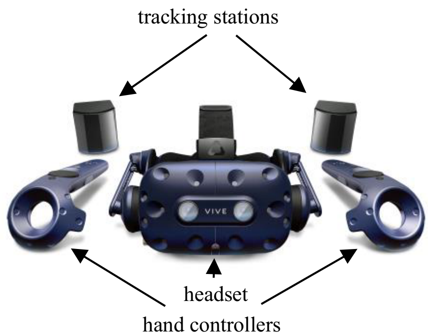

Figure 6. HTC Vive Pro system.

3.2. Reach and Touch in VR Environment

The VR application for the ambulance helicopter developed in this project can be used as a virtual experience inside Unity engine, which allows users to test all the functionalities of the application and perform changes or corrections as needed.

The main interaction tool while immersing in the virtual environment was the HTC Headset. Additionally, the users could use two controllers to interact with the 3D models inside the virtual environment. The controller appeared as a pair of gloves, which enable users to have a sense of realism. Users could press the buttons on the controllers to perform the basic operations, such as touch, grab, etc. as described in Figure 7.

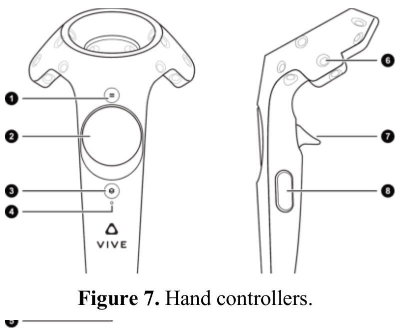

Figure 7. Hand controllers.

- Button 1: access setup menu
- Button 2: allows the user to tele transport to any part of the scene that cannot be reached by walking in the “real world”
- Button 8: allows the user to grab any object inside the virtual world.
- Button 7: allows the user to interact with the menu elements or with the models of the virtual world.

3.3. User-Defined VR Interaction

Using Unity engine, a virtual environment was developed, in which a scene trying to resemble an Australian outback landscape was built. In this scene the 3D models previously developed were included in addition to the terrain, lights, and textures. A screenshot of the scene is shown in Figure 8.

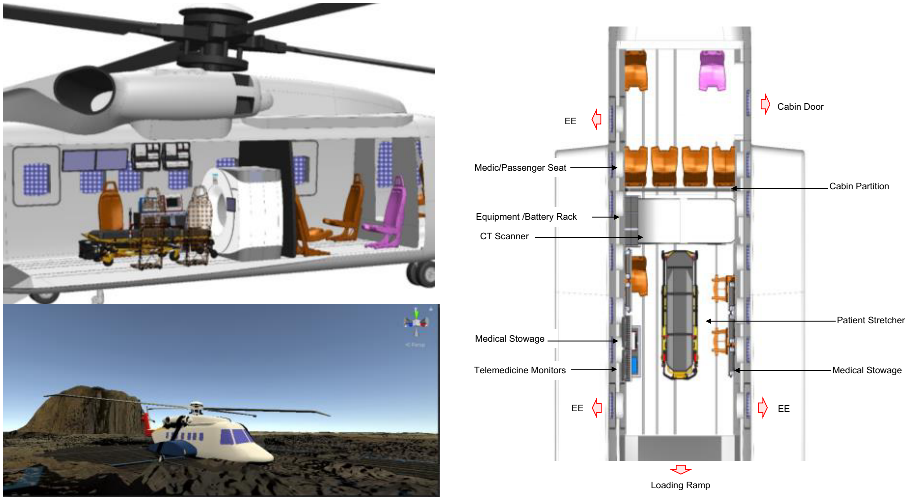

Figure 8. Virtual environment scene.

To achieve interactive actions like *grab*, *touch*, *launch* with the 3D models in the virtual environment, scripts available in the Unity engine library were used. The library was modified to achieve the behaviour relevant for the project such as *show* or *hide* controls. Several scripts where modified or newly written to get the desired behaviour of the virtual character inside the virtual environment.

When an object or any part of the virtual environment is touched, the object is highlighted with a coloured outline (visual) and the controllers vibrate to provide haptic feedback. Figure 9 shows images from virtual environment when using the controllers with reach and touch capability. Touch objects are highlighted with a yellow outline.

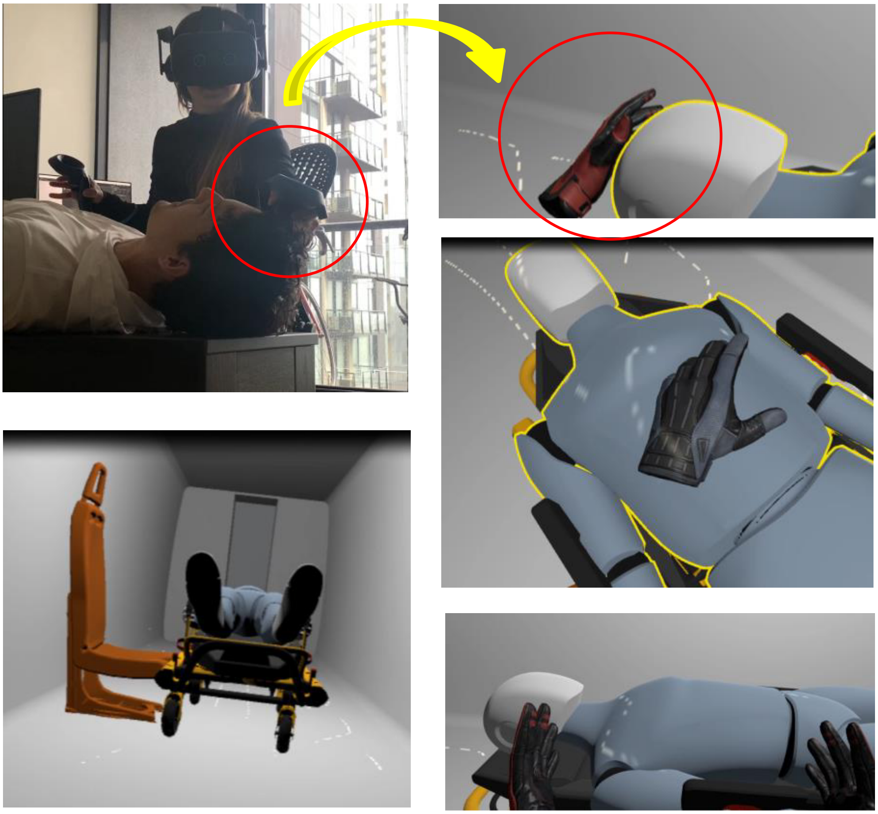

Figure 9. Interaction system sample.

The application is being built trying to simulate the scenario a team member of the Ambulance would have in case of a person needs attention. That is why a human dummy is shown in the figures above.

4. Medical Helicopter Cabin Design - Case Study

To investigate the effectiveness of research and touch capability in a VR environment, a model of a cabin of a medical helicopter was created with seats, stretcher, and a model patient. To test whether the interaction performance in the virtual environment represented accurately an ambulance scenario, a professional radiographer was invited to participate in an experimental setup and to provide feedback on perceived distance and interactions (Figure 10).

4.1. Apparatus and participants

For this case study a medical professional was invited to use the VR environment with modelled seat, stretcher and patient located inside a helicopter cabin. Various medical procedures were simulated, and feedback was obtained on realism, interaction experience and overall effectiveness.

As a new user of VR technologies, her opinions about the application performance and realism are very useful from the usefulness as a design and training tool point of view.

Figure 10. VR Environment Test Setup.

The test was performed at the RMIT VXLab (www.rmit.edu.au), using the equipment described in section 2.1. The virtual model consisted of a helicopter cabin with a CT-scanner and a stretcher with a modelled patient. Also in the scene was a seat next to the stretcher and a real seat was placed in the same location for the participant to sit on during the experiment. The participant was also asked to stand up and walkaround the stretcher. After giving some basic instructions on how to use the VR application, the participant was asked questions about how she perceived the distance and shapes of the 3D objects, the interaction with objects surfaces with the virtual environment.

4.2. Results

Overall, the participant was satisfied with the VR environment and the ability to interact with various objects and how real the experience of interacting with the virtual patient was, it was possible to "cradle the patient's head". Also, the participant said that the perception of the patient and stretcher sizes and distances felt very accurate. Additionally, it was also expressed that during the test there was no feeling of dizziness or any discomfort produced by the VR environment.

The lack of any force feedback while interacting with objects in the virtual environment was mentioned as a downside and would be noticeable in case of, for example, administering CPR. The participant also suggested to include other persons, e.g. co-workers, in the same environment to make collaboration and teamwork more realistic. In any outcall, there are five medical and support staff onboard and people need to manoeuvre around co-workers within a confined space.

Another comment was about the perceived distance of the CT-scan unit. The participant felt that the interior space of the helicopter seemed a lot bigger that the real world and expressed that object at a distance in the virtual environment seemed "very far away". Although the scale and dimensions of the helicopter cabin were correctly modelled the depth perception error seems more an issue with how the environment is displayed in the headset.

5. Conclusions

A basic reach and touch capability for a virtual environment was developed to support the design of workspaces where a human operator must interact with objects in the virtual world. The only device needed are standard hand controllers that are common accessories to a VR or AR device. These hand controllers can detect hand position, but is not able to interact with the environment, such as touching components, and the aim of this project is to develop the capability to use standard hand controllers to reach and touch objects in the virtual environment. More sophisticated and expensive haptic gloves are not always required for ergonomic workplace design where force feedback, etc. are not essential.

As a case study a cabin of a medical helicopter was designed to determine that a medical professional can adequately attend to the patient in a confined space. A medical professional was invited to use the virtual environment setup and provide feedback on realism, interaction experience and general effectiveness. The general observations were:

- The virtual environment gives the user a good experience while interacting with different surfaces and shapes and provided an accurate feeling of size and distance.
- To improve the feeling of realism and the usability as a design and training tool, it is needed to find a way to give the user a more realistic feeling of the surroundings and even force haptic feedback, for example in case of CPR.
- To get a more realistic training environment is important to create a "multi-user" environment in which the teamwork procedures can be reproduced accurately.

Feedback given during this case study will be used to improve the application aiming to develop a tool useful for aircraft design purposes, to improve the immersion experience for the user, a more detailed cabin interior is going to be modelled using CAD and 3D modelling software.

Future work will focus on the development a more realistic virtual working environment the interior space of the helicopter cabin. Additional trackers will be included in the environment, so the user will wear those in different body parts and then get feedback while in the virtual world if they are contacting the virtual surfaces. Finally, a multi-user environment will be developed allow multiple persons including hearing guidance of how to use the VR application and some common procedures developed in ambulances will be reproduced as a training exercise.

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References

[1] D. Chipperfield, M. Cheesman, C. Bil, G. Hanlon, Transdisciplinary Design Aspects of an Air Mobile Stroke Unit, *Advances in Transdisciplinary Engineering*, 2020, Vol. 12, pp. 250-259.

[3] P. Budziszewski, A. Grabowski, M. Milanowicz, and J. Jankowski, Workstations for people with disabilities: an example of a virtual reality approach, *Int J Occup Saf Ergon,* 2016, Vol. 22, No. 3, pp. 367-73, doi: 10.1080/10803548.2015.1131069.

[4] H. Nguyen, C. Pontonnier, S. Hilt, T. Duval, and G. Dumont, VR-based operating modes and metaphors for collaborative ergonomic design of industrial workstations, *Journal on Multimodal User Interfaces,* 2016, Vol. 11, No. 1, pp. 97-111, doi: 10.1007/s12193-016-0231-x.

[5] C. Pontonnier, G. Dumont, A. Samani, P. Madeleine, and M. Badawi, Designing and evaluating a workstation in real and virtual environment: toward virtual reality based ergonomic design sessions, *Journal on Multimodal User Interfaces,* 2013, Vol. 8, No. 2, pp. 199-208, doi: 10.1007/s12193-013-0138-8.

[6] F. Caputo, A. Greco, E. D'Amato, I. Notaro, and S. Spada, On the use of Virtual Reality for a human-centered workplace design, *Procedia Structural Integrity,* 2018, Vol. 8, pp. 297-308, doi: https://doi.org/10.1016/j.prostr.2017.12.031.

[7] Y. M. Anoffo, E. Aymerich, and D. Medda, Virtual Reality Experience for Interior Design Engineering Applications, *26th Telecommunications Forum (TELFOR)*, 20-21 Nov. 2018,, pp. 1-4, doi: 10.1109/TELFOR.2018.8612026.

[8] H. Lee and W. C. Cha, Virtual Reality-Based Ergonomic Modeling and Evaluation Framework for Nuclear Power Plant Operation and Control, *Sustainability,* 2019, Vol. 11, No. 9, doi: 10.3390/su11092630.

[9] S. Roberts, R. Page and M. Richardson, Designing in virtual environments: The integration of virtual reality tools into industrial design research and education, *DRS 2020: Synergy*, 2020: Design Research Society, pp. 1628-1643.

[10] F. De Crescenzio, S. Bagassi, S. Asfaux, and N. Lawson, Human centred design and evaluation of cabin interiors for business jet aircraft in virtual reality, *International Journal on Interactive Design and Manufacturing (IJIDeM),* 2019, Vol. 13, No. 2, pp. 761-772, doi: 10.1007/s12008-019-00565-8.

[11] H. Tilak and R. Cheng-Yue, *Egocentric Hand Tracking for Virtual Reality*. Stanford EE 267: Virtual Reality, Corpus ID: 173174646, 2016.

[12] J. Lin and J. P. Schulze, Towards naturally grabbing and moving objects in VR, *Electronic Imaging*, 2016, No. 4, pp. 1-6.

[13] H. Culbertson, S.B. Schorr, A.M. Okamura, Haptics: The Present and Future of Artificial Touch Sensations, *Annual Review of Control Robotics and Autonomous Systems*, 2018, Vol. 1, pp. 385-409.

[14] C. Fang, Y. Zhang, M. Dworman, and C. Harrison, Wireality: Enabling Complex Tangible Geometries in Virtual Reality with Worn Multi-String Haptics, *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1-10.

[15] J. Loomis & J. Knapp, Visual perception of egocentric distance in real and virtual environments, In L. J. Hettinger & M. W. Haas (Eds.), *Virtual and adaptive environments: Applications, implications, and human performance issues* Lawrence Erlbaum Associates Publishers, 2003, pp. 21–46. https://doi.org/10.1201/9781410608888.pt1.

[16] J.M Loomis JM, Da Silva JA, Philbeck JW, Fukusima SS. Visual Perception of Location and Distance. *Current Directions in Psychological Science*, 1996;5(3), pp. 72-77. doi:10.1111/1467-8721.ep10772783.

[17] V. Interrante, B. Ries and L. Anderson, Distance perception in immersive virtual environments, revisited, *IEEE virtual reality conference (VR 2006)*, 2006, pp. 3-10.

Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Patent Portfolio Analysis Related to Advanced VR Technologies and Applications for Treating Driving Phobia

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Abstract. Virtual reality technology enables people to interact with objects in three-dimensional simulated environments. The technology has been applied in many fields such as entertainment, education, and healthcare. Health treatment applications include psycho therapeutical treatments for post-traumatic stress disorders related to driving phobias. Patents that have been filed for treating patients diagnosed with driving phobias are searched and collected using global patent platforms including Derwent Innovation's solution. Patent analytic methods, including clustering, key term frequency analysis, correlation matrix creation, Latent Dirichlet Allocation (LDA), and technology function matrix mapping, are applied to analyze the patent portfolio and identify key technology development trends. The research goal is to identify patent strategies related to driving-related virtual reality psychotherapy treatment. The research identifies six technology clusters, including virtual reality technologies, vehicle driving simulations, diagnosis of driving phobia through bio-signal analysis, and artificial intelligence for health systems. Based on the cluster analysis, virtual reality related patents are increasing over the last decade. A lesser number of patents focus on virtual reality technology that includes exposure therapy for driving phobia treatment. The patent mining results show that virtual reality exposure therapy for driving phobias is still in the growth stage. There is a research gap for new treatments for driving phobias and other phobias such as post-traumatic stress disorder, which have great potential for transdisciplinary engineering research.

Keywords. Virtual reality exposure therapy, driving phobia, post-traumatic stress disorder, patent portfolio, vehicle simulation

Introduction

Virtual reality (VR) is an interactive and immersive experience where people interact within a lifelike environment created by integrating computer components. Driving simulation is a popular VR application where users equipped with VR apparatus experience driving a car in a virtual environment. The major advantage of VR driving simulation is safety. Users in a virtual environment do not expose themselves to actual road conditions yet the driving experience is very realistic and approaches the experience of actually driving a car. The virtual environment might be overwhelmingly realistic without being life-threatening. Researchers are developing VR driving programs and incorporating this technology into psychotherapy for driving phobia treatment since the

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patient is not exposed to the physical dangers of losing control of a motor vehicle on an actual road and causing harm to patient, the therapist, or others.

Driving phobia is a type of post-traumatic stress disorder (PTSD) associated with drivers who experience serious traffic accidents or develop unrealistic fears of driving through traumatic experiences associated with driving, such as the loss of a spouse who died in an accident present at the time. People may be severely impaired in their daily lives when suffering from driving phobia since it may limit employment and the ability to travel long distances from home. An emerging method to treat driving phobia uses VR technology. This medical approach is called Virtual Reality Exposure Therapy (VRET) and is a transdisciplinary engineering research topic. The research combines virtual reality immersive-based technology and psychotherapy. Using VRET, patients are allowed to expose themselves to a simulation of the phobic surroundings but do not physically encounter the feared situations. The immersive exposure conditions can be adjusted through patient feedback to protect patients from excessive mental stress that may worsen the mental condition. Patients are gradually exposed to fearful driving conditions that they can tolerate inside the immersive environment. Through adaptive exposure, the patient increases self-confidence in driving, and with continued therapy in real-world conditions will be able to drive without fear.

This research focuses on patents related to VRET driving phobia and VR driving applications. Studying related patents provides a concise view of the new technologies applied in the industry. Understanding the opportunities for creating patent portfolios and finding potential opportunities for new technologies in the VRET domain provides a strategic advantage. This research is divided into the literature review, the research methodology, patent portfolio analysis, and the conclusions. The literature review analyses non-patent peer-reviewed literature on VRET and the VR driving domain. In the methodology section, patent search strategies are devised to collect patents from the Derwent Innovation database, and analytic tools, including clustering (k-means), NTF-IDF, Latent Dirichlet Allocation (LDA), and the technology function matrix (TFM) are used to analyze patent topics for and classification. An ontology is constructed to present the analytical results. The patent portfolio analysis describes strategies applied to VRET and VR driving to create new development opportunities. The conclusions of this research are summarized in Section four.

1. Literature Review

VRET is a virtual reality system that assists the doctor and patient by integrating exposure and data collection in a safer clinical setting. By combining virtual reality devices and biosignal sensors, clinicians can customize and control the scene and simulate a virtual environment in a three-dimensional space to provide patients with a better sense of presence, provide adaptive exposure to increase exposure effectiveness and safety. VRET treatment can be provided in a small clinical space providing patient privacy (North, North & Coble, 1997). The clinician can control the environmental characteristics that lead to patient embarrassment, complexity, and irritation. The treatment is highly scalable, and the treatment environment's controllability demonstrates the flexibility of the system (Romano, 2005).

Several technology companies have invested resources in the development of virtual reality systems and components. Facebook acquired Oculus and released Rift which is a mobile version of Go and nowQuest. Google created Daydream for augmented reality solutions. HTC Vive, Sony Playstation VR, and Apple are developing virtual reality devices (Miloff, et al., 2020). With increasingly powerful hardware development resources, a solid foundation has been laid for advanced development of VRET used in clinical settings.

Literature related to VRET driving phobia treatment has been studied. In one VRET driving phobia pre-test experiment conducted at the Taiwan National Tsing Hua University (NTHU), 31 subjects participated in a seven-level driving scenario. The clinical design used a pre-test analysis to identify students with driving anxiety, a control group and random assignment. The exposure simulated driving on a country road, a highway, and a mountain road during the day and at night. The level of fear inducing driving exposure increases with successful completion of lower levels of exposure. The heart rate, respiration rate, skin conductance, and body temperature data were collected to measure the degree of anxiety degree. The pre-test result examined the effectiveness of the VRET system. The subject’s anxiety increases with level progression, verifying that the VRET system design affects the subjects’ mental state (Trappey, et al., 2020). Some issues were identified in pre-test experiment, and refinements were made in a new clinical experiment. In the refinement experiment, 130 subjects filled out the pre-treatment questionnaire. Sixty students with high fear of driving were randomly placed on a waiting list or selected as the treatment group to participate in clinical VRET experiment. The experiment results showed a significant improvement for the treatment group and their fear of driving in the exposure environments was reduced. The subjects rated that the immersive experience of the refinement experiment more favorably than subjects in the initial pre-test experiment (Trappey, et al., 2021). In another study (Wald & Taylor, 2000), patients received three treatments within ten days. The treatment included four VR driving scenarios. As a result, the patient's anxiety was reduced. The anxiety and avoidance scores began to decline after treatment and were maintained after a seven-month follow-up study.

Virtual reality technology has been applied to driver training. For professional driver research (Gąsiorek, et al. 2019), an experiment was used to compare the driver training effects between 2D and 3D simulations. Three dimensional simulations provide a more realistic immersive environment and realistic driving conditions. The drawback was some subjects could not endure the dizziness of 3d motion sickness caused by 3D simulators and preferred 2D simulations. A study by Fitzpatrick and Mangalore (2019) evaluated the use of virtual reality headsets to measure driving performance for driving simulation and training. The study provides justification for the use of VR headsets to better understand a drivers’ hazard anticipation behavior. The results were used to create a risk awareness training program. Physiological data were collected in the design of a virtual reality system (Herumurti, Yuniarti, et al., 2019). Herumurt's study proposed to treat a patients’ public speaking anxiety. The study simulates the scene of a speech on stage and the audience off stage. The system measures the subject's heart rate to determine changes given the difficulty of exposure level and different audience responses. If the patient's heart rate is very high, the researchers hypothesized the speaker was very anxious, and the simulation was changed so the audience would doze off and be inattentive, making the subject less anxious. If the subject’s heart rate was not high, the system would simulate an audience of attentive listeners and increase the difficulty of the speech to be delivered. Studies have confirmed that blood oxygen is the least effective among the many physiological feedback for measuring emotions, while blood volume and skin response are the most effective (Trivedi, 2018). A study recruited 36 people with fear of flying and 22 people without to participate in a VRET experiment. During the treatment, the participants’ heart rate, skin resistance, and skin temperature were used as indicators to record the physiological trends. As a result, the fearers and non-fearers show a significant difference in skin resistance, and as the treatment progressed, the skin resistance of the fearers tend to approach the non-fearers' skin resistance, showing that the skin resistance can effectively reflect human anxiety (Wiederhold, et al., 2002). Some studies don't directly define emotions and classify the exposure as going well or going badly, and then adjust the level of difficulty over time using this classification (Dingli & Bondin, 2019). A novel virtual reality driving system to teach driving skills to adolescents with autism spectrum disorder was introduced by Zhang, et al. (2017). This driving system monitors eye movement, electroencephalography, and peripheral physiology data in addition to driving performance data. The objective of the paper is to integrate multimodal information to measure cognitive load during driving such that driving tasks can be individualized for optimal skill learning. Results indicate that multimodal information can be used to measure cognitive load with high accuracy.

The concepts of convolution and machine learning have been applied to physiological data analysis. In Jacob Kritikos's research, he used skin resistance to measure emotion and used continuous deconvolution analysis to disassemble data to optimize the analysis results (Kritikos, et al., 2019). Another study used a 3x3 matrix to define the level of arousal, dividing the physiological data every 10 seconds as input for machine learning classification. The research results show that feature extraction is a key step in the classification process and support vector machines improve sentiment classification accuracy (Hinkle, et al., 2019).

To enhance the VRET system, it is important to improve the sense of presence for users when immersed in the virtual environment. Sheridan (2000) claims that four factors affect the sense of presence and include information quantity, sensor position and orientation, change of relative location of objects, and the active imagination in suppressing disbelief. Once these factors are managed, the VR will become more authentic and improve the user's immersion in the virtual environment. Illusion of presence also strengthens the users' sense of presence, which refers to a psychological phenomenon known as embodiment (Waldrop, 2017). Slater, et al. (2010) discovered that when the subject's virtual body is threatened with harm, the heart rate shifts into fright mode.

Heyse, et al. (2019) provide a semantic ontology for representing relevant concepts and relations related to VR anxiety therapy. The concepts used in their exposure therapy and VRET ontologies are refined using our research methods.

2. Research Methodology

In this section, patents related to VRET and VR driving domains are collected using Derwent Innovation search database. It is a proprietary patent research application that provides trusted patent data from patent offices worldwide. The patent search strategies are presented in section 2.1; clustering (k-means), NTF-IDF, and LDA are applied as patent classification tools to better understand the most critical VRET and VR driving domains Sections 2.2 and 2.3. The technology function matrix (TFM) for patent portfolio strategic analysis is described in Section 2.4. Using the patent classification results, the VR driving ontology is depicted as a tree diagram in Section 2.5.

2.1 Patent search strategy

This research collects patent data from Derwent Innovation and the results are presented in Table 1. The keywords combinations, the IPCs, and yearly filter setting used as patent search strategies have been listed. A total of 428 related patents are collected and analyzed.

Table 1. Patent search strategy.

Virtual reality immersive technology & driving phobia		
Keywords combinations	Virtual reality + Driving phobia	(195 outcomes)
	Virtual reality + Driving training + Therapeutic	(50 outcomes)
	Virtual reality + Virtual vehicle + Artificial intelligence	(54 outcomes)
	Virtual reality + Driving simulation + Sensor	(132 outcomes)
	Virtual reality + Psychotherapy + Car accident	(15 outcomes)
IPCs	G06F, G06T, G06K, G06Q, G09B, G02B, G16H, A61B, A63F	
Application year	1999~2020	

This study uses text mining to cluster and analyze the patents. The following uses k-means, LDA, and NTF-IDF methods to discuss the patent analytics.

2.2 Clustering

K-means is a clustering method used to partition a set of data with similar features into k groups (MacQueen, 1967). It has been successfully applied in patent cluster analysis in our previous research (Hsu, et al., 2006), so we adopt k-means in this patent research to better understand the most important topics in the VRET domain. 428 related patents were classified into 13 clusters, and the NTF-IDF algorithm is applied after clustering to rank the frequency of words in each cluster. If different clusters have similar word frequency, these clusters are integrated into a single cluster. The 13 clusters are reduced to 7 clusters as presented in Table 2. These clusters define the main topics related to VRET and the VR driving domain.

Table 2. Seven clusters classified using k-means and NTF-IDF.

Cluster	Meaning
System information	The internal information flow of the software used when running the VR system
VR scene construction	Design and build VR scene
Subject's feedback	The sensor receives the user's physical feedback
Visual	The screen presented to the user in the headset
Vehicle simulation	Increasing the authenticity of VR driving situations, and its key terms include simulation, drive, game, and motion
VR training	Applications related to training
Apparatus & System	The hard drives and device that will be used

2.3 Latent Dirichlet Allocation

LDA is a generative probabilistic model applied to collections of discrete data such as text corpora to identify topics, which has been successfully applied in our previous solar power patent research published in Applied Sciences (Trappey, et al., 2019). In this research, LDA is applied to classify the topics among patents and identify the key terms in each topic. A total of seven subtopics can be merged into four main topics: sensory receptor, simulation, scenario design, and application, as shown in Table 3.

Table 3. Four main topics classified using Latent Dirichlet Allocation.

Main topics	Meaning
Sensory receptor	Hardware receives user information
Simulation	Design and construction of virtual environment
Scenario design	Sensory stimulation from the device to the user
Application	VR driving applications, such as gaming, training, and healthcare

2.4 *Technology function matrix*

The Technology Function Matrix (TFM) is a useful approach for patent analysis. The matrix organizes information from patents so that users can readily visualize and interpret quantitative information that maps patented technologies to related functions. The map provides a brief sketch of patent development trends within the given domain, helping investigators understand what technologies and functions are leading industry trends and the gaps in development that offer opportunities (Jhuang, et al., 2017). This research analyzed and interpreted the patent search results using the Themescape Map function provided by Derwent Innovation. The function identified six leading technologies, including vehicle simulation, virtual reality technology, PTSD diagnosis, bio-signal analysis, health systems, and artificial intelligence (self-adaptive systems). To define the functions, three applications related to VR driving were defined based on LDA results: entertainment, driving training, and healthcare.

A total of 428 patents related to VR driving were analyzed using the TFM, and the output result is presented in Table 4. The two most popular fields are vehicle simulation (T01) and VR technology (T02) mapped with the function driving training (F03). Our research focuses on the development of VRET for driving phobia, which is highly related to PTSD diagnose (T03) with VRET (F02) and PTSD diagnose (T03) with driving training (F03). Based on TFM findings, patents related to VRET function are relatively scarce, with approximately one-third of patents related to driving training function. There is a noticeable gap and opportunity to develop VRET for driving phobia applications.

Table 4. Technology function matrix.

			Function			
			F01	F02	F03	F04
			Entertainment	VRET	Driving training	Healthcare application
Technology	T01	Driving simulation	14	6	92	12
	T02	VR technology	42	61	178	26
	T03	PTSD diagnoses	1	18	10	8
	T04	Bio-signal analysis	7	16	33	26
	T05	Health system	3	5	8	23
	T06	Artificial intelligence	7	15	39	5
		Total	74	121	360	100

2.5 *Ontology design*

The ontology was presented using a tree diagram. The root node is the main topic of VR driving. The nodes one step lower than the root node in the hierarchy are the four sub-domains, which are the main topics identified via LDA (sensory receptor, simulation, scenario design, and application). Each sub-domain is further sub-classified into detailed technologies and applications. The ontology is presented in Figure 1.

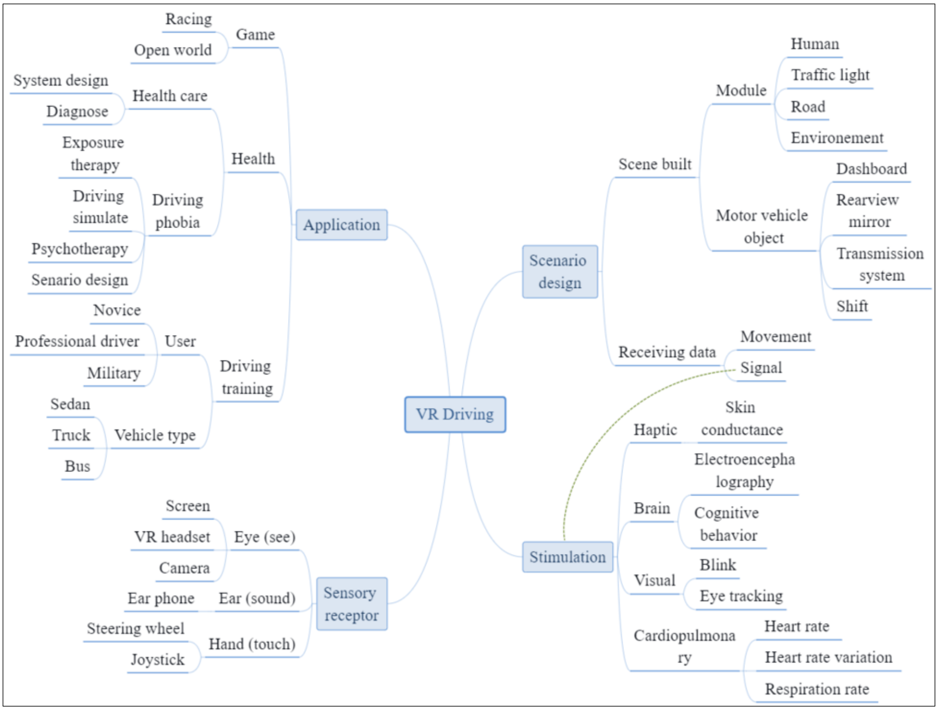

Figure 1. VR driving ontology design.

The first sub-domain is the sensory receptor. Subjects receive stimulations through sensory receptors – eye (visual), ear (sound), and hand (touch). The second sub-domain is stimulation feedbacks. When subjects were receiving stimulations, they will have haptic, brain, visual, and cardiopulmonary feedback. These stimulation feedbacks are often used to evaluate subjects' physiological status while using VR driving programs. The third sub-domain is scenario design. The sensory stimulation given to the user mostly depends on scene built and game objects, including interactive avatars, traffic lights, road, and background environment. The fourth sub-domain is the application that VR could be applied in gaming (entertainment), healthcare, and driving training. VR gaming has exploded in popularity in recent years with VR equipment become popular. People have always been concerned with health issues, and VR technology is suitable for diagnosing and treating mental disorders. The most widely used field of VR driving technology is driving training - regardless a novice driver wants to experience a drive on the road, veterans want to learn how to drive a truck, or even military training purposes. Various kinds of VR programs have been designed for driving training.

3. Patent portfolio analysis

Six technologies and four functions that correspond to the research domain were identified using TFM. Further information about the patent portfolio strategies used in different countries is summarized. Table 5 and 6 are the patent search results of each technology and function along with the number of related patents registered in the country patent platforms: USPTO (US), CNIPA (China), EPO (Europe), JPO (Japan), KIPO (Korea), and TIPO (Taiwan).

Assignees in the U.S. emphasize PTSD diagnosis (T03), health systems (T05), driver training (F03), and healthcare applications (F04). The results indicate that psychological medical technology in the US is more mature in comparison to other countries.

Assignees in China focus on vehicle simulation (T01), virtual reality technology (T02), artificial intelligence (T06), entertainment (F01), and VRET (F02). These technologies belong to emerging fields, so assignees in China pursue opportunities that have high potential strategic benefits.

Assignees in Japan are focused on driving simulation (T01). The automotive industry in Japan plays a leading role globally, so it is reasonable for Japanese assignees to focus on the automotive industry. For example, Toyota, Epson, Honda, and Hitachi automotive are the top Japanese assignees in this field. Assignees in Korea focus on bio-signal analysis (T04). The top assignees in this field are Samsung Electronics, LG Electronics, and Korea Electronics Technology.

The number of patents in Taiwan is fewer than other countries. Assignees in Taiwan often file their patent applications in other countries such as U.S., Japan, Europe, Korea, and China, because Taiwan is not a member of the World Intellectual Property Organization, and the market share in Taiwan is smaller than other countries.

T02 is Virtual reality technology and F02 is VRET. The number of patent applicants in T02 is approximately 100 times greater than patent applicants in F02. In comparison to other functions (entertainment, driving training, healthcare applications), there are relatively few patents related to VRET. Although people have studied about few companies and researchers have applied VR technology to exposure therapy and phobia treatment, our research domain is strategically important and in the introduction stage of development with few patents to challenge new developments.

Table 5 and Table 6 show relatively large markets for VRET related patents in Europe, Japan, and Korea. There have been many patents in the U.S. and China, which means that this technology may be relatively mature in these two regions, and if someone invests in it again, they may encounter patent landmines. As for Taiwan, although it looks like a blank market, its market share may be too small, making the investment efficiency not high. On the contrary, Europe, Japan, and Korea have a certain number of patents, which means they have a certain degree of maturity and investability, but they are not as easy to step on landmines as the U.S. and China, so they are suitable regions for applying for VRET-related patents.

Table 5. Technology related patents registered in different countries.

	Vehicle simulation	VR technology	PTSD diagnoses	Bio-signal analyze	Health system	Artificial intelligence
USPTO (US)	7540	12267	350	628	4213	5947
CNIPA (China)	23867	17530	51	245	2200	12452
EPO (Europe)	3319	3105	111	243	1201	900
JPO (Japan)	6681	1986	99	406	518	1052
KIPO (Korea)	2273	4501	52	2095	345	3316
TIPO (Taiwan)	224	887	12	35	160	179

Table 6. Function related patents registered in different countries.

	Entertainment	VRET	Driver training	Healthcare applications
USPTO (US)	4745	206	10297	5648

CNIPA (China)	6222	362	5977	3395
EPO (Europe)	1162	60	6289	1533
JPO (Japan)	1074	57	2388	870
KIPO (Korea)	716	97	1123	488
TIPO (Taiwan)	353	10	144	163

4. Conclusion and contribution

This research studies the transdisciplinary engineering applications of virtual reality immersive technology and psychotherapy. The immersive technology of virtual reality driving is in the early stage of development. The text-mining results of clustering (k-means) and LDA have classified the key terms and main topics of VR driving-related patents, helping identify the core technologies in this domain. Although there are VR driving applications for entertainment, driver training, and healthcare, few patents are related to driving-related medical treatments or VRET. From patent portfolio analysis, we noticed that most of the VRET patent research comes from the patent offices of the U.S. and China, while it has more opportunities to apply VRET related patents in Europe, Japan, and Korea.Further, for advanced VR technologies and AI technologies that can be largely applied to VRET, we found the patent counts in VRET functional categories (F02) are much smaller than their driving training (F03) applications. The result indicates a research gap for new treatments for driving phobias and other phobias, but it also represents great potential for transdisciplinary engineering applications of virtual reality immersive technology and driving phobia treatment.

Acknowledgement

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References

[1] M. M. North, S. M. North, J. R. Coble, Virtual reality therapy: an effective treatment for psychological disorders, *Studies in health technology and informatics*, 1997, pp. 59-70.

[2] D. M. Romano, Virtual reality therapy, *Developmental medicine and child neurology*, 2005, Vol. 47(9), pp. 580.

[3] A. Miloff, P. Lindner, P. Carlbring, The future of virtual reality therapy for phobias: Beyond simple exposures, *Clinical Psychology in Europe*, 2020, Vol. 2(2), e2913.

[4] A.J.C. Trappey, C.V. Trappey, C. M. Chang, R. R Kuo, A. P. Lin, C. H. Nieh, Virtual Reality Exposure Therapy for Driving Phobia Disorder: System Design and Development, *Applied Sciences*, 2020, Vol. 10, 4860.

[5] A.J.C. Trappey, C.V. Trappey, C. M. Chang, M. C. Tsai, R. R Kuo, A. P. Lin, Virtual Reality Exposure Therapy for Driving Phobia Disorder (2): System Refinement and Verification, *Applied Sciences,* vol. 11(1), 2021, 347.

[6] J. Wald, S. Taylor, Efficacy of virtual reality exposure therapy to treat driving phobia: a case report, *Journal of behavior therapy and experimental psychiatry*, 2000, Vol. 31(3-4), pp. 249-257.

[7] K. Gąsiorek, E. Odachowska, A. Matysiak, M. Pędzierska, Virtual Reality Technologies in the Training of Professional Drivers. Comparison of the 2D and 3D Simulation Application, *International Scientific Conference Transport of the 21st Century.* Springer, Cham, 2019, pp. 133-142.

[8] C. Fitzpatrick, G. P. Mangalore, S. Samuel, M. Knodler Jr, Y. Ebadi, D. Fisher, *Risk Awareness and Perception Training using VR Headsets: The Validation of VR Headsets to Measure Hazard Anticipation Behaviors*, University of Massachusetts, Amherst, 2019.

[9] D. Herumurti, A. Yuniarti, P. Rimawan, A. A. Yunanto, Overcoming glossophobia based on virtual reality and heart rate sensors, *IEEE International Conference on Industry 4.0, Artificial Intelligence, and Communications Technology (IAICT),* Bali, 2019, pp. 139-144.

[10] P. G. Trivedi, *Human Emotion Recognition from Physiological Biosignals (Unpublished thesis)*, Texas State University, 2018.
[11] B. K. Wiederhold, D. P. Jang, S. I. Kim, M. D., Physiological monitoring as an objective tool in virtual reality, *Cyberpsychol Behav*., 2002, Vol. 5(1), pp. 77-82.
[12] A. Dingli, & L. Bondin, Realtime Adaptive Virtual Reality for Pain Reduction, *IEEE Conference on Games (CoG),* London, 2019, pp. 1-4.
[13] L. Zhang, J. Wade, D. Bian, J. Fan, A. Swanson, A. Weitlauf, Z. Warren, N. Sarkar, Cognitive load measurement in a virtual reality-based driving system for autism intervention, *IEEE transactions on affective computing*, 2017, Vol. 8, pp. 176-189.
[14] J. Kritikos, G. Tzannetos, C. Zoitaki, S. Poulopoulou, D. Koutsouris, Anxiety detection from Electrodermal Activity Sensor with movement & interaction during Virtual Reality Simulation, *The 9th International IEEE/EMBS Conference on Neural Engineering (NER)*, San Francisco, 2019, pp. 571-576.
[15] L. Hinkle, K. Khoshhal, V. Metsis, Physiological Measurement for Emotion Recognition in Virtual Reality, *The 2nd International Conference on Data Intelligence and Security (ICDIS)*, South Padre Island, 2019, pp. 136-143.
[16] T. Sheridan, Interaction, imagination and immersion some research needs, *Proceedings of the ACM symposium on Virtual reality software and technology,* Seoul, 2000, pp. 1-7.
[17] M. M. Waldrop, News feature: Virtual reality therapy set for a real renaissance, *Proceedings of the National Academy of Sciences*, 2017, Vol. 114(39), pp. 10295-10299.
[18] M. Slater, B. Spanlang, M.V. Sanchez-Vives, O. Blanke, First person experience of body transfer in virtual reality, *PloS one,* 2010, Vol. 5(5), pp. e10564.
[19] J. Heyse, F. Ongenae, J. De Letter, A. All, F. De Backere, F. De Turck, Design of an ontology for decision support in VR exposure therapy, *13th EAI International Conference on Pervasive Computing Technologies for Healthcare,* Trento, 2019.
[20] J. MacQueen, Some methods for classification and analysis of multivariate observations, *Proceedings of the fifth Berkeley symposium on mathematical statistics and probability*, 1967, Vol. 1(14), pp. 281-297.
[21] F.C. Hsu, A.J.C. Trappey, C.V. Trappey, J.L. Hou, S.F. Liu, Technology and knowledge document cluster analysis for enterprise R&D strategic planning. *International Journal of Technology Management*, 2006, Vol. 36(4), pp. 336-353.
[22] A.J.C. Trappey, P.P. Chen, C.V. Trappey, L. Ma, A machine learning approach for solar power technology review and patent evolution analysis. *Applied Sciences*, 2019, Vol. 9(7), 1478.
[23] A. C. Jhuang, J. J. Sun, A.J.C. Trappey, C.V. Trappey, U. H. Govindarajan, Computer supported technology function matrix construction for patent data analytics. *IEEE 21st International Conference on Computer Supported Cooperative Work in Design (CSCWD)*, Wellington, 2017, pp. 457-462.

Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Development Trend of Human-Cyber Physical System in Manufacturing: Mixed Reality Patent Analytics

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Abstract. Mixed Reality (MR) is an advanced technology designed to enhance users' experience and perception of interactions with objects in both virtual and real worlds. MR has enormous potential for improving human-cyber physical systems (HCPS) in the manufacturing industry. The transdisciplinary engineering (TE) characteristics of this research emphasize integrating advanced patent mining techniques to trend analysis of innovative MR technologies and applications in the manufacturing. Despite the growing popularity of MR applications, trend analyses in this emerging technology have relied on qualitative literature reviews and insufficient patent macro-analytics. Therefore, mapping patents related to MR inventions provides technology experts with better insights of technology development in the manufacturing. This research consists of a thorough review of non-patent literature (NPL) for the construction of MR domain ontology and a systematic patent mining analysis, including patent map analysis, patent clustering, patent topic modeling, and trend analysis of MR applications. A total of 709 patents from the InnovationQ Plus patent database are systematically identified and analyzed for trend discovery. The key terminologies, top ten patent assignees, top five applicants' country origins, top six Cooperative Patent Classifications (CPC), and seven technology clusters and topics are identified. These findings provide reliable MR-enabled HCPS suggestions for the manufacturing.

Keywords. Transdisciplinary, mixed reality, manufacturing, patent analytics, clustering, topic modeling, human-cyber physical system

Introduction

Global competition pushes companies to become innovative in their technological know-how to enhance sustainable competitiveness in the marketplace. Due to the recent advances in information technologies (IT) and operational technologies (OT), the manufacturing industry has entered the era of Industry 4.0, equipped with so-called Cyber-Physical Systems (CPS). This revolution has increased productivity to meet the fast-growing consumer demands and support flexible and efficient manufacturing

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systems. On the contrary, some functions in the current manufacturing environment cannot be automated [1]. Therefore, allowing humans to collaborate with the CPS by playing "master" during manufacturing operations is a viable solution. The concept beyond CPS is considered the fifth industrial revolution, known as Human-Cyber Physical System (HCPS), as shown in Figure 1 [2]. HCPS is a type of composite intelligent system that combines humans, cyber systems, and physical systems to achieve specific goals at a high level of efficiency.

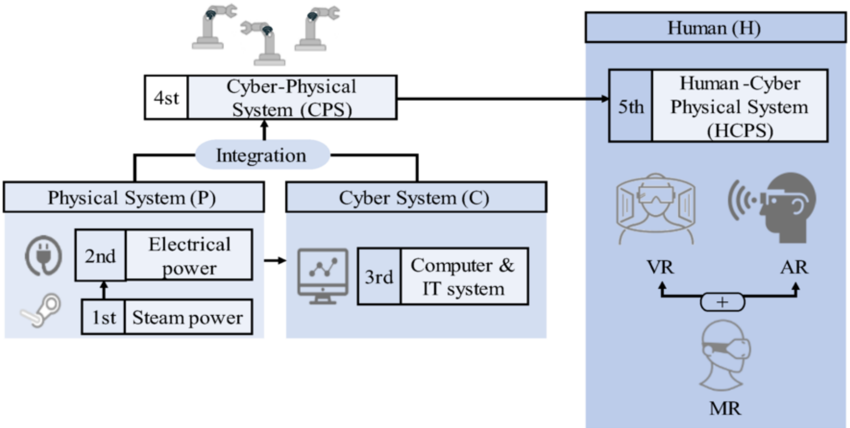

Figure 1. Human-CPS for advanced manufacturing (Industry 4.0).

Immersive technology is one of the best strategies to increase human involvement and realize HCPS in the manufacturing system. There is a taxonomy for this technology, which was developed by Milgram & Kishimo [3]. Table 1 describes differences among Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) [4] [5]. As we can see in table 1, MR is a combination between VR and AR. MR enhances user's perceptions and allows near-seamless interactions between objects in the virtual and real worlds. Information overlay enables remote collaborators to annotate the user's view to improve communications between collaborators. Therefore, MR has vast potential for realizing HCPS for smart manufacturing. To discuss MR technology and its implementation in different sectors briefly, we draw MR ontology based on the prior literature as shown in Figure 2.

This research depicts the MR technologies and applications using patent analytics as a tool for comprehensive technology mining. Technology mining helps discover state-of-the-art technology trends based on previous knowledge documents. Technology mining, adopting supervised and unsupervised learning, is considered an exercise of transdisciplinary engineering (TE), which provides complex engineering solutions by integrating a broad set of knowledge for practical problems [6]. Prior technology mining studies in the TE context are also found in [7].

Table 1. Classification of immersive technologies.

Category	**VR**	**AR**	**MR**
Immersive level	High	Low	Medium
User Interaction	Low	High	Medium
Environment	Virtual	Real	Mixed

This research focuses on the patent analysis of MR technologies and applications, mainly for the manufacturing industry. This study tries to fill the research gap by doing technology mining of MR in manufacturing to (1) highlight current technological trends that impact their respective application areas and (2) identify key technologies for drawing exciting research directions to support HCPS ideas. This study contributes to understanding MR's use in HCPS and manufacturing and gives the future research direction. The remainder of this paper is organized as follows. Following this introduction, the research methodologies are discussed. We will describe patent mining's analytical results in section 3 and conclude our study in the last section.

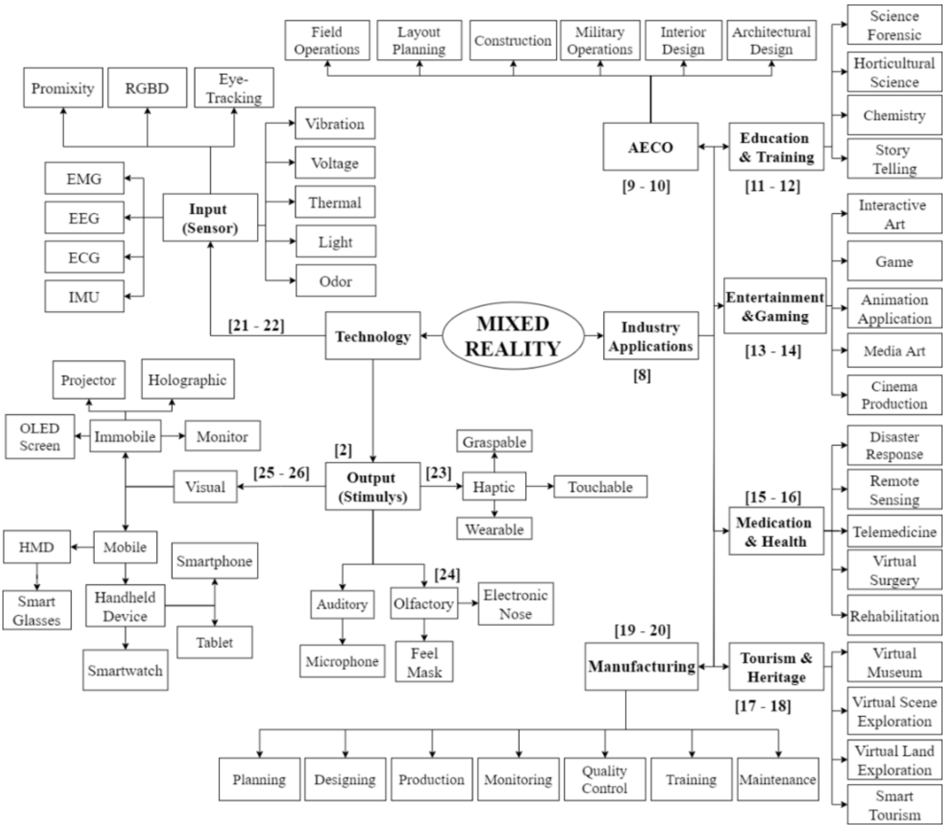

Figure 2. Mixed reality ontology-based literature review [2], [8]–[26].

1. Research methodology

We proposed technology mining based on patent analytics for this research, as illustrated in Figure 3, including technological specification and patent landscape. In the technological specification, we discuss the patent portfolio of MR in manufacturing. For patent landscape, clustering and each cluster's topic modeling (LDA) of domain patents are depicted. At the end of this section, we discuss the MR patent portfolio and its connections to HCPS implementations in the manufacturing industry.

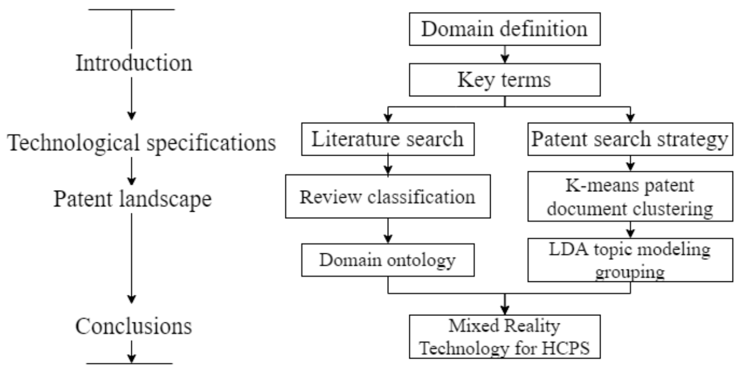

Figure 3. The research flow of comprehensive patent analytics.

1.1. Technological specification

This research analyzes patent literature by utilizing the InnovationQ Plus database from the last ten year (2010-2019) in different patent offices. Our keywords for this patent search are MR in Manufacturing in specific Cooperative Patent Classifications (CPC) (see Table 2 for more details). This study focuses on active and granted patent publication. Using the search strategy, we found 48,900 patent documents. We scan and read through those patent documents and choose patents that are mainly related to our topics. In the end, 709 patent documents are extracted and used for further analysis.

Table 2. Patent search strategy.

No	Criteria	Value
1	Database	InnovationQ-Plus
2	Keywords	Mixed Reality in Manufacturing
3	CPC Codes	Including: G01B; G01C; G01D; G01R; G01S; G02B; G02F; G03H; G05B; G05D; G06F; G06K; G06Q; G06T; G07F; G08B; G09B; G09G; G10L
4	Office Patent	All patent offices, including USPTO (United States), China (CNIPA), World Intellectual Property Organization (WIPO), Taiwan (TIPO), European (EPO), Japan (JPO), and Korea (KIPO)
5	Publication Year	1 January 2010 – 31 December 2019
6	Enforceability	Active and Granted

1.2. Patent landscape

In this subsection, we investigate our patent portfolio and briefly discuss three points: (1) top ten assignees; (2) five largest countries that contribute most to the technology development; (3) six CPCs mainly used in our portfolio. Our analysis's next step is by conducting K-means to cluster patent documents with similar technical specifications into a single group. In this clustering, we extracted some basic key terms from patent abstracts and claims. Based on those key terms and supported by the title of some patents, we named each cluster. From the technology cluster, we do topic modeling to explore the current topics for each cluster. We used Latent Dirichlet Analysis (LDA), an information retrieval algorithm, by considering topics as multinomial distributions over the words [27]. LDA is commonly used to collect words and topics from the combined publications, standards, and patent documents.

2. Patent mining results and discussions

2.1. Patent map analysis

Patent map analysis was developed based on a patent database from InnovationQ Plus. There are about 709 patent-related MR in manufacturing, as captured in Figure 4. First introduced in 1994 by Paul Milgram, patent publication related to MR in manufacturing experienced a linear increase until 2019. A significant increase was happened since the last three years ago; at least 406 (53%) patent documents were published in this range of time. Generally, this trend means there is enormous potential to be involved in this area of MR in Manufacturing.

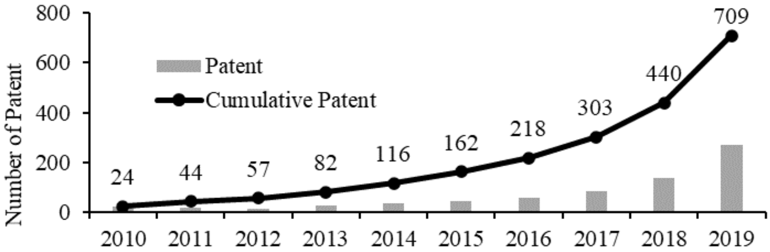

Figure 4. Numbers of patent publications per year (2010 – 2019).

Microsoft Tech Licensing still dominates the current assignee contributed about 131 patents document then followed by Canon and Ricoh from Japan (90 patents documents). These three companies contributed about 31%—Samsung from Korea in fourth place with 13 patents. Simultaneously, Apple Inc and Intel Corp were in the fifth and sixth positions with 11 documents each. Nine publications were contributed by Electronic & Telecom Research Institute, Facebook Tech LLC, and Magic Leap. Nokia is the only company from Finland in the last line with eight documents.

Regarding Figure 5, the US is still superior, with about 49% for patent publication MR in manufacturing. The top three Asia countries (Japan, Korea, and China) and Europe (represented by Germany) followed the US for their significant contributions. Japan contributes 21% of documents through its assignee and then followed by Korea (12%) and China (11%), respectively. Lastly, Germany contributed two percent.

Generally, most companies involved in a patent publication related to MR focus on creating a technology application concerned with 3D model manipulation for computer graphics, interface arrangement for data processing interacted with the human body, and optical systems apparatus. Based on Figure 5, the CPC scheme G06T concerned with manipulating 3D models for computer graphics using MR is the most dominant patent publication. About 224 documents were published with CPC G06T schemes. Furthermore, in the second row, 133 patents published the CPC Scheme G06F concerned with input arrangement for transferring data from processing in and out with human body interaction. G02B (CPC scheme for optical systems and apparatus characterized by visual features) in the third row with 100 patent publications. Data recognition (G06K), about 30 patent publications followed in the fourth. G06Q Data Processing System, with 29 patent publications, existed in fifth. Lastly, H04N related Pictorial Communication Scheme with 29 documents.

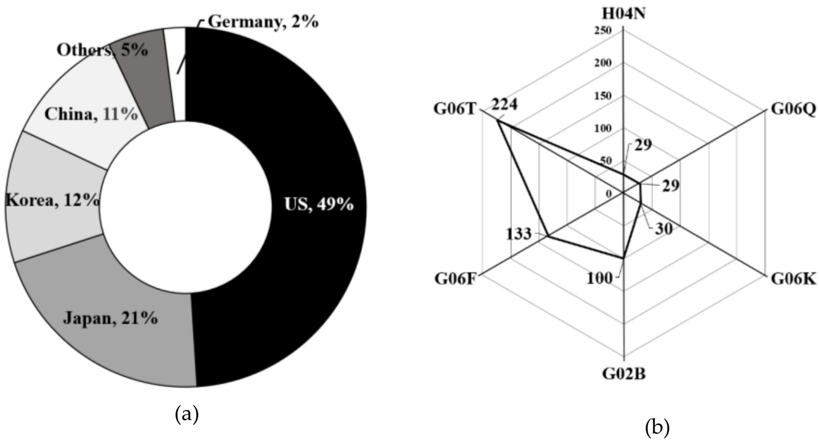

Figure 5. Patent analysis based on (a) country of origin and (b) cooperative patent classifications.

2.2. *K-means for patent document clustering*

We found seven technology clusters related to mixed reality in manufacturing. Most documents are in the OLED Screen and Holographic Technology cluster due to its early development and needs. While the technology generally causes minor documents in Smell and Taste Sensory Technology cluster, it is still only needed in a specific manufacturing industry. The rest distribution of the patent document can be accessed in Table 3.

Top words representative in each cluster were identified in the clustering process. Figure 6 shows the top words and key phrases for every cluster. In the auditory technology cluster (cluster 0), there are key phrase representatives related to the audio, signal, channel audio, audio track, and audio source. For the OLED screen technology cluster (cluster 2), five words are the most representative words related to technology equipment (screen, apparatus display, liquid crystal, electronic display, and crystal display. The holographic technology cluster (cluster 3) has five topic key phrases related to tracking position and object (holographic object, object distance, space physical, space object, and space superimpose). The haptic technology cluster (cluster 4) has six keywords: stylus, touch, glove, tactilely detectable, and electromagnetic wave. In the eye-tracking technology cluster (cluster 5), five keywords correspond to sensing using head movement/ gaze (eye content, eye display, eye position, eye gaze, and pupil position). Then, for the HMD technology cluster (cluster 6), the conductive material, bio-signal, sensor indicate, signal sensor, and synthetic object are five key phrases of the HMD cluster. The last, the smell & taste sensory technology cluster (cluster 6), has the head mount, gaze ray, geo-locate, position head, and plurality head.

Table 3. The patent document clustering result.

Cluster number	Cluster name	The number of patents
1	Auditory Technology Cluster	142
2	OLED Screen Technology Cluster	155
3	Holographic Technology Cluster	153
4	Haptic Technology Cluster	61
5	Eye-tracking Technology Cluster	76
6	HMD Technology Cluster	86
7	Smell & Taste Sensory Technology Cluster	36

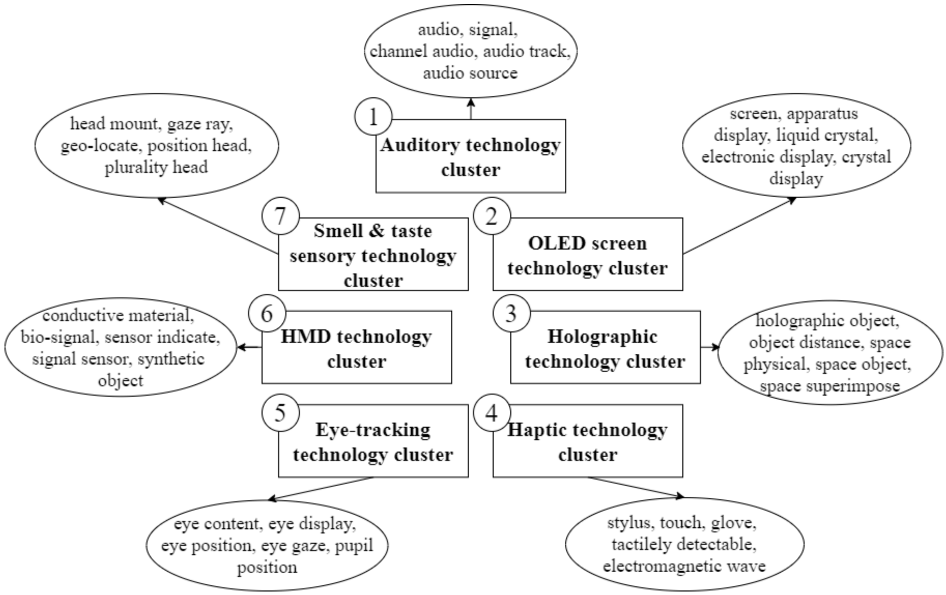

Figure 6. Technology cluster for mixed reality in manufacturing.

2.3. LDA patent topic modeling

Based on the simulation schemes, there is the optimum number of the topic for each cluster namely four topics for cluster 1 (auditory), three topics for cluster 2 (OLED screen), three topics for cluster 3 (holographic), three topics for cluster 3 (haptic), two topics for cluster 5 (eye-tracking), and three topics for cluster 6 (HMD). Unlike other clusters, for cluster 6 (smell & taste), we did similarity of top words, and we found that from 2 topic groups, the similarity of 30 top words is around 90%. Therefore, we merge both topics to become only one topic. These results can be seen in Table 4.

Table 4. List of topics for each cluster technology.

Cluster	Title	Topic	Words
1	Auditory	Detection System	Detection, Match, Threshold, Pose, Pattern
		Recognition System	Monitoring, Process, Flow, Condition, Scene
		Retrieval System	Information, Retrieve, Selectable, Readable, Audio
		Storage System	Audio, Signal, Sound, Storage
2	OLED Screen	Stereoscopic System	Stereoscopic, Imaging, Processing
		Apparatus System	Polarizing, Reflective, Layer
		Visualization System	Visualization, Representation, Environment
3	Holographic	Data Processing	Input, Orientation, Viewpoint, Physical, Dimensional, State
		Stereoscopic System	Superimpose, Color, Presentation, Extract
		Apparatus System	Processing, Video, Graphic, Projector
4	Haptic	Gesture Tracking	Tracking, Object, Marker, Angle, Hand
		Media Interface	Hardware, Interface, Apparatus, Equipment, Mobile
		Display Architecture	Refractive, Curvature, Radius, Characterize
5	Eye-Tracking	Object Recognition	Recognition, Text, Object, Marker
		Eye/ Head Tracking	Gaze, Eye, Direction, Pupil
6	HMD	Object Tracking	Tracking, Object, Movement, Distance, Direction, Visual
		Data Processing	Processing, Information, Content, Visual
		Object Rendering	Rendering, Object, Surface
7	Smell & Taste Sensory	Apparatus System	Feedback, Information, Apparatus, Sense

2.4. *MR technology for human-CPS*

Some interesting findings were derived from the patent analysis described in the previous section. We elaborate on these findings by providing possible explanations for technology mining, especially MR technology in manufacturing operations, to support the human-cyber physical system (HCPS). First, MR is the best immersive technology that creates a world where humans and machines interact seamlessly. The number of patent technology of MR is increasing year to year. However, there is a challenge for MR development, especially to make it more human-friendly [2] [4] [28]. Technology mining of patent analysis in MR technology and application is the best representative of the TE approach for accommodating engineering solutions in practice. Second, developing MR technologies still focus on manipulating 3D models, optical systems and apparatus, and data recognition & processing. Humans have some limitations, such as the human eye limitation for display, which can only be placed 3 to 4 cm away from the eye. It makes optical sensing and processing crucial elements for immersive systems [28]. Third, we got seven technology clusters from k-means analysis, but most of them use visual perception as the primary communication channel. Although visual clues are the most effective for discriminating between con- and hetero-specific individuals, excessive visual stimuli can distract human receivers. Therefore, creating the MR technologies which support multi-modality can be a practical approach for improving information dissemination or overcoming limitations in a real manufacturing environment. Thus, creating multisensory experiences is the dominant direction [2] [15] [16]. Last, based on LDA analysis, MR technologies emphasize apparatus, system, and method to deal with recognition, processing, and visualization. Some manufacturing operations still involve hand operations and human operators' decision-making [2] [5]. It requires close attention and awareness from human operators to identify the related cues or signals from the manufacturing environment. MR helps increase human context-awareness in real-time with a reduced mental workload, which can help prevent human errors and support the critical goal of HCPS.

3. Conclusions

MR enhances the Cyber-Physical System (CPS) through human collaboration and involvement with the intelligent machines, known as Human-Cyber Physical System (HCPS). Technology mining enhances the understanding of state-of-the-art MR technology development. MR technologies and applications are still emerging topics in manufacturing fields, as indicated by the growing patent literature in the past ten years (2010 – 2019). Most technology companies, such as Microsoft, Samsung, and Apple, dominate MR technology developments and their innovative applications. We extend our study by providing a technology cluster of MR and discovering critical topics related to those clusters by utilizing unsupervised clustering and topic modeling approaches. Visual perception is dominant in the MR patent landscape. Innovative sensory technologies, such as auditory, haptic, smell, and taste, are still being researched to bring an immersive environment for HCPS in various manufacturing sectors.

References

[1] J. Manyika, A future that work : Amazing progress in AI and Automation, *McKinsey Glob. Inst. Res.*, no. June, 2017.

[2] D. K. Baroroh, C.-H. Chu, and L. Wang, Systematic Literature Review On Augmented Reality In Smart Manufacturing: Collaboration Between Human And Computational Intelligence, *J. Manuf. Syst.*, pp. 1–16, 2020, [Online]. Available: https://doi.org/10.1016/j.jmsy.2020.10.017.

[3] P. Milgram and F. Kishimo, Taxonomy of Mixed Reality Visual Displays, *IEICE Trans. Inf. Syst.*, vol. 77, no. 12, pp. 1–15, 1994.

[4] S. Rokhsaritalemi, A. Sadeghi-Niaraki, and S. M. Choi, A review on mixed Reality: Current trends, challenges and prospects, *Appl. Sci.*, 2020, Vol. 10, no. 636, pp. 1–26, DOI: 10.3390/app10020636.

[5] G. Riexinger, A. Kluth, M. Olbrich, J. D. Braun, and T. Bauernhansl, Mixed Reality for On-Site Self-Instruction and Self-Inspection with Building Information Models, *Procedia CIRP*, 2018, Vol. 72, pp. 1124–1129, DOI: 10.1016/j.procir.2018.03.160.

[6] A. Kharlamov, G. Parry, and L. Newnes, When and where is transdisciplinary engineering applied in projects? A case study, *Advances in Transdisciplinary Engineering*, 2019, vol. 10, pp. 12–21.

[7] A. J. C. Trappey, C. V. Trappey, C. Y. Fan, and I. J. Y. Lee, Mining the customer's voice and patent data for strategic product quality function deployment, *Advances in Transdisciplinary Engineering*, 2017, Vol. 5, pp. 985-992, DOI: 10.3233/978-1-61499-779-5-985.

[8] R. A. J. de Belen, H. Nguyen, D. Filonik, D. Del Favero, and T. Bednarz, A systematic review of the

current state of collaborative mixed reality technologies: 2013–2018, *AIMS Electron. Electr. Eng.*, vol. 3, no. 2, pp. 181–223, 2019, DOI: 10.3934/ElectrEng.2019.2.181.

[9] W. Huang *et al.*, SMART: Design and evaluation of a collaborative museum visiting application, *International Conference on Cooperative Design, Visualization and Engineering,* 2015, Springer, Cham, DOI: 10.1007/978-3-319-24132-67.

[10] P. Kallioniemi *et al.*, Evaluating landmark attraction model in collaborative wayfinding in virtual learning environments, *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia*, 2013, DOI: 10.1145/2541831.2541849.

[11] D. Aschenbrenner, M. Li, R. Dukalski, J. Verlinden, and S. Lukosch, Collaborative Production Line Planning with Augmented Fabrication, *25th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2018 - Proceedings*, 2018, pp. 509–510, DOI: 10.1109/VR.2018.8446533.

[12] P. Galambos *et al.*, Design, programming and orchestration of heterogeneous manufacturing systems through VR-powered remote collaboration, *Robot. Comput. Integr. Manuf.*, 2015, DOI: 10.1016/j.rcim.2014.08.012.

[13] L. Peppoloni, F. Brizzi, E. Ruffaldi, and C. A. Avizzano, Augmented reality-aided tele-presence system for robot manipulation in industrial manufacturing, *Proc. ACM Symp. Virtual Real. Softw. Technol. VRST*, vol. 13-15-Nove, pp. 237–240, 2015, DOI: 10.1145/2821592.2821620.

[14] D. Borrmann, F. Leutert, K. Schilling, and A. Nüchter, Spatial projection of thermal data for visual inspection, *2016 14th Int. Conf. Control. Autom. Robot. Vision, ICARCV 2016*, vol. 2016, no. November, pp. 13–15, 2017, DOI: 10.1109/ICARCV.2016.7838617.

[15] H. Culbertson, S. B. Schorr, and A. M. Okamura, Haptics: The Present and Future of Artificial Touch Sensation, *Annu. Rev. Control. Robot. Auton. Syst.*, 2018, DOI: 10.1146/annurev-control-060117-105043.

[16] J. Wang, J. Erkoyuncu, and R. Roy, A Conceptual Design for Smell Based Augmented Reality: Case Study in Maintenance Diagnosis, *Procedia CIRP*, 2018, Vol. 78, pp. 109–114, DOI: 10.1016/j.procir.2018.09.067.

[17] W. Fang, L. Zheng, H. Deng, and H. Zhang, Real-time motion tracking for mobile augmented/virtual Reality using adaptive visual-inertial fusion, *Sensors (Switzerland)*, 2017, Vol. 17, no. 5, DOI: 10.3390/s17051037.

[18] J. Wang, Y. Feng, C. Zeng, and S. Li, An augmented Reality based system for remote collaborative maintenance instruction of complex products, *IEEE Int. Conf. Autom. Sci. Eng.*, vol. 2014-Janua, pp. 309–314, 2014, DOI: 10.1109/CoASE.2014.6899343.

[19] A. Shekhar Nittala, N. Li, S. Cartwright, K. Takashima, E. Sharlin, and M. C. Sousa, PLANWELL: Spatial user interface for collaborative petroleum well-planning, In *SIGGRAPH Asia 2015 Mobile Graphics and Interactive Applications, 2015*, DOI: 10.1145/2818427.2818443.

[20] A. R. Singh, V. Suthar, and V. S. K. Delhi, Augmented reality (AR) based approach to achieve an optimal site layout in construction projects, *ISARC 2017 - Proc. 34th Int. Symp. Autom. Robot. Constr.*, no. February 2018, pp. 165–172, 2017, DOI: 10.22260/isarc2017/0022.

[21] S. Fleck and G. Simon, An augmented reality environment for astronomy learning in elementary grades: An exploratory study, In *Proceedings of the 25th Conference on l'Interaction Homme-Machine*, 2013, DOI: 10.1145/2534903.2534907.

[22] I. M. Gironacci, R. Mc-Call, and T. Tamisier, Collaborative Storytelling Using Gamification and Augmented Reality, In *International Conference on Cooperative Design, Visualization and Engineering*, 2017, DOI: 10.1007/978-3-319-66805-5_12.

[23] E. Ch'ng, D. Harrison, and S. Moore, Shift-life interactive art: Mixed-reality artificial ecosystem simulation, *Presence Teleoperators Virtual Environ.*, 2017, DOI: 10.1162/PRES_a_00291.

[24] M. McGill, J. H. Williamson, and S. Brewster, Examining the role of smart TVs and VR HMDs in synchronous at-a-distance media consumption, *ACM Trans. Comput. Interact.*, 2016, DOI: 10.1145/2983530.

[25] G. Kurillo, A. Y. Yang, V. Shia, A. Bair, and R. Bajcsy, New emergency medicine paradigm via augmented telemedicine, in *International conference on virtual, augmented and mixed reality*, 2016, DOI: 10.1007/978-3-319-39907-2_48.

[26] L. A. Shluzas, G. Aldaz, and L. Leifer, Design thinking health: Telepresence for remote teams with mobile augmented Reality, in: H. Plattner, C. Meinel, L. Leifer (eds.) *Design Thinking Research: Making Design Thinking Foundational*, 2015, pp. 53-66.

[27] U. H. Govindarajan, A. J. C. Trappey, and C. V. Trappey, Intelligent collaborative patent mining using excessive topic generation, *Adv. Eng. Informatics*, 2019, Vol. 42, no. January, p. 100955, DOI: 10.1016/j.aei.2019.100955.

[28] U. H. Govindarajan, A. J. C. Trappey, and C. V. Trappey, Immersive Technology for Human-Centric Cyberphysical Systems in Complex Manufacturing Processes: A Comprehensive Overview of the Global Patent Profile Using Collective Intelligence, *Complexity*, vol. 2018, 4283634.

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Enhancing Human Perspectives in CPS Models: Application to Collaborative Problem-Solving in Translational Medicine

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Abstract. Cyber Physical Systems (CPS) have been developed for providing seamless, resilient and high-fidelity services in areas such as manufacturing, healthcare, agriculture, transportation and everyday living. Yet, conceptual and methodological frameworks of CPS that effectively incorporate human perspectives have not been well addressed in research and practice. The success of system design can only be achieved when all stakeholders can mentally and behaviorally position the system in the complex environments and situations by forming user knowledge and meanings through the system lifecycle. Such close human-system collaboration in CPS would enable the real-world system performance such as adaptivity, robustness and resilience in dynamic environments. The goal of this research is to enhance human perspectives by introducing a semiotic framework for representing different aspects of human and organizational meaning formation. It also intends to explore how the semiotic approach can be integrated with Human System Integration (HSI), CPS or Cyber Physical Human Systems (CPHS) methodologies to further enhance human perspectives in CPS lifecycles by transdisciplinary approaches. The paper then introduces an early stage of the project that applies the approach to represent a collaborative problem-solving infrastructure for clinical research process innovation in a multi-institutional translational medicine organization.

Keywords. Cyber Physical Systems, Human System Integration, transdisciplinary approach, semiotic approach. clinical studies, translational medicine

Introduction

The concept of Cyber Physical Systems (CPS) has been widely adopted in both research and practice of complex system development incorporating advanced technologies in areas such as computing, network, sensors, information and physical systems. CPS' goal is to implement seamless, effective, resilient and high-fidelity services for human and organizational activities such as industrial processes, healthcare, agriculture, transportation and everyday living. CPS integrate multiple subsystems across physical and cyber spaces such as numerous sensors, computing, data and knowledge bases, networks, process controllers and effectors. While such technologies can pervade our activity space and deliver services where and when we need them, the quality of these

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services and human-system interaction becomes critical for their effective development, deployment and usage. The National Institute of Standards and Technologies report on CPS framework points out that more research is required to better understand the relationship between a human operator's cognitive cycle and the CPS conceived, built, and operated by humans [1].

The goal of this paper is to introduce a roadmap and requirements for further development of transdisciplinary approaches that will enhance human perspective in CPS design. First, Chapter 1 will review scopes and issues of human modeling schemes in two existing approaches: Cyber Physical Human Systems (CPHS) that incorporate humans in CPS scope; Human System Integration (HSI) that addresses integration issues of systems, humans and organizations through the system lifecycle. Chapter 2 discusses qualitative representation of humans in the system used in Human Centered Design (HCD) and Semiotic Approach. Chapter 3 introduces the Semiotic Approach and Design Information Framework (DIF) as integration mechanisms between qualitative human concerns and technical system representation. Chapter 4 introduces an early stage of the project that applies the proposed approach to a design of a transdisciplinary collaborative problem-solving platform in Translational Medicine research. Chapter 5 summarizes issues and requirements found from the application case and introduces a roadmap for the further development of the application project.

1. **Modeling humans in CPS**

The original CPS concept primarily focused on technical systems. As the CPS technology became mature and the number of implementation cases increased in broad areas, awareness and needs for modeling humans in the CPS have been increasing. The concept of CPHS has been developed in order to address critical roles of humans in the system, human perspectives and performance [2] [3]. HSI and Socio-Technical System also have been addressing issues from the lenses of human factors and large-scale complex system design, operation, management and social impacts [4] [5].

1.1. Cyber Physical Human Systems (CPHS)

CPHS' primary approach for enhancing human concern in CPS is to integrate human subsystem models together with models of technical subsystems. One method is to apply technical modeling schemes such as Unified Modeling Language (UML) and its adaptation to systems engineering, System Modeling Language (SysML), to represent aspects of human subsystems such as activities and cognitive architecture. This allows the integration of human and technical subsystems into a unified representation of human and technical systems [7] [8]. This approach can be positioned in the scope and conceptual foundation of HSI research. The following section overviews HSI's conceptual and methodological research for enhancing human perspectives that is effectively extendable to the CPS context.

1.2. Human System Integration

HSI is defined by the US National Research Council: *Human-system integration (HSI) is concerned with ensuring that the characteristics of people are considered throughout the system development process with regard to their selection and training, their* *participation in system operation, and their health and safety. It is also concerned with providing tools and methods meeting these same requirements to support the system development process [8].* Besides inheriting the human factors and systems engineering resources, HSI further extended the human factors scope to large-scale complex systems by including much wider concerns and scopes of humans in the system lifecycle such as decision making and organizations [9].

The HSI ontology domain diagram by Orellana and Madni in Figure 1 shows how HSI ontology defines a meta-model and constrains an extension profile to enable extensions of SysML and Model Based System Engineering (MBSE) for enhancing human considerations [5]. This enables better transdisciplinary understanding and communication of HSI concerns, and also identifies *core building blocks for creating the ontology for human system interaction, interfaces, and integration* [5].

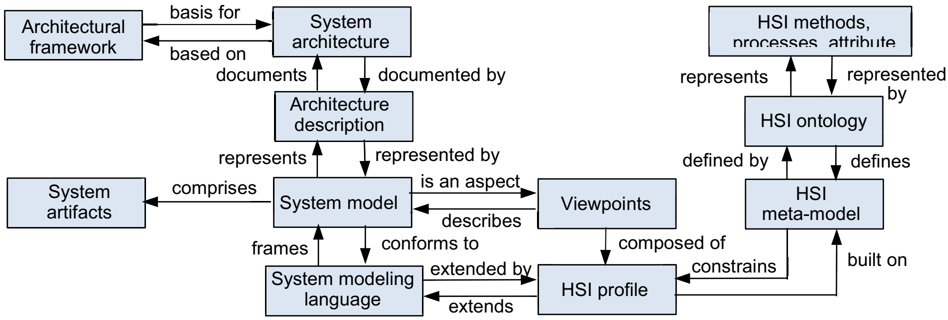

Figure 1. HIS Ontology Domain Diagram [5].

2. **Representing qualitative information in system design**

In the human engagement with systems, meaning generation, communication and interpretation are fundamental mechanisms to drive human action cycles. Meaning is fundamentally qualitative information. Here, the following sections explain how the Semiotic Approach can be used in the Human Centered Design context.

2.1. Human Centered Design

Human Centered Design (HCD) concept has been contributing to raise awareness and establish principles and guidelines concerning human viewpoints [6]. Yet, bridging the language of qualitative and conceptual information concerning humans (also referred as soft information) developed through field observation in the HCD approach and formal language of technical system discipline remains as a major challenge for pursuing holistic approaches to systems design. There are two fundamental questions, (1) how to combine qualitative information with formal representation, and (2) how to represent high-level concepts such as meanings and values.

2.2. Semiotic frameworks for information systems design

The approach based on the Semiotic Framework demonstrates a possible path to the issues represented by the two questions above. Many successful methods for quantifying "qualitative" information have been developed and applied in research and practice. In many cases, quantification enhances information; however, translation of qualitative information to a metric space often causes degradation and oversimplification. Therefore, subjects' information that is fundamentally qualitative in nature, such as meaning formation, transformation and interpretation processes and the nature of meaning itself can be better represented in logical form than quantitative form.

The Semiotic Approach in organization and information system design by Stamper and Liu focuses on sense making and meaningfulness to people [10] [11]. Stamper introduced the Semiotic Framework that reflects people's interaction with technical systems and organizational behavior. Three layers, physical, empiric and social layers, were added to the original framework of semiotics by Pierce composed of syntax, semantics and pragmatics as shown in Figure 2 [10]. The framework works as an interpretive mechanism for representing different levels and aspects of human and organizational meaning formation and behavioral reasoning. Stamper's framework became a foundation for organizational design and information system design by effectively addressing users views and needs from operational, organizational, social and cultural environments. With this framework, a comprehensive methodology of incorporating human perspectives into organization and information system design called MEASUR was developed [11]. The Semiotic Framework based methods have been used in the Semiotic Approach to Product Architecture design (SAPAD) for products and service systems design [12].

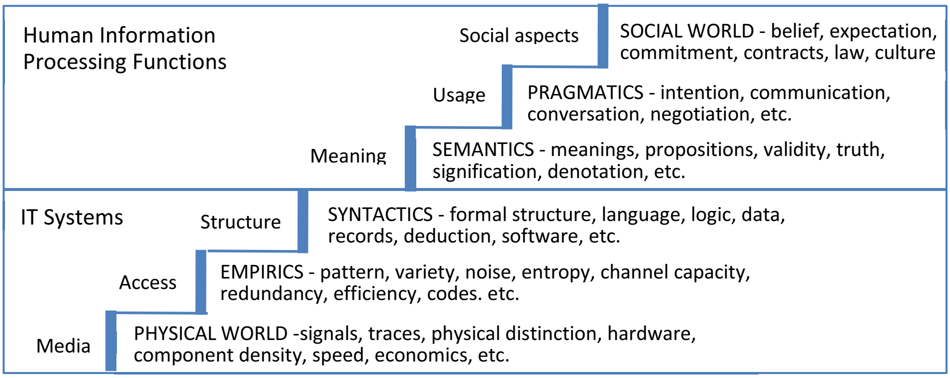

Figure 2. Semiotic Framework by Stamper [10].

Norms are identified as forces that govern or influence human behavior and manifest as principles, guidelines, customs and conventions in social, cultural and organizational communities. They are implicitly referenced for forming interpretation, meaning, judgment and behavior. A norm addresses specific concerns, in other words, is formally or informally defined as permissible ranges in certain dimensions for meaning formation. At meta-levels, these dimensions can be overlaid on system models as constraints or specifications and integrated into systems development lifecycles.

3. **Bridging the Semiotic Approach with system modeling**

Disconnection between human concerns and technical system representation has been a major obstacle to ensuring the quality of new systems and system operations in organizations and our living environments. Human concerns are often elicited by field or user observation that result in textual and graphical documents of qualitative data. The compiled information from field and background studies are reviewed, analyzed, then insights are derived to identify requirements and generate specifications. Although some systematic methods and tools have been developed and used in practice, a lack of common ontology and language between qualitative research outcomes and formal documentation of technical system development impedes effective communication and collaboration between the two efforts.

3.1. *Design Information Framework (DIF) for bridging different views and representations*

The Design Information Framework (DIF) was introduced as a platform for bridging different representations by providing ontological structure for categorization and modularization of qualitative information. This mechanism can translate field notes, narrative documents, video or photographic documents through coding based on the ontological decomposition representing both human and technical perspectives [13] [14]. Figure 3 depicts the DIF platform and different formats of representation such as structured scenarios SysML models such as state models and sequence models [13]. The following chapter explains how DIF can bridge qualitative information of semiotic approaches to HSI ontology and system modeling languages to further enhance human perspectives.

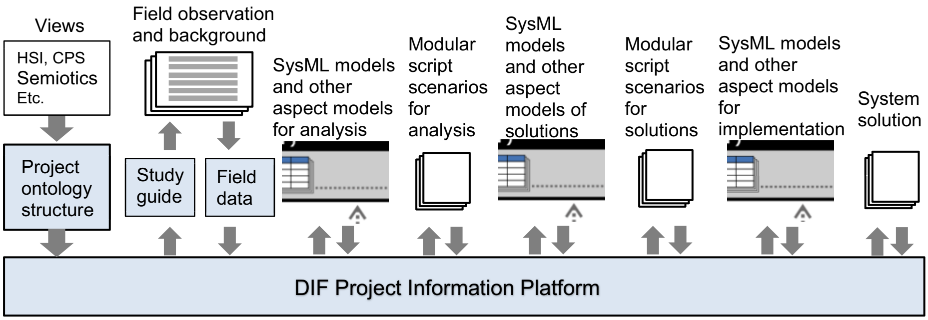

Figure 3. The process of generating scenarios and aspect models with DIF [13].

3.2. *Semiotic approaches to CPS development*

The original Semiotic Framework was introduced with its focus on understanding and analyzing organization and information systems. The upper three layers are allocated for understanding human information processing and the lower three layers are allocated for describing information systems. As Liu points out though, physical space and objects are also a critical part of the human work environment for information system usage [10]. Human cognition, knowledge, and learning are deeply embedded in the physical world through our activities. CPS performs sensing, decision making and social interactions that overlap with human activities. Therefore, all six levels of the semiotic framework should be applied to both human and technical systems.

4. Semiotic approach to ITM-TRIO program as service-oriented CPS

The mission of the Institute for Translational Medicine (ITM) 2.0 [15] is to provide cross-institutional infrastructure for promoting, educating, networking and supporting translational medicine/science. Its aims are: translational science workforce development; patient and community engagement in translational research (TR); equity across special and underserved population and lifespan in translational research; process innovation for quality and efficiency of multisite trials; and integration of advanced informatics. One of the key ways to achieve the aims is the TRIO Studio program. In this section, we highlight how the TRIO Studio is a service-oriented CPS and how the semiotic approach was utilized to achieve the work of the TRIO studio.

4.1 TRIO Studio program as a service-oriented CPS

The Trial Innovation Office (TRIO) architects the infrastructure for the cross-institutional and transdisciplinary process innovation program that supports clinical research recruitment processes. The Studio's mission is to support clinical studies for enhancement of translational medicine. It has been providing collaborative and transdisciplinary problem-solving sessions (TRIO Studios) involving researchers, practitioners and administrators from diverse areas and roles of medicine, healthcare and sciences. The two-hour TRIO Studio hosts a topic presenter and participants consisting of researchers and administrators primarily from ITM member institutions. The presenter introduces issues of her/his clinical research problems, particularly in participant recruitment that are often bottlenecks of the project.

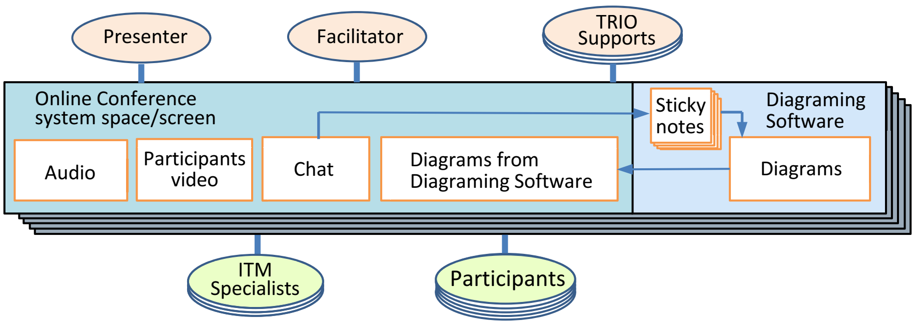

Figure 4. Configuration of online TRIO collaborative problem-solving sessions.

The roles involved in the Studio session are: 1) organizer who promotes the program, attracts presenters and participants and coordinates session plans and post session follow-up with presenters, 2) facilitator who navigates the discussion along the process of the chosen problem-solving approach, 3) session monitor who observes and analyses the session to maintain adherence to the chosen approach and suggest improvements, 4) TRIO staff for program support, 5) several ITM experts who are willing to share their experience and knowledge of problem-solving, 6) a topic presenter who presents his/her research project and problems and 7) participants who are interested in the topic and willing to contribute to the Studio. For productivity of the two-hour sessions, they are structured by one of two alternative approaches to problem-solving, Quality Science Approach (QSA) and Design Science Approach (DSA) for comparative studies between them (See [16] for detail).

At its inception four years ago, the TRIO Studio was conducted in-person. However, COVID-19 restrictions required a transformation to an online delivery mode. The structured session format enabled relatively smooth transition from in-person to online modes. The online session interaction is supported by three channels, Zoom audio/video, Zoom chat function, and Mural visual collaboration software replacing whiteboards and sticky notes.

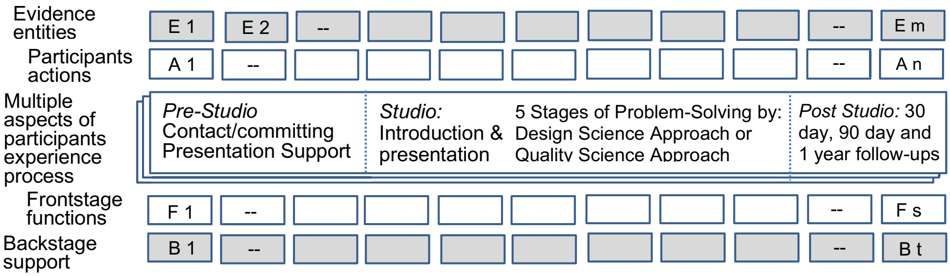

Figure 5. Service Blueprint View of TRIO Studio Process.

Figure 5 shows a service blueprint model of the general studio process with both human and technical system elements. In the model, the participants and the frontstage functions interact together and generate the system process and participants experience. Individual frontstage and backstage functions can be performed by human actor/s, system elements or both. A service action can be performed by any combination of human and system role allocations to frontstage and backstage based on the goal of the session design. The process is composed of three phases, preliminary, primary and follow-up phases. The primary phase is structured with five stages defined by either DSA or QSA.

4.2. Semiotic approach for CPS analysis and envisioning of the TRIO Studio

All the session records have been transcribed and coded with a coding scheme based on the research project ontology for further analysis. This coding scheme works as does DIF that enables further analysis by deriving formal representation with aspect models along with qualitative analysis on original documents.

The intent of applying the CPS framework to such case is to explore possibilities of the CPS framework as a platform for supporting human intensive system design and envisioning its transformation with advance technologies. The modality of the studio can range from fully in-person mode to fully virtual mode composed of all session functions supported or replaced by computerized tools and agents of CPS.

time	phase	actor	act	object	function	objectiv	actor state	----	----
9:18	identifying problems	A3	propose	alternative view	level shift	consistent structure	concerning consistency		
time code	phase	actor	statement	statement type	content type	SF type	situatio	norm type	meaning
1236	P3	E	S-43	B3	process	L-5	S7	Role-	extra time

Figure 6. Example of DIF coding.

Some aspects of the human behavior and architectural models can be represented with SysML. For example, activity and sequence/interaction models of the Figure 5 process can be integrated with corresponding models of the technical subsystems as proposed by the CPHS frameworks. In order to enable transdisciplinary approaches to the complexity and heterogeneity of human systems, particularly to understand the governing forces of human-system behavior, the Semiotic Framework and other information categorization frameworks help researchers compose the ontological structure of the research information on the DIF platform. Use of the DIF platform with the embedded semiotic ontology enables quantitative and qualitative modeling for facilitating semiotic approaches in order to effectively explore human views of the system.

The upper row of Figure 6 shows an example of the general coding scheme of DIF documentation. Each row of the table accommodates an action description that is composed of the items specified by the scheme. Every project could have a different coding scheme based on the concern of the project. The example coding scheme works as: (at time: 9:18) (in phase of the process: identifying problems) (actor: A) (acted: propose) (on object: alternative view) (with function: level shift) (with objective: to consistent structure) (in actor state: concerning consistency). It is not necessary to fill all slots. The lower row of the figure shows an example of a data coding scheme that represent the information items relevant to the purpose and approach of the project. The example reads: (at time 1236) (in session phase 3) (expert E2) (make statement S-43) (about the problem B3) (in process) (referring Semiotic Frame: L-5 pragmatics) (S7: in general) (that relates to the norm type Role-5) (meaning: caught in detail). Currently the coding of approximately 20 sessions is in progress to track the patterns of the problem-solving process from problem identification, to solution emergence, to implementation.

5. **Discussion**

Reflective insights were gained through the session experiences and the review of recorded data. The following insight examples are more concerned with the general nature of the problem-solving session regardless of its mode.

- Visually shared memories such as diagrams, maps and lists for easy access are critical for summarizing and supplementing individual and group processes.
- In order to ensure flexible and cumulative discussion, the facilitator needs to ensure frequently reference to earlier discussion by using the earlier generated diagrams and effectively using the current diagrams in progress.
- The key role of experts is to provide solution architypes and relevant knowledge from their experience at appropriate times during the discussion.

A roadmap for possible transformation of the current TRIO platform to a CPHS-based platform can be set as follows:

Current project phase

- Identify information transformation patterns in the program process and nature of output concerning success, types, impact etc. from the session data analysis,
- Develop system models of the collaborative problem-solving session and platform that embodies the governing principles, strategy and approach of the next generation ITM program, Health Equity and Sociome.

- Develop human-machine collaboration models of the TRIO program to envision future system development as a CPHS.

Next project cycle

- Implement an effective TRIO mission platform and collaborative problem-solving mechanisms for addressing health equity issues with social, cultural and ecological viewpoints (Sociome).
- Standardize the protocol and format for physical, online and hybrid modalities and achieve transportability, adaptivity and resilience by introducing modular system architecture with combinations of human actors and computing tools.
- Explore effective applications of Information and Communication Technology (ICT) to enhance TRIO session performance and experiment with these applications.

Possibilities beyond the scope of the current project goal

- Implement studio facilitation tools and knowledge bases to provide the best possible configuration of human actors and software tools in the Studio.
- Develop a self-learning, facilitation and simulation system for self-operating personal or small group studio sessions based on accumulated records of the previous studios and experts' knowledge in clinical research planning.

This roadmap for future system development of a collaborative problem-solving platform as a CPHS demonstrated the CPHS framework can work as a conceptual design tool for human intensive systems unlike most of current advanced technical systems where human roles are often limited.

Currently detailed study of the Studio session records is being conducted by coding and identifying patterns of collaborative problem-solving by a transdisciplinary community of the ITM organization. The result of this analysis will be combined with our insights and participants feedback and used to set the strategy for the next generation TRIO program as a service system. Integration of semiotic approaches with HSI, CPHS and service system frameworks on the DIF platform will be further explored to enhance CPHS design methodology.

6. **Conclusion**

This paper outlined the formulation of requirements for further development of transdisciplinary approaches for enhancing human perspectives in CPHS design. First, it reviewed scopes, capabilities and issues of human modeling schemes in existing approaches in HSI, Service System Design and CPHS. Second, it demonstrated a Semiotic Approach and DIF platform for structural representation of qualitative human information that can be integrated with technical system representation. This also works as a conceptual instrument for TRIO session record analysis in order to understand the collaborative problem-solving patterns. It will also be applied to identify issues and needs of future TRIO program planning in the ITM initiative. The next phase of the TRIO project study is to determine specific goals, requirements and conceptual specifications for future program development. A methodological architecture that closely links different frameworks and approaches including HIS, CPHS, semiotic approach, and DIF needs to be further developed to enhance scalability, accessibility and adaptivity for transdisciplinary approaches to system design.

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References

[1] Cyber-Physical Systems Public Working Group, Framework for Cyber-Physical Systems: Volume 1, Overview, *NIST Special Publication 1500-201,* National Institute of Standards and Technology, 2017.
[2] S. K. Sowe, E. Simmon, I. Zettsu, F. deVaulx, and I. Bojanova, Cyber Physical-Human Systems: Putting People in the Loop, *IEEE Computer Society IT Professional,* Vol. 18-1, 2016, pp. 10-13.
[3] H. Stern and T. Becker, Development of a Model for the Integration of Human Factors in Cyber-physical Production Systems, *Procedia Manufacturing,* 2017, Vol. 9, pp. 151-158.
[4] M. Hause and M. Wilson, Integrated Human Factors Views in the Unified Architecture Framework, *Annual INCOSE International Symposium (IS 2017)*, Vol. 27, Issue 1, July 2017, pp. 1054-1069.
[5] D.W. Orellana, A.M. Madni, Human System Integration Ontology: Enhancing Model Based Systems Engineering to Evaluate Human-System Performance, *Procedia Computer Science*, 2014, Vol. 28, pp. 19-25.
[6] M. E. Watson, C. F. Rusnock, J. M. Colombi, and M. E. Miller, Human-Centered Design Using System Modeling Language, *Cognitive Engineering and Decision Making,* Vol. 11-3, 2017, pp. 252-269.
[7] M. Krugh and L. Mears, A complementary Cyber-Human Systems framework for Industry 4.0 Cyber-Physical Systems, *Manufacturing Letters*, Vol. 15- B, January 2018, pp. 89-92.
[8] R. W. Pew, A. S. Mavor (ed.), *Human-System Integration in the System Development Process,* The National Academies Press, Ashintong D.C., 2007.
[9] G.A. Klein, Naturalistic Decision Making, *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 2008, Vol. 50-3, pp. 456–460.
[10] K. Liu, *Semiotics in information systems engineering*, Cambridge University Press, Cambridge, 2000.
[11] R. Stamper, K. Liu, M. Hafkamp and Y. Ades, Understanding the roles of signs and norms in organizations-a semiotic approach to information systems design, *Behaviour & Information Technology*, 2000, Vol. 19-1, pp 15-27.
[12] F. Hu, J. Li, W. Wang and K. Sato, Meaningful Experience in Service Design for the Elderly: SAPAD Framework and its Case Study, In: *International Conference on Engineering Design*, July 2019, Delft, pp 3081-3090.
[13] Y-K. Lim and K. Sato, Describing multiple aspects of use situation: applications of Design Information Framework (DIF) to scenario development, *Design Studies*, 2006, Vol. 27, pp. 57-76.
[14] E-C. Jung, K. Sato, Y. Chen, X. He, T. MacTavish, D. Cracchiolo, DIF Knowledge Management System: Bridging Viewpoints for Interactive System Design, In: *The Human-Computer Interaction International 2005 Conference*, Las Vegas, July, 2005, pp. 423-437.
[15] Institute for Translational Medicine 2.0 (ITM 2.0), 2021, *Trial Recruitment Innovation Office (TRIO),* Accessed: 31.05.2021. [Online]. Available: https://chicagoitm.org/itm-trio/
[16] S. Basapur, R. Shah, K. Sato, S. Robinson, Infrastructuring Transdisciplinary Problem-Solving in Translational Medicine, *Advances in Transdisciplinary Engineering,* 2021, Vol. 15, in press.

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Development of Method for Visualizing Behavioral States of Teams

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Abstract. Visualizing behavioral states of teams is useful when providing effective reflection on teamwork for team members, monitoring and intervening teams, and analyzing team processes for teamwork researchers. This paper aims to develop a method to visualize behavioral states in meeting settings. We assumed that team processes follow several periods where behavioral states are stable and tried to detect these periods by focusing on change of communication patterns and facial expression. Detailed methods of detection and subsequent visualization are provided. We then test our method by comparing visualized team states in an idea generation workshop with qualitative observation of its team process. The result shows our method can effectively express some team states and provides viewpoints for more rigid quantitative verification.

Keywords. Teamwork, visualization, behavioral state, workshop

Introduction

Increasing number of transdisciplinary teams have been formed to address complex socio-technical issues nowadays. Although transdisciplinary teams have the potential to bring different skills and knowledge and create innovative solutions for complex issues, such teams are more prone to collapse without sufficient support for teamwork [1]. Inefficient teamwork could demotivate members and prevents information sharing, resulting in deterioration of efficiency, creativity, and resilience of the system.

Visualization of teamwork draws attention as a method for understanding current teamwork states and improving it. With a trend of advancement of information technology and online collaboration, various types of data about team interaction are accumulated such as text data in Social Networking Service and audiovisual data in virtual meetings. There are mainly two levels of focus; macro-level and meso-level visualization. Macro-level visualization deals with an interaction within a large organization or community consisting of several small groups or individuals. This type of research usually analyzes communication for a longer term, typically for several weeks or months. [2] used Sociometric Badges to collect data of the social network of workers at a call center of a large bank, and drew implication that was demonstrated to increase productivity. [3] developed software for visualizing communication flow and showed differences in communication patterns and network structures among three global communities on technology development. On the other hand, meso-level visualization deals with real-time interaction within a small group for a shorter term.

Researchers have used nonverbal data to predict various constructs such as addressing [4], floor control [5], interest [6], team roles [7] and influence [8]. Given strong predictive power of nonverbal cues, visualizing and feedbacking these cues is proposed for manipulating teamwork. [9] developed “Second Messenger" which visualizes balance of speaking time among members and tested its usefulness in group decision making. [10] developed “Meeting Mediator” which can show interactivity of teams and participation of each member in real time based on data in sociometric badges. Although both of these projects prove the usefulness of the visualization for improving the member’s behavior, it is the individual state that is visualized, not the team state that emerges from interaction of individuals and has strong relationship with team effectiveness [11]. By visualizing team states, members can stand on team’s perspectives and consider a variety of ways to improve team states, not just thinking about increasing or decreasing the amount of speaking as in the previous visualization methods.

Thus, this paper attempts to visualize team states, particularly focusing on communication patterns. A communication pattern denotes the amount of interaction between every combination of group members. It can intuitively show participation of each member and indicators predicting performance of teams such as variance in the number of speaking turns [12] and centralization [13]. We present a method for visualizing a time-to-time change of communication pattern in a remote meeting setting, and demonstrate its usefulness in understanding and improving teamwork.

We focus on remote meetings because of two reasons. First, remote communication is rapidly becoming dominant with the outbreak of COVID-19 in 2020, leading to a drastic change in teamwork in any types of organizations. Decrease in face-to-face communication makes remote meetings an important place where team members integrate their knowledge and create values. Second, data in remote meetings provide audiovisual data of better quality for analysis. It contains less noise and can be easily separated by speakers because each speaker uses different microphones on their own computer. Besides, meetings can be recorded without preparing and setting recorders. Thus, supporting tools adjusted to remote settings can be easily applied to the real world.

1. Method for Visualization

1.1. Data collection

In order to calculate a communication pattern, we need speaking data including start time, end time, and index of a speaker for each utterance. For practicality, it is preferable to use a prevailing virtual communication tool to acquire data. Among widely-available tools, “ZOOM” would be suitable because it can allow users to record audio data of each account separately. Thus, this paper utilizes speaking data extracted from recording of ZOOM although our method can be applied to data from any other sources involving information described above.

1.2. Detecting stable section of a communication pattern

The simplest way to visualize communication patterns is to calculate a pattern every five minutes and to arrange it along a timeline. However, communication patterns change depending on the time span, which should be carefully considered upon visualization. We assumed that discussion is composed of multiple sections where communication patterns are relatively stable for more than five minutes, and decided to detect borders of these time spans. Five minutes are considered as a minimum length of time where communication patterns indicate a team state. To this end, we define degree of change (DC) as cosine similarity between a speaker change vector of the previous five minutes and the next five minutes. The speaker change vector consists of the number of turn-taking between every combination of members as its element.

$$DC(t) = 1 - \begin{pmatrix} x_{11}^{t-5} \\ \vdots \\ x_{ij}^{t-5} \\ \vdots \\ x_{nn}^{t-5} \end{pmatrix} \cdot \begin{pmatrix} x_{11}^{t} \\ \vdots \\ x_{ij}^{t} \\ \vdots \\ x_{nn}^{t} \end{pmatrix} \quad (t \geq 5) \tag{1}$$

x_{ij}^{t}: number of turn-taking between speaker i and speaker j within t to t+5 minutes

We firstly calculate DC every thirty seconds. Then we calculate "peak" which satisfies the following conditions; the DC at the "peak" is maximal, its value is over 0.3, and between neighboring "peaks" is at least one minimal DC which is smaller than the DC at the "peak" by at least 0.3. Figure 1 shows the DC (blue line) along the time and "peak" (red dot) of our test data. "Peak" indicates the time point where the communication pattern of the previous five minutes and the next five minutes are highly different. Thus we use time of the "peak" as a border.

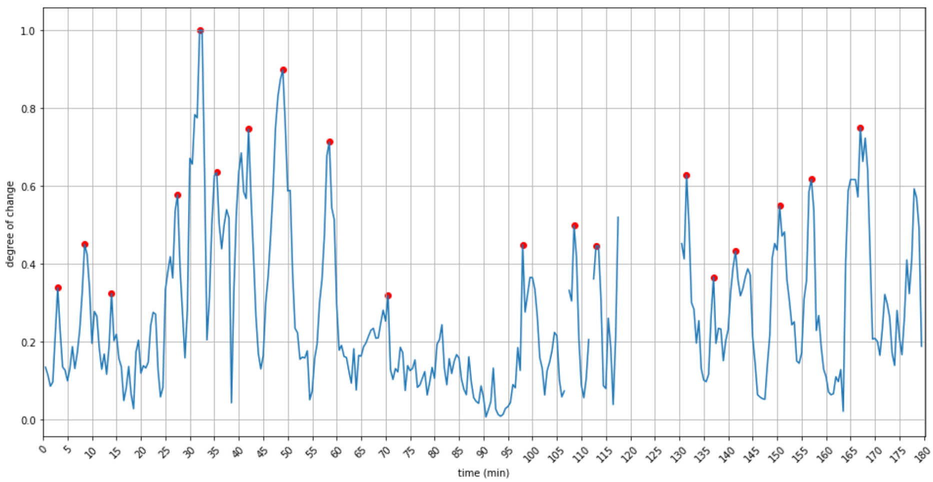

Figure 1. Degree of change and "peak" point of test data.

1.3. Visualization with combining other features

Finally, we calculate communication patterns in time spans between borders. To supplement information relating to team states, we additionally calculate coefficient of variance of the number of turn-taking between members (CV), the number of turn-taking per one minute (NUM), and speaking time of each member, and express them in the graph as Figure 2. Horizontal axis is time, vertical axis is the CV, the line width correlates with NUM. The diagram above the line shows the communication pattern, where each member is assigned to each vertex and the width of lines indicates the normalized number of turn-taking between two members and the size of circles at the vertex indicates the rate of speaking time. All of these features are calculated in time spans between borders. If the duration of the time span is shorter than five minutes, we change the color of the line and communication pattern to gray because it does not express team states in our definition. We additionally calculate a communication pattern during the whole period and display it in upper right. We have adopted a method of displaying these indicators that we thought is most intuitive and easy for viewers to understand.

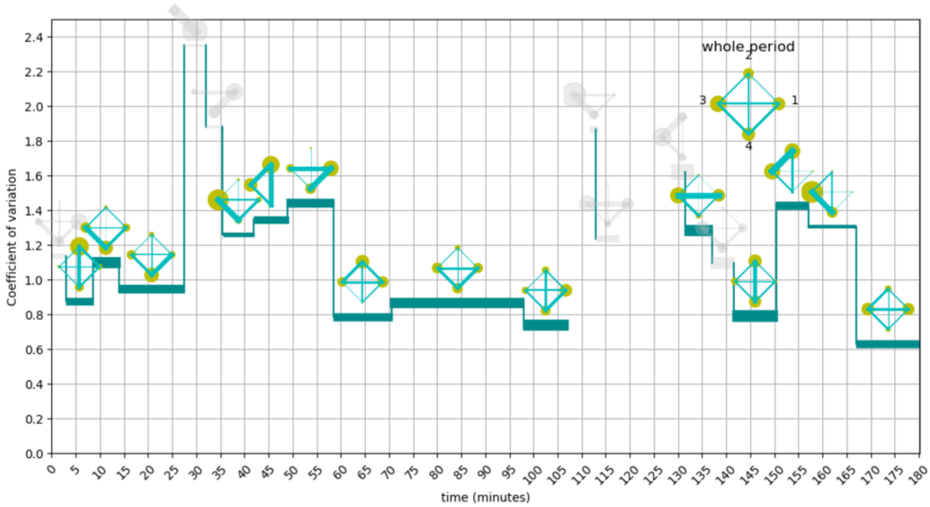

Figure 2. Visualization of teamwork in test data.

2. Case study

To demonstrate the usefulness of our visualization method, we applied it to remote discussions in an idea generation workshop.

2.1. Workshop

The "innovation in super-aged society" workshop was held in i.school, which is an innovation education program developed in University of Tokyo. This workshop aimed to create an idea to increase the number of "super-active senior people." The workshop consists of eight three-hour sessions and one eight-hour session within three months. All sessions in the workshop were conducted remotely using three virtual communication tools; ZOOM, Slack, and Apisnote. Six teams of five to six students joined the workshop.

Participants include university students and company employees. Many of the participants were familiar with each other before the workshop started.

2.2. Method

As cases for analysis, it is suitable to select sessions with different communication patterns while controlling factors affecting communication patterns other than team states, so that the differences in communication patterns relating to team states would be clear. We choose the sessions of different groups on the same day in the early phase of the workshop. Because teams were instructed to generate ideas from scratch, the work were expected to be similar among all teams. We selected teams with six members, which are team A, C, D and F, considering its effect on communication patterns.

We examined the usefulness of the visualization method from two perspectives. First is within-session differences. In one session, the state of the team can change over time. For example, there can be times when only a few people are talking actively, and times when everyone is discussing equally. As within-session differences, we checked if our visualization can capture meaningful changes of team states in one session by qualitative comparison between visualized pictures and observation of video data. We particularly focused on the difference between sections with high and low CV or NUM. Another perspective is between-group differences. Overall team state can vary depending on sessions. Some teams may be in a positive mood and actively engage in discussion while anothers is not. we checked if our visualization can demonstrate differences of overall team state between sessions. Because our goal is to make hypotheses of what our method can indicate, rather than to test specific hypotheses, the investigation described above was conducted in an exploratory way. We listed insights from our visualization method, which will be tested in the future work.

2.3. Result

Figure3, Figure 4, Figure 5 and Figure 6 show the visualized teamwork of team A, C, D, and F, respectively. In order to make them easier to analyze, the mean value of CV is indicated by a dotted line, and sections with higher NUM than its average among all sections are colored orange, and those with lower NUM are colored blue.

2.3.1. Relationship between change of communication patterns and change of topics

We compared visualized figures and observation of video data and found that most of the changes in communication patterns are associated with a change of topic of discussion. For example, Table1 shows discussion topics in the first one hour of team A. With a few exceptions (13:10 and 26:00), the communication pattern changes with the change of discussion topics.

2.3.2. Negative correlation between CV and NUM

There is a common tendency that sections with higher NUM have lower CV. Negative correlation was found between these two values ($n=64$, $r=-.66$, $p=.0000$). This could simply mean that sections with lower NUM didn't have enough opportunity for everyone to speak even if everyone had an equal probability to speak. Another interpretation would be that discussion by a limited number of members tends to be inactive in this workshop

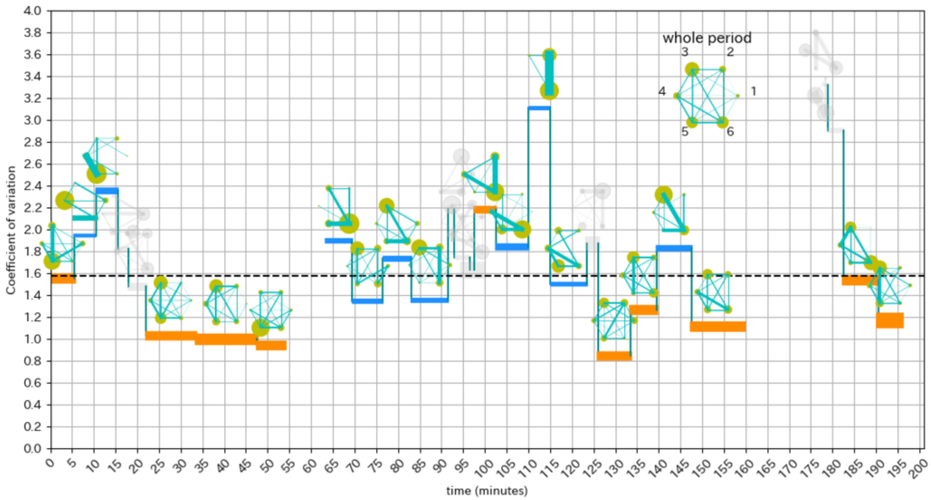

Figure 3. Visualization of teamwork of team A.

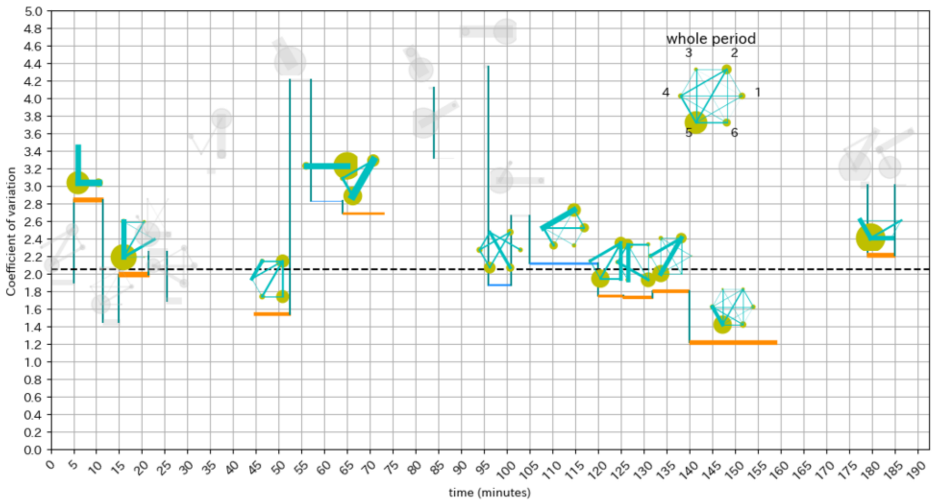

Figure 4. Visualization of teamwork of team C.

conditions. The latter interpretation could be true provided that the negative correlation was found even if CV and NUM are calculated for whole hours, where all participants have enough time to speak, with all sessions with six members (n=29, r =-.51, p=.0047). We further provided detailed observations of team states in sections with both higher and lower CV (lower and higher NUM, respectively) in the following part.

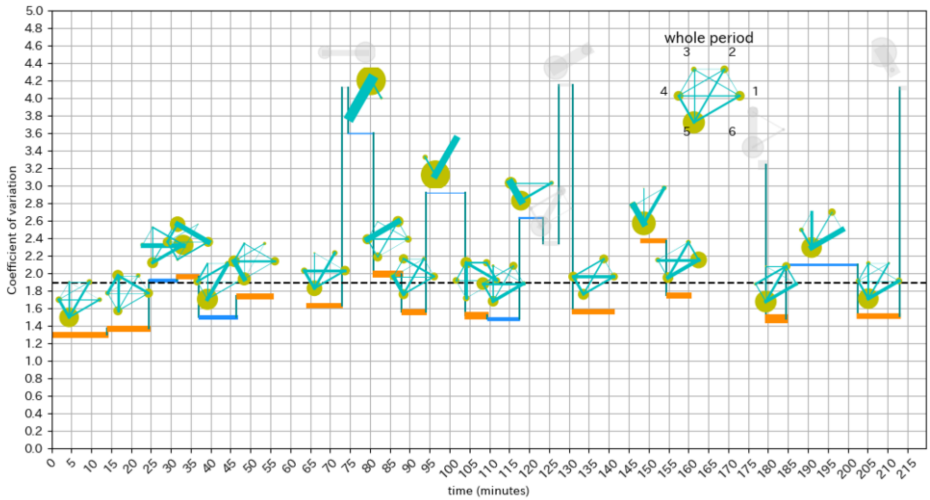

Figure 5. Visualization of teamwork of team D.

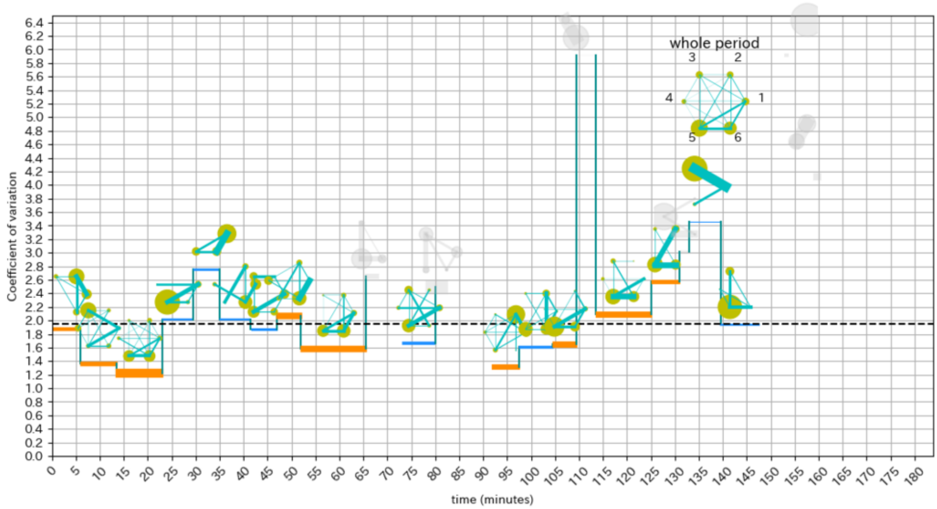

Figure 6. Visualization of teamwork of team F.

2.3.3. Active discussion in a section with low CV and high NUM

Discussion seems to be more active in sections with low CV and high NUM. In these periods, members listen to each other and build on others' opinions, resulting in seamless discussion where topics were developed continuously. Even members with lower numbers of speaking seem to be concentrating on discussion. They show acceptance of others by smiling and nodding their head, creating a harmonious mood. Even when they

Table 1. Discussion topics in the first one hour of team A.

time	Discussion topic
0:00	How to proceed today's discussion
5:42	Definition of "super active senior"
13:10	How to choose cases for analysis
21:45	Categorizing cases
26:00	Commonalities of cases
34:46	Evaluation and selection of cases for analysis
48:38	How to proceed the next discussion
51:15	Confirmation of the reason for choosing the case

disagree with others and provide critical comments, their relationship would not be broken. These characteristics are more pronounced in a section with even lower CV and higher NUM such as a section from 22 to 54 minutes of team A.

2.3.4. Shared understanding in a section with particularly lower CV and higher NUM

Whether the team could build a shared understanding of the topics seems to differentiate sections with slightly lower CV than its average and sections with far lower CV. For example, both the discussion of team A from 22 to 54 minutes, and from 125 to 160 minutes were about evaluation of proposed ideas. Because ideas had been already shared among members, it was relatively easy for them to share their opinions. Hence, more members were able to actively participate in discussion, which resulted in lower CV and higher NUM. On the other hand, the discussion of team A from 0 to 5 minutes, and from 70 to 90 minutes were about sharing and elaborating new ideas. Because ideas were newly introduced, members had to simultaneously understand them and share their opinions, which resulted in relatively higher CV and the NUM. Another example is a discussion of team D from 15 minutes to 55 minutes. During this section, the team was discussing the criteria for evaluating ideas, but in the middle of the discussion, they started a conceptual discussion about the definition of "needs". This occurred from 14 to 37 minutes, when the CV was relatively higher. This indicates that in a conceptual discussion, it was difficult for members to understand others' opinions and create a shared understanding, resulting in decrease in the number of comments and participation.

2.3.5. Several patterns of team states in period with high CV and low NUM

As opposed to sections with low CV and high NUM, sections with high CV and low NUM contain several types of team states. Observed patterns were discussion about the next topic by limited members with higher engagement (team A from 10 to 15 minutes and from 98 to 110 minutes, team D from 148 to 155 minutes), discussion combined with a short individual work (team A from 64 to 70 minutes, team C from 68 to 73 minutes, team D from 73 to 81 minutes and from 94 to 103 minutes, team F from 23 to 28 minutes,

Table 2. Mean CV, mean NUM, and the number of change of communication pattern in all teams.

Team	Mean CV	Mean NUM	Number of changes in communication patterns
A	1.58	6.59	20
C	2.05	2.81	12
D	1.89	4.06	20
F	1.95	3.44	17

from 31 to 40 minutes, and 133 to 138 minutes), sharing information without discussion (team C from 56 to 73 minutes, team F from 125 to 131 minutes), and discussion facilitated by one member (team C from 5 to 11 minutes).

2.3.6. Overall activity level

Table.2 shows mean CV and mean NUM of all sections and the number of change of communication patterns in all teams. Team A and team D show lower mean CV, higher mean NUM, and more number of changes of communication patterns. We got an impression from the video data that discussion of these two teams are more active overall than the others in terms of fluency in discussion, higher concentration of members, and harmonious mood. Although the activity level of teams varies depending on the content of the discussion and the psychological state of the team members at the time, the baseline activity level can be assumed to be relatively stable, and the average value may represent it. We expect this value to be correlated with cohesiveness or other affective states measured by questionnaires in previous teamwork research.

3. Discussion and Conclusion

Although our result is based on qualitative observations of a limited number of cases, it provides some insights stimulating future research. Firstly, the possibility of our method of detecting active discussion is worth noticing, which is characterized by listening to and building on others' opinions, constant flow of discussion, concentration of all members, friendly mood, and critical comments while maintaining relationships. Previous research shows the importance of detecting such a moment. For example, group flow, which shares some traits with the active discussion, was considered as an optimal experience for a group where it can perform at its peak [14]. Empirical studies show its relationship with an increase of group efficacy [15] and an interest in discussion topics [16]. Other research on "hot spots," which are regions in which participants are highly involved in the discussion, claims that contents discussed in such a moment are worth putting into summary of discussion [17]. Although clarification of relationship between these moments and active discussion in our case and validation of our insights by a more rigid and generalizable method are needed, our paper contributes on research on teamwork visualization by showing direction of the future research. Our results also show the possibility to detect other team states such as discussion combined with a short individual work, sharing information without discussion or discussion facilitated by one member. To distinguish these states, additional audiovisual features need to be considered. Once we can identify team states with some degree of precision, large scale research about its antecedents and consequences would be possible with relatively lower effort than traditional method relying on observing and coding teamwork. In addition, our research can be utilized to develop a tool for supporting teams by displaying team states, which will enhance the performance of transdisciplinary teams. Some assumptions for applying our method are the team size and the length of teamwork. Our method works the best for small teams which have roughly 3 to 7 members and the teamwork for more than 1 hour. Additionally, our result of visualization is sensitive to the quality of an audio data, which is not always guaranteed. We hope our research contributed to the effort for automatic visualization of teamwork.

References

[1] S. K. Horwitz, and I. B. Horwitz, The Effects of Team Diversity on Team Outcomes: A Meta-Analytic Review of Team Demography, *Journal of Management*, 2007, Vol. 33, No. 6, pp. 987–1015.

[2] B. N. Waber, D. Olguin Olguin, T. Kim, and A. Pentland, Productivity Through Coffee Breaks: Changing Social Networks by Changing Break Structure, Social Science Research Network, 2010, http://dx.doi.org/10.2139/ssrn.1586375

[3] P. A. Gloor, F. Grippa, J. Putzke, C. Lassenius, H. Fuehres, K. Fischbach and D.Schoder, Measuring social capital in creative teams through sociometric sensors, *Int. J. Organisational Design and Engineering*, 2012, Vol. 2, No. 4, pp. 380-401.

[4] Y. Takemae, K. Otsuka, and N. Mukawa, An analysis of speakers' gaze behavior for automatic addressee identification in multiparty conversation and its application to video editing, In: *13th IEEE International Workshop on Robot and Human Interactive Communication*, Nashville, 2004, pp. 581–586.

[5] L. Chen, R. Travis Rose, Y. Qiao, I. Kimbara, F. Parrill, H. Welji, T.-X. Han, J. Tu, Z. Huang, M. Harper, F. Quek, Y. Xiong, D. McNeill, R. Tuttle, and T. Huang, VACE Multimodal Meeting Corpus, In: *Workshop on Machine Learning for Multimodal Interaction*, Edinburgh, 2005.

[6] D. Gatica-Perez, L. McCowan, Dong Zhang, and S. Bengio, Detecting group interest-level in meetings, In: *IEEE International Conference on Acoustics, Speech, and Signal Processing*, Philadelphia, 2005, pp. 489.

[7] R. Vivian, H. Tarmazdi, K. Falkner, N. Falkner, and C. Szabo, The Development of a Dashboard Tool for Visualising Online Teamwork Discussions, In: *37th IEEE International Conference on Software Engineering*, Florence, 2015, Vol. 2, pp. 380–388.

[8] S. Basu, T. Choudhury, B. Clarkson, and A. Pentland, Towards measuring human interactions in conversational settings, In: *IEEE CVPR Workshop on Cues in Communication*, Hawaii, 2001.

[9] J. M. DiMicco, K. J. Hollenbach, A. Pandolfo, and W. Bender, The impact of increased awareness while face-to-face, *Human–Computer Interaction*, 2007, Vol. 22, No. 1–2, pp. 47–96.

[10] T. Kim, A. Chang, L. Holland, and A. S. Pentland, Meeting mediator: enhancing group collaborationusing sociometric feedback, In: *ACM 2008 conference on Computer supported cooperative work - CSCW '08*, San Diego, 2008, pp. 457-466.

[11] S. T. Bell, S. G. Brown, A. Colaneri, and N. Outland, Team Composition and the ABCs of Teamwork, *American Psychologist*, 2018, Vol. 73, No. 4, pp. 349–362.

[12] A. W. Woolley, C. F. Chabris, A. Pentland, N. Hashmi, and T. W. Malone, Evidence for a Collective Intelligence Factor in the Performance of Human Groups, *Science*, 2010, Vol. 330, No. 6004, pp. 686.

[13] A. Gaggioli, E. Mazzoni, L. Milani, and G. Riva, The creative link: Investigating the relationship between social network indices, creative performance and flow in blended teams, *Computers in Human Behavior*, 2015, Vol. 42, pp. 157–166.

[14] K. Sawyer, *Group genius: The creative power of collaboration*, Basic books, New York, 2017.

[15] M. Salanova, A. M. Rodríguez-Sánchez, W. B. Schaufeli, and E. Cifre, Flowing Together: A Longitudinal Study of Collective Efficacy and Collective Flow Among Workgroups, *The Journal of Psychology*, 2014, Vol. 148, No. 4, pp. 435–455.

[16] S. Culbertson, C. J. Fullagar, M. J. Simmons, and M. Zhu, Contagious Flow: Antecedents and Consequences of Optimal Experience in the Classroom, *Journal of Management Education*, 2015, Vol. 39, No. 3, pp. 319–349.

[17] C. Lai, J. Carletta, S. Renals, K. Evanini, and K. Zechner, Detecting summarization hot spots in meetings using group level involvement and turn-taking features, In: *INTERSPEECH*, Lyon, 2013, pp. 2723–2727.

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Quantification of User's Preference on Product Shapes Using Automobile as a Case Study

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Abstract. Product shapes have tight relations with user's preference. However, it is difficult for product designers to quantify the characteristics of product shapes and predict the preferred shapes. The author proposed a numerical method to quantify characteristics of smartphone shapes. Since the result showed a negative correlation between product impression strength versus user's preference, it was suggested that vigorous and weak impression is preferred. However, since smartphone has small shape variations, it is not a good example in validating the effectiveness of the method. In this research, a new case study for automobile shapes was carried out. As the result, it was suggested that the users can be categorized to some groups having different shape preferences. Since both groups preferred the shape with weak impression, it was suggested that people generally prefer simple and clear shapes for products. However, since the difference of the induction field value was small, this tendency should be examined through further study.

Keywords. User's preference, Semantic difference, Analytical hierarchy process, Induction field, Regression analysis

Introduction

In many products, product shapes must have tight relations with user's preference. Nowadays, since users' preferences are getting more and more various, some may require high functionalities and some may prefer sophisticated outlooks. The modern design activities should be transdisciplinary between functional and shape designs. However, it has been an unsolved problem for product designers to quantify characteristics of the shapes preferred by user and predict the user's preference on product shapes in advance. The recent trend is to combine numerical approaches with Kansei engineering methods. Many approaches [1-5] have been proposed for this purpose, in these days. The author also proposed a method in a previous paper [6] based on a numerical method named induction field [7,8]. The method was applied to quantify characteristics of smartphone shapes and calculate the correlation with the user's preference extracted by analytical hierarchy process [9].

Since the result showed a negative correlation between product impression strength versus user's preference, it was suggested that vigorous and week impression is relatively preferred by users. However, smartphone has small variations in terms of product shapes. In addition, people may guess the maker of the smartphone by the shapes used in the

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previous study. It will lead the users to consider about the product functions. Thus, smartphones might not be good examples in validating the effectiveness of the method. In this research, a new case study for automobile shapes was carried out. Since automobile is one of the products in which user's preference is affected by product shapes, it can be a good example for a case study. As for the automobile shapes there are previous achievements [10] in characterizing the product shapes. Since the automobile is one of the most important industrial products for modern societies, systemized approaches in designing shapes of the products may lead us to a promising outcome.

If this type of approach is successful, it will be possible to propose a more efficient and systemized design process that can also contribute in functional design of products. If the relation between product shapes and user's preference is clarified, it is also possible to determine which of shapes and functions should be focused on.

1. Basics of induction field

In the previous paper [6], the author has shown the procedure to apply the theory named induction field of vision [7, 8] in extracting the characteristics of product outlook quantitatively. The theory is to assume a "field" similar to an electrostatic field around a shape, when people see the shape. Such field is basically consisted of 2 major areas. Based on a Physiological observation, the human vison can be well-explained by stimulation of photoreceptor cells in the central area and suppression of the cells in the surrounding area. Such reaction was named side suppression. And people can recognize the edge of the object clearly by this reaction.

In order to simulate this reactions of photoreceptor cells numerically, expression like eq.(1) has been formulated. The shape of the object is expressed in the X-Y plane and the corresponding photoreceptor cells are expressed by $\xi-\psi$ plane. As it is expressed in the equation, when an optical stimulation comes to a certain point in the $\xi-\eta$ plane corresponding to the object shape in the X-Y plane, the nearby cells where difference of X- ξ and Y- η are small, are stimulated while surrounding cells will be suppressed.

$$S(x,y) = \int_{\Delta S} \{\exp\left(-\frac{(\xi - x)^2 + (\eta - y)^2}{2 * 5^2}\right) - \frac{5^2}{14^2} \times \exp\left(-\frac{(\xi - x)^2 + (\eta - y)^2}{2 * 14^2}\right)\} L(\xi,\eta) d\xi d\eta \qquad (1)$$

S(x,y): value of induction field at point (x,y),
$L(\xi,\eta)$: strength of the stimulation at point (ξ,η)

As for the practical value of the strength of the stimulation expressed by $L(\xi,\eta)$, bit map value of the corresponding bitmap file is used in the study. Since the bitmap data of a pixel is expressed as a discrete value from 0 to 255, the practical calculation value of eq.(1) and (2) will be discrete values.

2. Abstract result of the previous study

2.1. Case study on smartphone shapes

In the previous study, using smartphone as the example, characteristics of product shapes was extracted by the induction field theory. 4 product shapes shown in Figure 1(a). through (d) were analyzed and the induction fields were calculated.

(a) Type A shape (b) Type B shape

(c) Type C shape (d) Type D shape

Figure 1. Four different smartphone shapes

In analyzing the shape, two additional indices were introduced. Equation (2) and (3) are the formulation of two indices. *PE* is expressing the total strength of the impression and *DI* expresses the contrast of the shape.

$$PE = \iint_0^{+\infty} |S| \cdot A(|S|) d([S]) \quad (2)$$

$$DI = S_{\max} - S_{\min} \quad (3)$$

PE: potential value of the induction field
DI: peak to peal value of the induction field

2.2. User's preference of smartphone shapes

In the previous study, characteristics of the product shapes were compared to the user's preference of the shape extracted by AHP (Analytical Hierarchy Process). In the study, three criterion of the shape evaluation were selected. Based on those three criterion indicated in Table 1, four smartphone shapes were evaluated through questionnaire. Table 2 is the total weight of four design plans and compositions of the plans regarding the three evaluation criterion.

Table 1. Three criterion of the smartphone shape and its' relative weight.

Criterion	Relative weight
Familiar	0.25634
Easy-to-use	0.54234
Sophisticated	0.20132

Table 2. Total weight of four design plans and compositions.

Design plans	Familiar	Easy-to-use	Sophisticated	Total weight
A	0.12411	0.24242	0.065962	0.43249
B	0.05382	0.13058	0.041518	0.22592
C	0.04403	0.09037	0.040858	0.17525
D	0.03437	0.07897	0.052985	0.16633

2.3. Correlation between characteristics of the shapes and user's preference

The previous carried out regression analysis and calculate the regression coefficient with above-mentioned user's preferences and characteristics of the shapes. Table 3 shows the result of the regression analysis with PE and DI of the induction fields of the 4 designs and weight of each criterion.

The calculation showed negative correlations between, familiarity, easy-to-use and overall weight with the user's preferences. It basically means relatively weak and vigorous impressions are preferred by users.

Table 3. Correlations of evaluation criterion with induction fields

Regression coefficient	Familiar	Ease to use	Sophisticated	Overall weight
PE	-0.529	-0.449	-0.196	-0.461
DI	-0.564	-0.475	-0.304	-0.498

2.4. Points to be discussed

Although the afore-mentioned result showed a rather clear negative correlations, the result should be carefully examined. Since there are some possibilities.

- The figures let the respondents image the actual product and the answers were affected by experiences and knowledges
- There is not a big difference in smartphone shapes and user's preferences are not affected by impression of the shapes

In order to answer these questions, another case study have been carried out.

3. A new case study regarding automobile shapes

3.1. Evaluation criteria

In the previous study, negative correlations between overall impressions of shapes and user's preference were shown. However, since there is a research question that in case of smartphones, user's thought will not strongly affected by product shapes, a new case study was carried out in the study.

Automobile is a popular product that everyone can show one's preference and the product shapes affect the user's preference for sure. Based on the previous study [11], four criteria to evaluate automobile shapes were extracted. Those are "Sophisticated," "Sporty," "Familiar" and "Gentle."

3.2. Weight of the criteria

Table 4 is the result regarding the relative weight of criteria extracted through pair comparison of the criterion. In addition, it was found that it is possible to clarify user's preference better by the segmentation of respondents. The paper categorized the respondents into two groups. One is "Sporty-oriented" who puts emphasis on "sophisticated" and "sporty" rather than "familiar" and "gentle." The other is "Casual-oriented" who has opposite preference. Table 5 and 6 are the typical analysis result of the respondents' answer who can be categorized to Sporty-oriented and Casual-oriented correspondingly.

Table 4. Average weight of four criteria

Criteria	Relative weight
Familiar	0.249
Gentle	0.141
Sophisticated	0.229
Sporty	0.381

Table 5. Typical weight categorized to Sporty oriented group

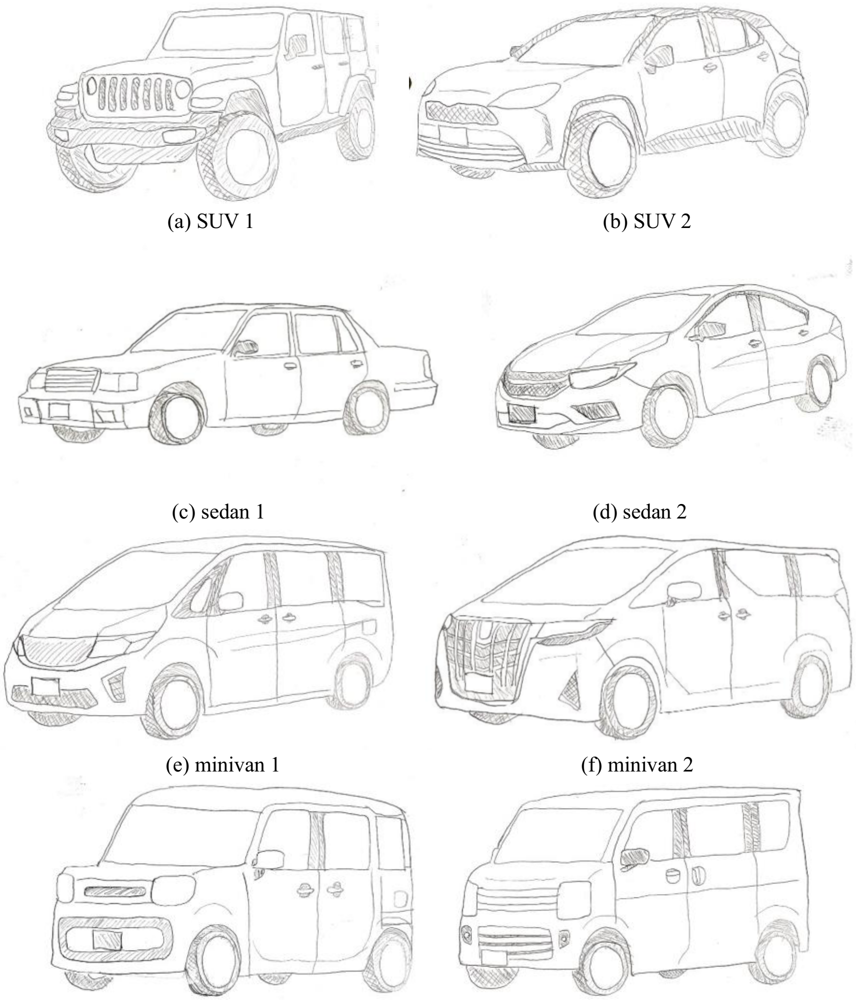
Criteria	Relative weight
Familiar	0.025
Gentle	0.075
Sophisticated	0.225
Sporty	0.675

Table 6. Typical weight categorized to Casual oriented group

Criteria	Relative weight
Familiar	0.615
Gentle	0.188
Sophisticated	0.063
Sporty	0.134

3.3 Preference on automobile shapes

As it was mentioned before, knowledges and experiences of the actual products may affect the user's preference. Such effect should be eliminated to clarify user's preference purely based on product shapes. In order to avoid such affection, illustrations made from photos were used in the study. Information to specify the actual products such as make's logos were eliminated from the illustration. Figure 2.(a)-(h) are the illustrations.



(a) SUV 1 (b) SUV 2

(c) sedan 1 (d) sedan 2

(e) minivan 1 (f) minivan 2

(g) wagon 1 (b) wagon 2

Figure 2. Illustrations to quantify user's preference

Two user's group had rather different preferences on the illustrations. As for the second half of the survey, respondents' feeling on four pairs of automobile shapes regarding four evaluation criterion was investigated. Table 7 shows the result of the survey regarding relative weight two illustrations of four automobile types, for "Sporty-oriented" users and "Casual-oriented" users separately. In other words, the table shows which one of two is preferred by which user group. Especially for SUV and minivan differences of preference for two groups were observed clearly.

Table 7. Relative weights of 4 pairs of illustrations by two groups

	SUV		sedan		minivan		wagon	
	1	2	1	2	1	2	1	2
Casual-oriented	0.14	0.86	0.28	0.72	0.80	0.20	0.71	0.29
Sporty-oriented	0.78	0.22	0.57	0.43	0.26	0.74	0.86	0.14

3.4. Induction field values

While the two groups have rather different feelings against the illustrations, induction fields did not show clear tendencies. Induction fields of two illustrations of wagon had about 3% differences. However, for other three automobile types, there were no clear differences of induction field values. Table 8 shows the PE and DI values of two illustrations of wagon.

Table 8. Induction fields of the illustrations of wagon

	PE	*DI*
1	6.1533E+13	4.1311E+05
2	6.3363E+13	4.2437E+05

3.5. Correlation of induction field and user's preferences

As for the final steps of this procedure, correlation coefficients of two groups regarding the values of PE with relative weight of wagon illustration were calculated. As the result indicated in Table 9, for both groups, user's preference showed strong negative correlations with PE value extracted from the induction fields. Correlation with DI value was almost the same. However, it is premature to say it based on this calculation. Some further discussions are necessary.

Table 9. Correlation coefficients of 2 indices and PE value

User groups	Casual-oriented	Sporty-oriented
Correlation coefficient with P*E*	-0.881	-0.935

4. Discussions

As it was mentioned in the previous chapter, it is too premature to say "there is a negative correlation between the overall strength of impression of the shape expressed by PE with user's preference." These are the reason to hesitate to jump to the conclusion.

- Although there were little differences regarding the two indices from induction field for automobile types except "wagon," clear differences of user's preference have been observed.
- The differences of user's preference may depend of the actual products that the illustrations suggest, rather than the pure impressions of the shapes.

- Although the user's preference is affected by impression of the shape, but the proposed induction field does not express the impression correctly.

However, there are, on the other hand, some points that the authors think induction field is a hopeful method to extract the characteristics of the shape and can be helpful in clarifying and predicting user's preference on the product shapes.

- As it is shown in the formulation, calculation of the induction field is a process based on the bitmap data. Thus, in fact, the illustrations have such characteristics.
- Since the theory of induction field is based on psychological observations. In addition, the calculation procedure is similar to convolutional neural networks often used in deep learning of AI. So, it might be true that induction field expresses the human impression on shape exactly.
- Previous study also showed a negative correlation between impression strength and user's preference. It can be said that people do not like busy or messy shapes for product outlooks.

Whichever the fact is, it is necessary to evaluate the correlation between characteristics of the shapes and user's preference more precisely. In the aspect, below is the further research questions to be answered.

- It is necessary to survey user's preference by using shapes having rather different tendencies in tendencies of induction fields. By this effort, it will be possible to quantify correlations of the two items more clearly.
- Color might affect user's preference greatly. It is necessary to propose a method to quantify shape characteristics including color.
- The procedure used in this study is only applicable to two-dimensional shapes. An idea to treat three-dimensional shapes will be necessary.

5. Conclusions

In this paper, a procedure to extract characteristics of shapes by induction field theory and compare the characteristics to user's preference analyzed by AHP, by using illustrations of automobile as case studies.

It was found that respondents can be categorized to two major groups and the tendencies of preferences on automobile shapes were different corresponding to the group.

Only a pair of illustrations showed a little difference of induction field value, while the other 3 pairs showed little differences. And for the pair, negative correlation between overall impressions of the shapes and user's preference was shown. The fact suggests that people prefer weak and vigorous shapes for automobile, as well as for smartphones.

However, since still there are adore-mentioned problems in the procedure, it is necessary to proceed more precise examination regarding the issue. It is also necessary to analyze the people's perceptions against colors and three dimensional shapes. But, in future, this kind of effort to combine numerical analysis of product shapes and Kasie Engineering methods may reach to a more systematic and efficient stage of shape design of the products.

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References

[1] F.G. Wu and C.Z. Yu, Parametric Design and Kansei engineering in Goblet Styling Design, *Mathematical Problems in Engineering*, 2020, Volume 2020, Article ID 8259698.

[2] Y, M, Chang and C. W. Chen, Kansei assessment on constituent elements and the overall interrelations in car steering wheel design, *International Journal of Industrial Ergonomics*, 2016, Vol.56, pp. 97-105.

[3] Q. Jiang and L. Peng, Kansei Image Evaluation of Teacup based on GA-ELM, In: *3rd International Conference on Mechatronics and Information Technology*, 2018, pp. 246-253.

[4] M. D. Shieh, Y. Li and C. C. Yang, Comparison of multi-objective evolutionary algorithm in hybrid Kansei engineering system for product form design, *Advanced Engineering Informatics*, 2018, Vol. 36, pp. 31-42.

[5] Z. Xiong, M. Liu, Y. Weng and Y. Liu, Research of Customer Product Form Preference based on Kansei Engineering, *First International conference on Advanced Algorithm and Control Engineering*, 2018, 1087, 062051.

[6] N. Mishima, Quantification of Shape Design and It's Correlation with User's Preference, *Advances in Transdisciplinary Engineering*, 2019, Vol. 10, pp. 252-260.

[7] I. Yokose, A Study on Character-Patterns Based Upon the Theory of Psychological Potential Field, *Japanese Psychological Research*, 1970, Vol. 12(1), pp. 18-25. (In Japanese)

[8] M. Nagaishi, A Consideration of Pattern Recognition using the Theory of Field of Induction on the Retina, IEICE technical report. *Image engineering*, 1995, 95(129), pp. 45-52.

[9] T. Saaty, Decision making with analytic hierarchy process, *International Journal of Service Science*, 2008, Vol.1, No.1, pp. 83-98.

[10] E. Ostrosi, J.B. Bluntzer, Z. Zhang and J. Stjepandić, Car style-holon recognition in computer-aided design, *Journal of Computational Design and Engineering*, 2019, Vol. 6, Issue 4, pp. 719–738.

[11] K. Inomata, G. Fujii, S. Hashimoto, T. Katahira, N. Nagata, T. Asano, K. Kawasaki and K. Nikata, Classification of Individuals based on Relationship between their Impression and Preference of Exterior Design of Vehicles, *Transaction of Japan Society of Kansei Engineering*, 2020, Vol.19, No. 2, pp. 223-233. (In Japanese)

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A Conceptual Framework for Designing Smart Domestic Health Enhancement Devices

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Abstract. The process of product design and development can be complex, especially in transdisciplinary practice. A design framework is often adopted to better govern this process. In recent years, there is a growing trend for domestic devices promoting health enhancement. However, due to its specific functionality and a strong need for safety emphasis, domestic health enhancement devices need to be distinguished from other domestic consumer products from the initial stages of designing. Therefore, this study aims to explore the influence of design principles on the artefacts by developing a framework for the design and development of domestic health enhancement devices. It adopts the approach of targeting a selected lifestyle or demography and tailoring a set of device functionalities to its needs. Throughout the process, the proposed framework provides disciplined guidelines to achieve its three design objectives – safety, effectiveness, and user receptiveness. A case study is performed to demonstrate the application of the proposed framework in the context of high heel wearers. The sensor-based real-time feedback is integrated into the user involved design process. The first design iteration in accordance to the framework is completed and evaluated.

Keywords. Design framework, domestic health enhancement device, product design and development, transdisciplinary

Introduction

Technological advances have encouraged a stay-home lifestyle. Indoor entertainment such as video streaming and online shopping removes the physical need to leave the comfort of home. The result is a great potential to escalate into a sedentary lifestyle, which is closely associated with increasing chronic and lifestyle diseases. Hence, there is a growing trend for domestic devices promoting health enhancement in recent years. This is partly attributed to an increasing health awareness along with widely available health information. The emergence of the COVID-19 pandemic further supplemented this appetite as people are spending more time at home, where become the all-in-one place for work, play, exercise, etc.

However, the design and development of domestic health enhancement devices may encounter various setbacks due to its specific nature. This category of devices needs to be distinguished from that of other domestic consumer products, with a specific set of functionality and a much stronger emphasis on safety [1].

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1. Literature Review

1.1 Domestic health enhancement devices

A domestic health enhancement device is to be differentiated from a "home medical device". They are similar in terms of "use in a nonclinical or transitory environment, which is managed partly or wholly by the user, requires adequate labelling for the user, and may require training for the user by a health care professional in order to be used safely and effectively" [2]. While the latter is intended "for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment or prevention of disease", domestic health enhancement, for the scope of this project, focuses solely on independent illness prevention.

A huge range of domestic health enhancement devices exists in the market. This is due to different approaches catering to different market segments. Firstly, general health enhancement devices are of the widest variety in the market. They range from large equipment such as treadmills to small portable dumbbells and yoga blocks. However, uninformed use of such devices may cause aggravation or discomfort to these users with pre-existing health conditions.

Secondly, condition-specific health enhancement devices are of medical nature, ranging from prevention and treatment to rehabilitation. Depending on the severity of the condition, professional supervision may be necessary to ensure patient safety [3]. Clinical directions and supervision are necessary to ensure patient safety, making stretching unsuitable for domestic implementation. Without deep interest and profound expertise, it is difficult to achieve under domestic conditions.

Lastly, the demography/lifestyle-specific devices serve a defined target group, along with its associated symptoms and risk hazards. These symptoms tend to be mild in nature, as they have yet to develop into more severe health conditions. Therefore, solutions are largely preventive in nature, and are safer to administer in the domestic context. Furthermore, a domestic solution is ideal for this market segment, as people tend to not seek clinical aid for mild discomfort.

1.2 Design frameworks

Designers nowadays encounter transdisciplinary challenges more than ever. Design frameworks can be useful as a guiding strategy providing a clear structure to allow them to communicate with stakeholders in a more holistic way [4]. It supports a broader take on new product development, where every decision in the product life cycle has an impact on innovation [5]. Pragmatic considerations, including but not limited to technical, economic and company strategic decisions, highlight the importance of an efficient and competitive design process. Hence, these frameworks tend to suggest applying an iterative procedure to review internal and external sources of knowledge.

Some design frameworks are largely user-centric [6], for specific demography such as the older workforce [7], or promoting a pleasurable interaction between human and technology [8]. The latter asserts that upon the satisfaction of ergonomic factors – safety and functionality, designers should account for hedonomic factors – usability, pleasurable experience and individuation. This is interpreted as a concise hierarchy of needs in design and development, with an emphasis on the appeal of customizability offering a value adding edge to user appeal.

Individual motivation is cited as an important factor to engagement and eventually recovery for a home-based rehabilitation system [9]. Methods to achieving motivation include inspiration, manageability, benefit awareness and progress awareness through feedback. Notably, sensor feedback is also helpful in detecting unsafe compensatory movements, thereby ensuring the quality of engagement [10].

Understanding the characteristics of various existing product design frameworks is essential in assessing their applicability for domestic health enhancement devices. A tailored framework is recommended to guide safe and effective designs due to its many unique features. Furthermore, the influence of the design frameworks on the artefacts has not been fully understood. This paper is interested in crafting a framework to incorporate the specific design principles to facilitate the design and development stage.

2. Method

This project aims to outline a conceptual framework for the ease of use by designers of domestic health enhancement devices. The proposed framework is depicted in Figure 1.

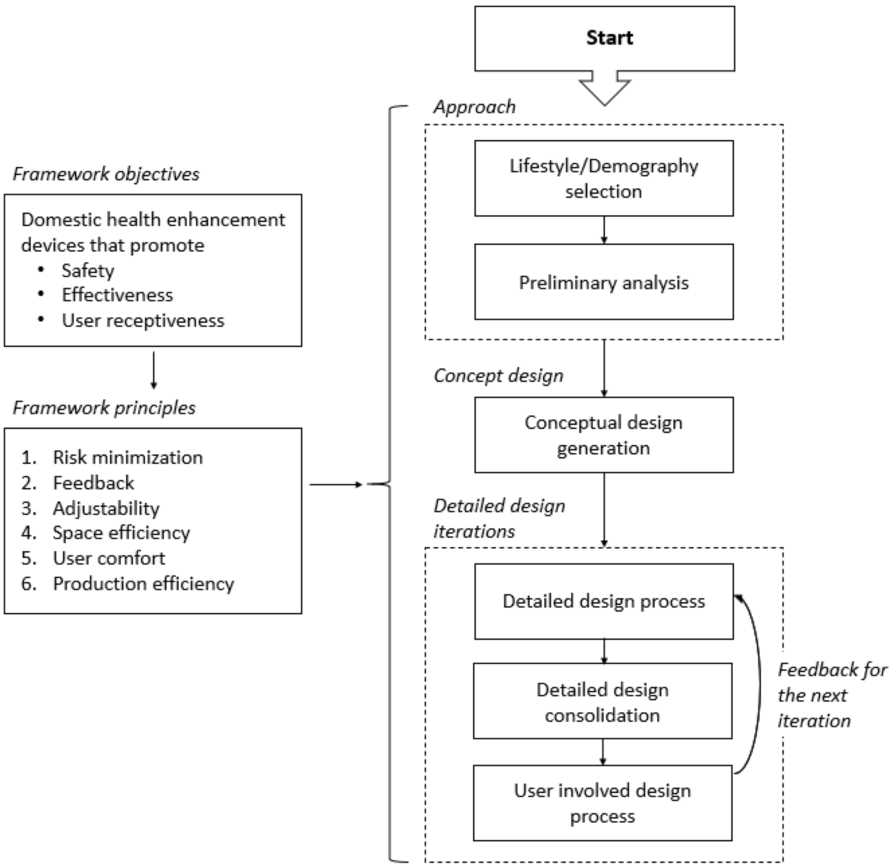


Figure 1. Overview of the conceptual framework.

The left side of the framework details the predetermined objectives and principles, which compile the collective concerns of designing for domestic health enhancement. They serve to govern the entire design and development process.

The right side of the framework outlines the path that future designers can follow in their design process. The process of conceptual design generation depends on the preference of each product designer. Common tools such as functional analysis, morphological charts, decision matrix can be useful.

An advice integrated in the framework is to begin the design process targeting a lifestyle or demography. This eliminates the outcome possibilities of generic products that are prone to misuse, or condition-specific devices that are unsuited for domestic implementation. Preliminary analysis should be complete and thorough with the following:

- Short- and long-term health implications of lifestyle or demographic group.
- Expert and clinical recommendations, and if an unsupervised activity is safe.
- Analysis of existing solutions evaluated with framework principles.

2.1 Identify framework principles

There are three objectives identified for the scope of domestic health enhancement devices. **Safety** is the top priority of the framework. The goal of domestic health enhancement means that device engagement will occur without professional supervision. Extra precautions must be made throughout the design and development stage to ensure minimal risk for the users. **Effectiveness** is a measure of degree that the device can achieve its purported functionality, given that the device is used ideally as intended. **User receptiveness** can be defined as the level of inclination that users will engage with the device. It is affected by various hedonomic factors, including user experience and personalization option. Six design principles are then derived. Figure 2 is a pictorial representation of the relationships between objectives and principles.

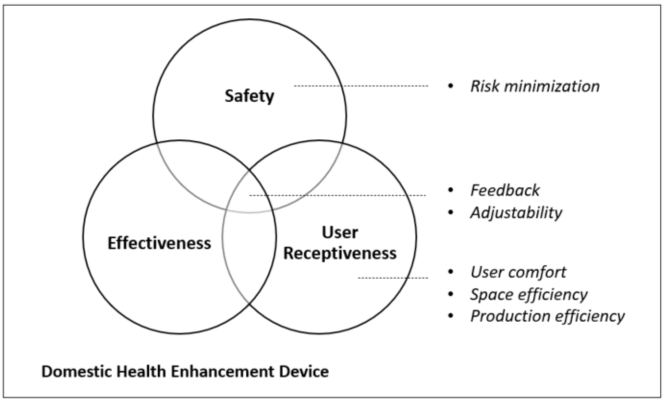


Figure 2. Relationship between design objectives and principles.

2.2 Detailed design iterations

Notably, the detailed design stage involves multiple iterations to optimize device design, where user feedback is continually injected for improvement. Each iteration is complete with a rigorous detailed design process (Figure 3), detailed design consolidation and feedback from user involvement. The last stage of the detailed design process should clearly outline areas requiring user input and assess the level of maturity, with design principles largely satisfied and details complete with production considerations.

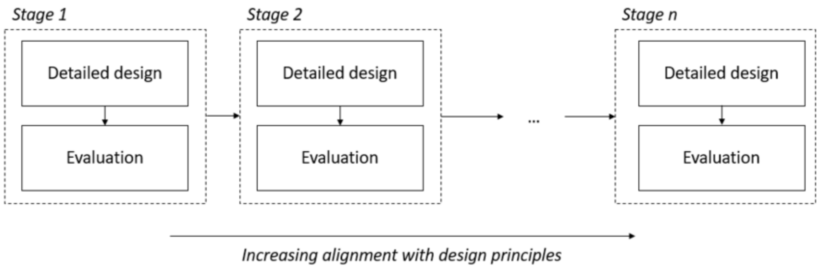


Figure 3. Detailed design iteration process.

In the interest of time and efficiency, the idea should proceed to the next stage once both criteria are met. Detailed design consolidation includes engineering concerns such as material selection and dimensioning, and user interaction considerations in the form of a user manual. While the improvement process can be endless through prototype and experimentation, the device can be considered market ready once all framework objectives are met i.e., safety, effectiveness, and user receptiveness.

3. Case study

A case study on the design and development of domestic health enhancement devices for High Heeled Shoe (HHS) wearers is performed to demonstrate the use of the proposed framework. HHS wearers encounter both temporary discomfort and long-term health implications. The severity of these symptoms varies according to the characteristics of HHS selected, in terms of heel height and width of heel base and tip. Hence, they make an ideal group to introduce domestic options that promote both pain relief and health enhancement.

3.1 Preliminary Analysis

Firstly, the main causes of HHS health implications are identified. The posture and gait are altered during normal walking, generating cause muscle fatigue in the calf gastrocnemius muscles [11]. Elevated heel height also puts additional pressure on the wearers' knees due to a larger knee joint extensor moment [12]. This leads to a large increase in bone-on-bone forces in the knee joint and may increase the risk of degenerative joint and musculoskeletal disease [13]. Functional mobility including movement velocity, directional control and excursions are compromised at a heel height of 7 cm, which standing balance worsens at 10 cm [14].

The fact that HHS wearers tend to shift the body's centre of mass forward during both standing and walking concentrates pressure at their forefoot. This may result in the development of metatarsalgia [15]. Moreover, long-term HHS wearing can cause stiffening of the Achilles tendon and shortening in the medial gastrocnemius muscle fascicles [16]. This adaption has several implications - a smaller ankle's active range of motion and greater angles of ankle plantarflexion at rest, as well as reduced force generation capacity [17].

As a consequence, expert and clinical recommendations are made to alleviate the implications such as to avoid aggravation in spinal disks and knee joints associated with high impact activities, stretch calf to prevent calf shortening and aid in pain relief, and stretch ankle to increase eversion range of motion for stability [18]. Products marketed to address symptoms include but are not limited to adjustable stretch boards, resistant bands, and metatarsal pad insoles.

3.2 Concept design

To analyse the intended functions of the device, the functional analysis is employed and two main functions are shortlisted.

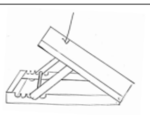
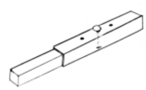
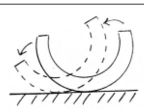
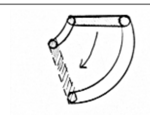
- Dorsiflexion stretching, which offers both short term pain relief in foot and calf tightness, as well as lasting benefits against calf shortening *(Framework design principle: Effectiveness, User comfort)*
- Eversion stretching, which works on the same leg region *(Framework design principle: Space efficiency)*

Next, sub functions are identified to set the direction of design thinking.

- Adjustable device to accommodate different anthropometrics and flexibility *(Framework design principle: Adjustability)*
- Provide feedback to enable motivation, track progress and integrate safety limits *(Framework design principle: Feedback, Risk minimisation)*
- Integrate soft padding to prevent aggravation in stressed areas *(Framework design principle: Risk minimisation, user comfort)*

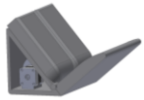
A morphological chart is derived based on the key technical function identified in functional analysis. Table 1 shows the possible solutions for adjusting device dimensions.

Table 1. Possible solutions in the morphological chart.

Solution 1	Solution 2	Solution 3	Solution 4
			
Adjustable angle by adjusting rod's position in groove	Adjustable length using telescopic tubes, which are secured by a bolt	Rounded frame that can be adjusted readily to reach a new equilibrium	Frame adjustment through moving pivots to reach new equilibrium

Three designs are conceptualized based on the morphological chart. A rating value is accorded to each concept based on how well it meets the criteria. Rating values range from a scale of 1 to 5, 1 being very poor and 5 being ideal. Rating values are subsequently multiplied by the weights to generate weighted values (W.V.). Using a decision matrix approach, one final conceptual design is shortlisted (Table 2), in accordance with its performance in the framework design principles.

Table 2. Concept evalutaion based on the decision matrix.

Criteria	**Concept A** 		**Concept B** 		**Concept C** 	
	Value	W.V.	Value	W.V.	Value	W.V.
High safety (30%)	3	90	4	120	5	150
High effectiveness (20%)	2	40	3	60	5	100
High comfort level (10%)	2	20	5	50	5	50
High ease of use (20%)	1	20	4	80	2	40
Low Cost (10%)	5	50	4	40	1	10
Min maintenance (10%)	3	30	4	40	1	10
Sum of weighted values		250		390		360

3.3 Detailed design process – iteration 1

In this case study, iteration 1 is defined in three stages (Figure 4). Stage 1 design caters to the user being in the most comfortable position without having to shift in between modes of use. During dorsiflexion, the user leg is extended for maximum effectiveness. During eversion, the user bends her knees and have a firm footing. In Stage 2, changes of pivot plot are made accordingly to compact the mechanism. Platforms are redesigned to accommodate ankle during dorsiflexion. Cushion height is also accounted for to reserve space for ankle. To reduce the size of the device while maintaining the advantage that user does not have to shift positions, a dynamic design is proposed in Stage 3.

The most significant change from Stage 1 to 3 is in its size, an important consideration for domestic devices *(Framework design principle: Space efficiency)*. Padding and flexibility in device have also been improved *(Framework design principle: User comfort, Adjustability)*.

Figure 4. Iterative improvements from Stage 1 (left) to Stage 3 (right).

The intended setting of use is from a seated position (Figure 5). A simplified static structural analysis was performed on the state of the device when a user (seated at 450mm seat height) rests her legs on the foot platform, with zero dorsiflexion. Since strain in the device is minimal and negligible, there will be no plastic deformation nor changes to device operations. In summary, key features of the design include:

- Diversion of weight of leg to dorsiflex foot.
- Moving pivots in the dynamic frame to accommodate a range of flexibility and anthropometrics.
- Lever mechanism to facilitate ankle eversion stretching.
- Sensors delivering real-time feedback through tilt angles and applied force.

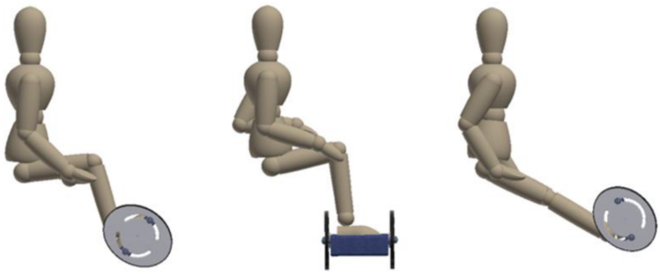


Figure 5. The flexed knee dorsiflexion (left), eversion (centre), extended leg dorsiflexion (right).

In accordance to the framework, the design is ready for user testing since it has largely improved and satisfied design principles. Concise areas that require user inputs include stretching effectiveness quantified by dorsiflexion angles, and subjective assessment of user comfort level with the novel dynamic frame.

Prototype making furthered manufacture considerations and design maturity. The experiment setting simulates the intended engagement setting (Figure 6). Two types of sensors were used concurrently to track the user's dorsiflexion activity. Tilt sensors were employed to detect the incline angle when the foot platform was engaged. To ensure that the tilt detected was associated with user activity, force sensors were placed behind each ankle to detect pressure from the ankle when the foot platform was pushed down.

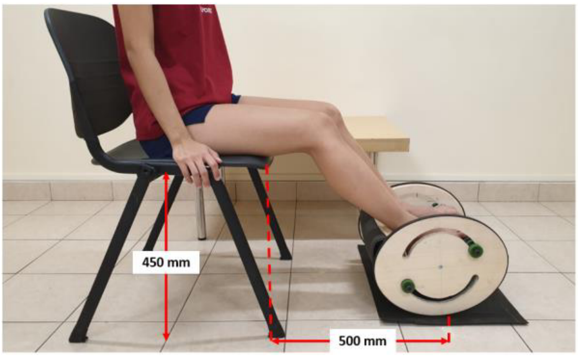


Figure 6. Experiment setting.

The participants were asked to exercise in a sequence. They began with the resting position, dorsiflexion mode (flexed knee) with a manual counter of 1 minute, eversion mode, dorsiflexion mode (extended leg) with a sensor-activated counter of 1 minute, and then return to resting position. Along the process, real-time feedback is accorded to different levels of user engagement – "Not in use", "Push ankle down" during the insufficient stretch, counting when sensor threshold is met, as well as "Very good" with counting when exceeding sensor threshold.

In total, 44 dorsiflexion angles were tracked in the experiment, with 22 female participants (age between 19 to 25 years old) and both feet taken as separate data. The results showed a normal distribution of change in dorsiflexion angle (Figure 7). It reveals a positive mean value of 1.7, suggesting the stretching effectiveness of the device in a singular use. A relatively large standard deviation at 3.0 may be attributed to individual factors such as lack of motivation or uneven stretch in left and right foot due to existing different flexibilities (e.g. ankle sprain history).

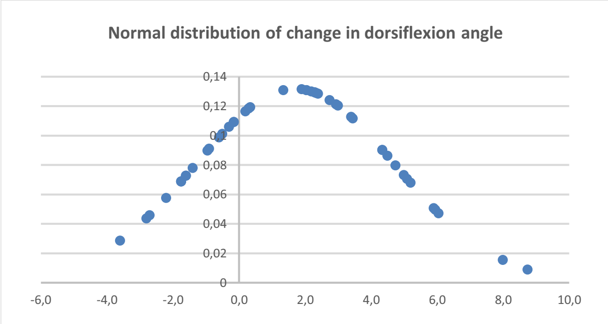


Figure 7. Normal distribution of change in dorsiflexion angle.

Additionally, over 75% of participants have rated at least four out of five for the usefulness of feedback in motivating dorsiflexion activity. This emphasises the importance of feedback as a framework design principle. Both objective and subjective results from the experiment set the direction for the next iteration of detailed design. Room for improvement, along with suggestions, is listed below.

- Presence of stretch beyond the intended region necessitates a professional re-evaluation of safety limits.
- Reconsideration of device centre to reduce additional user effort required to stabilise the dynamic frame.
- Improve the frame shape to minimise the biased eversion stretching due to device asymmetry.
- Comprehensive visual or physical indicators (e.g. arrows and handles) to facilitate an intuitive use of the novel dynamic framework.

4. Conclusion

This study explores a novel approach to develop a conceptual framework that facilitates the attainment of three design objectives – safety, effectiveness, and user receptiveness. The proposed framework puts an emphasis on increasing alignments with design principles during the design iteration process. This is done by identifying and analysing the gaps in existing frameworks in addressing the design and development of domestic health enhancement devices.

The proposed framework proves to be helpful in the case study from topic selection, concept generation to detailed design and user-involved experiments. A case study has demonstrated the use of the framework in guiding the early stages of design up to recommendations for the second design iteration. The results are channelled to begin the next iterative process to improve the device design.

Continual professional consultations with healthcare practitioners should be included to enhance the reliability of the framework design process. There is also an unaddressed contradiction between user receptiveness and effectiveness, which is likely to surface in the later iterations of designs. Further studies are needed to bring it to completion for a systematic hierarchy in design objectives and greater generalizability.

Acknowledgement

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References

[1] N. R. Council, *The role of human factors in home health care: Workshop summary*. Nat. Acad., 2010.
[2] N. Ear and T. D. Branch, *Guidance for Industry and FDA Staff Regulatory Requirements for Hearing Aid Devices and Personal Sound Amplification Products*, U.S. Department of Health and Human Services Food and Drug Administration Center for Devices and Radiological Health, 2009.
[3] H. Alfredson, T. Pietilä, P. Jonsson, R. Lorentzon, Heavy-load eccentric calf muscle training for the treatment of chronic Achilles tendinosis, *The Am. journal of sports medicine,* 1998, 26(3), pp. 360-366.
[4] W. Song and T. Sakao, A customization-oriented framework for design of sustainable product/service system, *Journal of Cleaner Production*, 2017, Vol. 140, pp. 1672-1685.
[5] C. Vila and J. C. Albiñana, An approach to conceptual and embodiment design within a new product development lifecycle framework, *Int. Journal of Production Research,* 2016, 54 (10), pp. 2856-2874.
[6] X. Sun, R. Houssin, J. Renaud, and M. Gardoni, A review of methodologies for integrating human factors and ergonomics in engineering design, *International Journal of Production Research*, 2019, Vol. 57, No. 15-16, pp. 4961-4976.
[7] I. Gonzalez and P. Morer, Ergonomics for the inclusion of older workers in the knowledge workforce and a guidance tool for designers, *Applied Ergonomics*, 2016, Vol. 53, pp. 131-142.
[8] P. A. Hancock, A. A. Pepe, and L. L. Murphy, Hedonomics: The power of positive and pleasurable ergonomics, *Ergonomics in design,* vol. 13, no. 1, pp. 8-14, 2005.
[9] S. Rennick Egglestone, L. Exelrod, T. Nind, R. Turk, A. Wilkinson *et al.*, A design framework for a home-based stroke rehabilitation system: Identifying the key components, *2009 3rd International Conference on Pervasive Computing Technologies for Healthcare*: IEEE, 2009, pp. 1-8.
[10] Y. Wang, S. Yu, and N. Ma, A requirement-scenario-experience framework for evaluating wearable and fashionable design: Presenting underlying factors of user loss, *International Journal of Industrial Ergonomics*, 2018, Vol. 68, pp. 137-148.
[11] J. Yu, D. W.-C. Wong, H. Zhang, Z.-P. Luo, and M. Zhang, The influence of high-heeled shoes on strain and tension force of the anterior talofibular ligament and plantar fascia during balanced standing and walking, *Medical engineering & physics*, 2016, Vol. 38, No. 10, pp. 1152-1156.
[12] K. Y. Chew, Y. Q. Tan, S. C. Chan, The effects of different high heeled shoes during gait at the kinetic and kinematic impact, *2017 IEEE 15th Student Conf. on Research and Development*, 2017, pp. 481-486.
[13] E. B. Simonsen, M.B. Svendsen *et al.*, Walking on high heels changes muscle activity and the dynamics of human walking significantly, *Journal of applied biomechanics*, 2012, Vol. 28, No. 1, pp. 20-28.
[14] V. D. Hapsari, S. Xiong, and S. Yang, High heels on human stability and plantar pressure distribution: Effects of heel height and shoe wearing experience, *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 2014, Vol. 58, No. 1, pp. 1653-1657.
[15] D. Y. Lee, D.-O. Lee, and H.-G. Jung, Metatarsalgia and toe deformities,in H.-G. Jung (ed.) *Foot and Ankle Disorders*, Springer, Berlin Heidelberg, 2016, pp. 77-119.
[16] R. Csapo, C. Maganaris, O. Seynnes, and M. Narici, On muscle, tendon and high heels, *Journal of Experimental Biology*, 2010, Vol. 213, No. 15, pp. 2582-2588.
[17] A. Farrag and W. Elsayed, Habitual use of high-heeled shoes affects isokinetic soleus strength more than gastrocnemius in healthy young females, *Foot & ankle international,* 2016, 37(9), pp. 1008-1016.
[18] Y. Kim, J.-M. Lim, and B. Yoon, Changes in ankle range of motion and muscle strength in habitual wearers of high-heeled shoes, *Foot & ankle international*, 2013, Vol. 34, No. 3, pp. 414-419.

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User Interface Design for Multi-Objective Decision Making

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Abstract. We seek to accelerate the adoption of multi-objective decision making (MODM) methods within transdisciplinary engineering. To this end, we specify a generic user interface that makes computational systems models more accessible to non-technical decision makers. The collection of user stories presented in this paper allude to minimum viable features to include in the future development and testing of a generic user interface for multi-objective decision making.

Keywords. Multi-Objective Decision Making, Decision Support Systems, User Interface Design, Systems Modeling, Transdisciplinary Engineering

Introduction

Research engineers (i.e. model developers) who create high quality computational models for multi-objective decision making (MODM) rarely have time nor resources to consider the design of thoughtful user interfaces to go along with them. This is especially painful for decision-makers who might benefit most from such computational models. To help bridge the gap between decision makers and model developers, we specify the design of a generic user interface that allows decision makers to more easily configure and evaluate engineering solutions using computational models. We present the design of this interface via a set of user stories that are compatible with agile software development techniques, as we intend to expedite future software development based on our findings.

Multiple Objectives in Transdisciplinary Engineering

Transdisciplinary projects are implicitly complex endeavors, if only due to the diversity of stakeholders that they necessitate. Each stakeholder in a transdisciplinary engineering endeavor indeed brings one or more unique perspectives from which they may judge an outcome's success. It is common to describe judgements with an objective function that dispassionately reduces some aspect of an outcome's performance to a single number. For instance, an environmental engineer might judge an outcome by its total carbon footprint, while a financial manager might judge the same outcome by its cost [1]. Therefore, we might expect that most transdiciplinary endeavors are especially burdened by multiple objective functions.

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Multi-Objective Decision Making

Multi-objective decision making (MODM) is the science of picking one or more engineering solutions that satisfy two or more objective functions. A valid solution is described as "non-dominated" when there exists no solution that performs better in all objectives [2]. The sum of such solutions is described as the "solution space," or the set of all solutions that one might argue are acceptable given known alternatives. A common phenomenon in MODM, however, is that the number of non-dominated solutions can increase dramatically as one incorporates more objectives into the process of decision making. Without other methods to narrow down the solution space, this can lead to decision paralysis [3]. Therefore, we believe that the narrowing of solutions, while considering multiple objectives, is a principal pain point in the realm of transdiciplinary engineering.

Decision Support Systems

A decision support system (DSS) is a computerized interactive system that utilizes data and models to support a decision maker (DM) [4, 5]. As such, the typical components of a DSS include a (1) database, (2) model, (3) user interface, and (4) decision maker. In their comprehensive survey of DSS applications, Eom identifies an ongoing yet urgent need to bridge the gap between practitioners and DSS researchers. Despite much progress discovering the general components of DSS, they argue, there is not enough focus given to generic methods and techniques that would give practitioners better access to DSS in a number of underdeveloped subspecialties.

DSS and MODM Integration

Integrating methods of MODM with DSS is not terribly new. In fact, Razmak and Aouni published a study of multi-criteria decision support systems (MCDSS), observing dozens of use cases across multiple fields [6]. Weistroffer et al observed, however, that the vast majority of software in this subfield is "quasi-experimental, developed by academic researchers to test specific algorithms or to solve a specific problem on an ad hoc basis" [2]. While there are some examples of generic MCDSS, such as the OMOptim tool in OpenModelica, we believe that much work can be done to create generic MCDSS that is sufficiently user-friendly to be readily adopted by contemporary non-technical decision makers [7].

Decision Makers and Model Developers

Prior research by Mieg clarifies the bifurcated roles of "system experts" (i.e. model developers) and "decision making experts" in transdicsiplinary engineering. While Harald identifies a need for decision makers to "professionalize themselves" so that they can more adeptly consider multiple systems domains, the research declines to offer concrete means of such professionalization [8]. As such, we believe that a thoughtfully designed generic user interface for MCDCC will help decision makers participate more "professionally" by allowing them to interface more smoothly with one or more systems models in any given transdiciplinary engineering problem.

Though the primary benefactor of our proposed generic user interface would be quintessential decision makers (e.g. non-technical executives), we must also consider the needs of model developers (e.g. engineers). For instance, imagine a logistics team and a financial analysis team are developing a multi-criteria computational model to help an adjacent executive team make a difficult decision about how to deploy a logistic network for their company (Figure 1) [9].

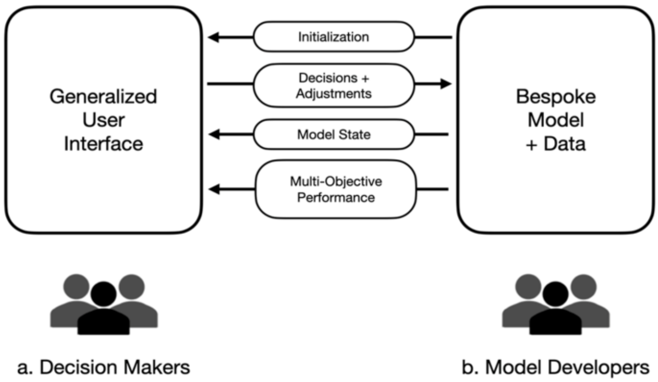

Figure 1. This diagrams shows the interactions between users and different DSS components.

In this case, the executive team are the (a) decision makers, while the logistics team and financial team working together are the (b) model developers. Model developers have proficiency in both their domain of expertise (e.g. logistics and finance) as well as computation. In practice, however, small teams of model developers are usually not well-versed in the nuances of user interface design. Therefore, we would like to specify a generic user interface to bridge this gap. Such an interface connects directly to a multi-objective systems model encoded by systems engineer(s) with specialized knowledge.

1. Objective

We seek to accelerate the adoption of multi-objective decision making methods for transdisciplinary engineering by specifying a generic user interface that makes computational systems models more accessible to decision makers. Our principal objective in this paper is to specify key features and capabilities of a generic user interface that might make it easier for researchers to effectively deploy multi-objective decision models to decision makers.

2. Method

We present our generic interface design as a set of user stories, a term borrowed from agile software development. A user story is an informal description of a feature from the point of view of the eventual user of a software system [10]. By adopting the language of user stories, we hope to expedite the development of future software that incorporates our findings.

We identify key user stories for a generic MCDSS for decision makers via qualitative analysis of patterns observed across a set of already-completed bespoke user interface case studies. The case study set includes pieces of bespoke MCDSS software developed during the course of the author's prior research. While we considered case studies outside of our own research, this proved difficult for two reasons. Firstly, the vast majority of user interfaces developed for MODM seem to be meant for model developers, rather than decision makers. OpenModelica, for instance, may practically be used by a model developer to generate a report for the benefit of decision makers, but is not meant to be used in the board room, per se. Secondly, despite incidents of bespoke MCDSS software in literature, documentation of user experience is lacking.

We expect to be among the first users of this new tool, so operationalizing features that we have consistently implemented across multiple projects and domains should also expedite future research within our laboratory. We hope, however, that our conclusions will be applicable to other researchers who desire a standard user interface for their own multi-criteria decision models.

Figure 2. Case studies of bespoke multi-criteria decision support systems built by the author. They include (A) maritime shipping simulation, (B) tangible interactive urban planning, (C) pharmaceutical manufacturing simulation, (D) campus design, (E) autonomous vehicle impact analysis, and (F) real estate financing.

3. Results

3.1. Case Studies

Our set of MCDSS case studies includes examples from the following domains: maritime shipping [11, 12], urban master planning [13, 14], pharmaceutical manufacturing, campus design [15], autonomous vehicle impact analysis [16], and real estate investment financing (Figure 2).

3.2. User Stories

We summarize our results as user stories within ten broad categories of user experience. In brackets, we identify which of our six case studies {A, B, C, D, E, or F} inspired each category. For each story, we distinguish decision makers and model developers.

3.2.1. Logical and Quantitative Decision Making {A, B, C, D, F}

1. A decision maker can configure one or more decisions related to the specification of a solution using intuitive means such as toggles, radio buttons, and sliders. A set of decisions constitutes a solution.
2. A model developer can specify the nature of decisions available in the user interface.
3. A model developer's model can receive decisions from the user interface formatted as a series of booleans, integers, or floating point numbers.

3.2.2. Geographic Decision Making {B, F}

1. A decision maker can specify geo-located points and polygons via a map or abstract surface.
2. A model developer can specify the extent and nature of geo-located decisions available in the user interface.
3. A model developer can receive geo-located inputs as a series of coordinates from the interface.

3.2.3. Adjusting for Uncertainty {E, F}

1. A decision maker can adjust assumptions inherent to the model, including probabilistic distributions. Assumptions are clearly distinct from decisions.
2. A model developer can make certain data and assumptions in the model changeable via the user interface.
3. A model developer's model can receive updates to assumptions, including any probabilistic uncertainty.

3.2.4. Model State Diagram {A, B, C, D, E, F}

1. A decision maker can view an abstraction of a model as a 2D or 3D diagram of its state.
2. A model developer can specify the content of model's state, which is then automatically rendered as a 2D or 3D diagram by the interface

3.2.5. Save, Recall, and Viewing of Solution Iterations {A, D, F}

1. A decision maker may save, preview, and recall any number of solution configurations from memory. Multiple solutions are automatically organized as a tree of iterations that reveal the evolution of a user's decisions over time.

3.2.6. Multi-Objective Plots {A, B, C, D, E, F}

1. A decision maker can view a plot of solution performance according to multiple objectives. They may also assign weights and thresholds to specific objectives, or hide them altogether. They may also automatically filter for non-dominated scenarios.
2. A model developer can specify any number of objectives, their description, their units, and any minimum or maximum thresholds.
3. A model developer's model can simulate the performance of a solution and send them back to the user interface as absolute quantities or probability distributions.

3.2.7. Deployability {A, B, C, D, E, F}[2]

1. A decision maker can easily access a pre-configured interface (e.g. via secure web application)
2. A model developer can easily generate and share their model to decision makers as an interactive MCDSS.

3.2.8. Adoptability {A, B, D}

1. A model developer can easily understand the application programming interface (API) for the interactive simulation.

3.2.9. Sensitivity Analysis {F}[3]

1. A decision maker may see decision sensitivities before they are even made. For instance, a slider might indicate which direction it may be moved in order to improve the outcome of one or more objectives.

3.2.10. Solution Generation { }[4]

1. A decision maker user may leverage algorithms (e.g. genetic algorithms) to help them discover local optimizations within a solution space.

4. Discussion and Future Work

This paper leaves us with at least two major tasks ahead. First, there is the issue of building a minimum viable piece of software that satisfies all of our user stories.

[2] The authors believe that all six case studies were generally lacking in the area of deployability, which may explain why all of them inspired a need for improvement.

[3] Sensitivity analysis is a feature only recently developed, so it is only inspirated by a sole case study.

[4] Solution generation is the only user story without any prior precedent among our case studies. However, we believe it is necessary to include some form of automated solution generation in order to test the performance of the interface during development. We explain this further in the section on future work.

Secondly, we must formulate a method for testing the effectiveness of our generic interface compared to some status quo condition.

We expect to build out the software as an open source project made freely available on a platform such as GitHub using the MIT Licence. While initial work will be conducted jointly by the UTokyo Industrial Systems Laboratory and the MIT Engineering Systems Laboratory, we welcome contributions from our peers.

As for testing and validating the generic user interface, we will develop an experimental method for measuring a user's ability to satisfactorily discover non-dominated solutions in a series of toy models. Over a number of statistically significant trials, we will compare human decision maker performance to that of a genetic algorithm that is designed to search for local optimizations within these toy models. To be considered successful, a decision-making human should be able to perform at least as well as a locally-optimizing algorithm. Ideally, we may find that a human can sometimes be better than their algorithmic counterpart at finding a global optimimum.

5. Conclusion

The user stories in this paper define minimum viable research objectives to kick off the long-term development and testing of a generic user interface for multi-objective decision making. While the authors of this paper intend to subsequently embark on this endeavor, we welcome members of the research community to review our preliminary findings and, furthermore, we invite them to join us in any capacity. Ultimately, we hope this work will lead to increased adoption of multi-objective decision making methods in transdisciplinary fields.

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References

[1] F. Ascione, N. Bianco, De Masi, R. F., Mauro, G. M., & Vanoli, G. P. Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimization towards nearly zero-energy performance, *Energy and Buildings*, 2017, Vol. 144, pp. 303–319.

[2] H.R. Weistroffer, C.H. Smith and S.C. Narula, Multiple criteria decision support software. In J. Figueira, S. Greco and M. Ehrogott (eds.) *Multiple Criteria Decision Analysis: State of the Art Surveys*, Springer New York LLC, 2005, Vol. 78, pp. 989–1018.

[3] G. Montibeller, H. Gummer and D. Tumidei, Combining scenario planning and multi-criteria decision analysis in practice, *Journal of Multi-Criteria Decision Analysis*, 2006, Vol. 14(1–3), pp. 5–20.

[4] S.B. Eom, S.M. Lee, E.B. Kim and C. Somarajan, A survey of decision support system applications (1988-1994), *Journal of the Operational Research Society*, 1998, Vol. 49, pp. 109-120.

[5] S. Eom and E. Kim, A survey of decision support system applications (1995-2001), *Journal of the Operational Research Society*, 2006, Vol. 57(11), pp. 1264–1278.

[6] J. Razmak and B. Aouni, Decision Support System and Multi-Criteria Decision Aid: A State of the Art and Perspectives, *Journal of Multi-Criteria Decision Analysis,* 2015, Vol. 22(1–2), pp. 101–117.

[7] P. Fritzson, A. Pop, K. Abdelhak, A. Ashgar, B. Bachmann, W. Braun, D. Bouskela, R. Braun, L. Buffoni, F. Casella, R. Castro, R. Franke, D. Fritzson, M. Gebremedhin, A. Heuermann, B. Lie, A. Mengist, L. Mikelsons, K. Moudgalya, … P. Östlund, The OpenModelica Integrated Environment for Modeling, Simulation, and Model-Based Development. *Modeling, Identification and Control: A Norwegian Research Bulletin*, 2020, Vol. 41(4), pp. 241–295.

[8] H.A. Mieg, System experts and decision making experts in transdisciplinary projects, *International Journal of Sustainability in Higher Education*, 2006, Vol. 7(3), pp. 341–351.

[9] I. Winder, *Lego Logistics: Tangible Interactive Matrix Meets Last Mile Logistics Simulation — Interactive Simulation*. Massachusetts Institute of Technology, 2016, https://ira.mit.edu/blog/lego-logistics

[10] S. Dimitrijević, J. Jovanović, V. Devedžić, A comparative study of software tools for user story management, *Information and Software Technology*, 2015, Vol. 57, pp. 352–368.

[11] L. Pelegrin, B. Moser, S. Wanaka, M.-A. Chavy-Macdonald and I. Winder, Field Guide for Interpreting Engineering Team Behavior with Sensor Data. In E. Bonjour, D. Krob, L. Palladino, F. Stephan (eds.) *Complex Systems Design & Management, CSD&M 2018*, Springer, Cham, 2019, pp. 203–218.

[12] I. Winder, D. Delaporte, S. Wanaka and K. Hiekata, Sensing Teamwork during Multi-objective Optimization. *IEEE World Forum on Internet of Things, WF-IoT 2020 - Symposium Proceedings*, 2020, pp. 1–6.

[13] C.M. Rose, E. Saratsis, S. Aldawood, T. Dogan and C. Reinhart, A Tangible Interface for Collaborative Urban Design for Energy Efficiency, Daylighting, and Walkability. *Proceedings of the 14th Conference of International Building Performance Simulation Association*, 2015, https://dspace.mit.edu/handle/1721.1/106597, Accessed July, 1 2021.

[14] J.I. Winder and K. Larson, (2017). Bits and Bricks Tangible Interactive Matrix for Real-time Computation and 3D Projection Mapping, *Future Technologies Conference (FTC) 2017*, 29-30 November 2017, Vancouver, Canada, pp. 1113-1116, https://saiconference.com/Downloads/FTC2017/Proceedings/160_Paper_469-Bits_and_Bricks.pdf, Accessed July, 1 2021.

[15] P. Manandhar, K. Rong, K. Carroll, R. De Filippi, I. Winder, J. Dieffenbach and B. R. Moser, Sensing systemic awareness and performance of teams during model-based site design. *IEEE World Forum on Internet of Things, WF-IoT 2020 - Symposium Proceedings*, 2020, June 1, DOI: 10.1109/WF-IoT48130.2020.9221406.

[16] J.F. Finn III, D. Vasquez, A. Starr, K. Kusina, K. Silvester, I. Winder, *Autonomous Vehicles and Their Impact on Real Estate*, Gensler Research Institute, 2018.

Transdisciplinary Engineering for Resilience: Responding to System Disruptions
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Functional Approach for Summative Risk Management of Medical Products

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Abstract. In the search to maintain the integrity of all systems and components over the span of the product's life, a tightly integrated risk management process and system shall enable a discrete but frequent enough calculation method. The challenge is finding a methodology where risk management is living, concomitant process throughout the lifecycle, which is cumulative, so the risk assessments refine with the product's definition while adhering to a tightly regulated enviroment for medical devices. This process needs be fully embedded in the PLM processes so it is able to accompany the product at any change throughout its life. The Multi-interfaces Entity Model (MIEM) was introduced integrated with a summative risk management concept that allows an incremental risk analysis, while the entities in the MIEM are refined. The results were a recursive methodology that supported with a PLM integrated risk management, can be automated to make sure the risk assessment is complete, re-usable and configurable as an additional PLM function. The focus of this paper lies on the generation of the functional structure of a product which is connected with the Multi-interfaces Entity Model. This allows to create a configured design structure, applying recursively the same cumulative properties of the risk assessment where a new configuration would create new interfaces.

Keywords. Product Risk Management, Configuration Management, Modular Design, Product Lifecycle Management

Introduction

Modern medical devices are launched with ever higher expectations with regard to functional requirements and shorter development times due to market pressure. This development implies new working approaches including both supporting methods and tools, especially if the supervisory authorities monitor and validate the product's compliance. Medical Devices include instruments, apparatus and software intended for use in diagnosis, cure or prevention of diseases in humans or other animals [25]. Product development of highly regulated products as known in medical industry is usually facilitated by contemporary PLM systems as an information backbone that reflects and

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supports various business processes. With this system changes can be approached in a systematic manner and their effects are continuously provided transparent by the configuration management [1].

The continuous quality enhancement is one of the dominating approaches in the industrial process improvement [2]. Attempting to maintain the desired integrity of all systems and components over the span of the product's life, a tightly integrated product risk management process and system shall enable a discrete but frequent enough method to assess potential hazards, and to evaluate whether changes are necessary or if the next step of in the product's lifecycle can be started [3]. The challenge is finding a methodology where risk management is living process throughout the lifecycle, that is (a) cumulative so the risk assessments refine with the product's definition from the first idea on and the sum of the component risks add up to the entire product's risk assessment, and (b) embedded in the PLM processes so it is able to accompany the product throughout its life representing all variants and changes. It shall comprise all activities, from the technology roadmap to the start of production, including common and approved methods; e.g. Failure Mode and Effect Analysis (FMEA), Value Analysis, Kano model [4].

The outline of the paper is as follows. In section 1, the background of risk management and PLM is introduced. In section 2, the problem statement is presented. The solution concept is explained in section 3. Discussion of the challenges that still exist in the manufacturing domain is presented in section 4. The paper ends with a brief conclusion and outlook.

1. Background

Risk is a natural companion of all activities of the company, at all levels, and can result in visible deterioration in the quality of products and services, and, therefore, a decline in competitiveness [5]. Therefore, risk is often subject of internal and external regulation and audits (e.g. by a regulation body) to ensure devices meet user's needs and intended use. The business environment described in this paper, in which the global medical device manufacturer operates, is strictly regulated [6]. Just as regulators have increased their ability to receive information electronically, in terms of the speed and growing capacity to analyze large amounts of data, so do medical device manufacturers, in order to anticipate and detect risks resulting from product failure or poor performance. In this sense, they should have higher reaction rates than regulators [7].

Unlike risk, which is defined as a known but potentially unfavourable outcome, the probability of which can be estimated, called uncertainty, is a situation where a decision has more than one possible outcome and in which the probability of adverse outcomes is unknown, due to lack of information or unstable variable structure in the given environment [10].

Risk management involves the use of consistent and repeatable procedures with the aim of identifying, assessing and interpreting risk in the given scenarios so that risky activities could be monitored [11] and controlled. Risk management does not seek to eliminate risks - it is unable to do so, but it creates an environment in which optimal business decisions can be made taking into account identified risks, developing potential risk management alternatives and identifying their associated costs and benefits [12]. The technical risks associated with the product primarily are based on insufficient knowledge and experience with the used technology, and may have consequences for quality, costs and deadlines. They often arise due to the budgetary constraints during the development project [13].

Once the risks have been identified and gone through the above procedures, it is crucial to select an appropriate technique that will effectively eliminate or control the risk exposure. There are four potential responses to risks: acceptance, avoidance, control, and transmission. When making decisions, compromises are inevitable. Trade-offs are made based on the logic that it is better to embark on a lower but known cost, in order to in turn reduce the potentially higher unknown costs associated with the risk [14].

As the main purpose of a medical device is related to the health of patients and human life, the risk management process must go through the lifecycle of the medical product in order to avoid potential dangers. Product quality metrics in the future will go in the direction of data enrichment in order to get a clearer picture of product quality risks [6].

Addressing the cumulative risk assessments, it is an opportunity to create an appropriate product risk model with interdependencies between product components. With this, the usage of the Multi-interfaces Entity Model (MIEM) can be investigated in order to define the interdependencies between components and functions that will enable a risk management concept that is incremental and adjusted with product refinement to be in line with re-usable assets, modularity and configuration of products. During design milestones, when a certain degree of product maturity is achieved, the risk assessment of the product shall be crucial input to confirming the gate for the next step in development.

There are a number of risk evaluation methods available focused on different goals; e.g. project management, products, organization [8]. However, the purpose of this paper is to explore an implementable model for risk handling in a more precise and integrated manner rather than to develop a new method. This enables a holistic product risk assessment based on reused components, systems and modules of the product as family of variants. The outcome would yield a recursive methodology that supported with a PLM integrated risk management, can be automated to make sure the risk assessment is complete, reusable and configurable [14]. If this concept would be implemented with the PLM architecture, it would provide to support further views of the products for the nest lifecycles: production planning, production, assembly, operation, maintenance and recycling [15].

2. Problem statement

The goal of an effective product risk management system is to allow continuous business operation and achieve the goals of an organization. In order to achieve this product risk management should be a living actor of the design process, linked to regulatory compliance needs to roll-out a product while meeting market and customer requirements. Integrating risk management to the design process enforcing it as real-time development driver ensures better design and project decisions, shortening time-to-market and reducing the risk of cost intensive product failures during the phases of usage and maintenance. As risk management is a process that accompanies the product during these later life-cycle phases it becomes also a driver of better new product development.

The sustained success of technical risk management is possible only through the efficient control of risks based on singular items or systems of a product. Different methods (FMEA, DRBFM etc) need to be applied for any instance of a product or product families, for this reason risk management needs to be used within the context of reusables assets, browsing through the product structure and considering all configured items. Therefore, the risk assessment and control methods need to become fully interoperable with configuration management within PLM as a fully integrated process, method and application [16]. As basis for the method, leveraging the structured nature of PLM product representation, the items in the product structure can be associated to a vector of failures, evaluations and controls, enabling a systematic identification of risks based on the aggregation of the singular items and their associated risk vector. The goal is the transparent presentation of all risk consequences, which then will be assessed qualitatively and quantitatively based on a specific product configuration [17]. The impact on each change of an item and the associated risk assessment of the singular parts can be directly identified being able to extrapolate the impact in case that the items is reused in several product configurations.

With an appropriate model and method, the elimination of deficits (time delay, lower accuracy, etc.) within the assessment of interdependencies in risk consequences and the efficient control of technical risks becomes possible. The assessment and control of technical risks for any configuration need to complete the closed loop of product risk management within PLM that contains the process phases identification, analysis and assessment and control. In such a way, the overall gain of knowledge in form of verification and validation of product risk assessments can be realized. The impact of any design change can be investigated in the early phase of the product development. The simulation of risk control measures should ensure the success of product risk management [18]. The developed conceptual solution should fulfil the requirements for product development of medical products based on international standards (FDA, ISO14971).

Finally, the formalisms for product assessment of medical devices should be proposed. To make these formalisms fully operational, several research issues should be addressed [19]. What are the relevant characteristics of a configurated system based product with regard to product risk management [20]? How these characteristics can be described in a formal way to propose appropriate methods? How the risk vectors can be mapped to product structure components and modules and used subsequently in similar products [21]?

3. Conceptual solution

This conceptual solution aims is to create risk assessments in each step of the development process understanding the data describing the product will evovle with each lifecycle, fom the product ideation to the design phase, throughout the saturation life-cycle (operation, maintenance, etc.) until the end-of-life. Levering the PLM Systems ability to create filtered views to make the product data available for different processes and needs of business. The foundation of creating views in PLM are a product strucuture [15]. The product structure evolves steadily while the product matures. Specific configurations such as E-BoM, M-BoM, as designed, as ordered, as serviced, etc. represent different views for different purposes.

The concept proposed in this paper is based on the asumpution we are updating an existing product and that the performance information is accesible, and appropriate requirements that ensure user needs and intended use are documented in a measurable way. The idea is that with this information, designers can start decomposing the product using the Multi-interface Entity Model (MIEM) [22]. This modelling technique is performed iteritably until a complete description of the entities and interfaces that compose the product is well defined. The MEIM methodology considers the products as entities and their directly associated interfaces in a top-down manner. At first the product is seen a black box, one entity, plus its external interfaces. Subsequently every entity is then decomposed into sub-entities, resulting in new interfaces between these as shown in Figure 1.

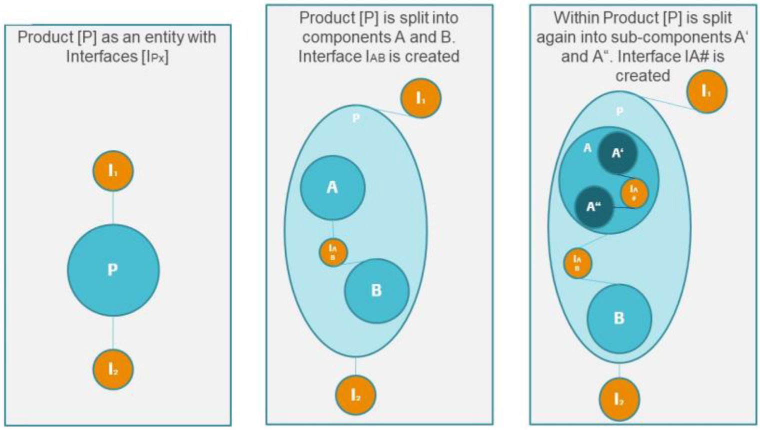

Figure 1. Decomposition of a Product using the Mult-interfaces Entity Model.

Figure 2 shows the MIEM methodology applied to a medical device lancet. The device of this example is the Accu-Chek® Softclix lancet which aims to safely pierce the the patient's skin to draw blood for a glucose reading in a separate device, the glocumeter. The lancet consists of a polymer body specially designed to be inserted into the Softclix Lancing Device. The lancet is fixed into the Lancing Device, the Lancing Device has a mechanisms to control the penetration deepness as well as push and retrieve mechanism to pierce the skin and quickly hide the Lancet's needle in the Lancing Device. The lancet shall not be reused but disposed of in a sharps box like other used needles. The Lancet is composed of a body that houses a needle and a cap that protects the needle and the user or patient from the needle itself.

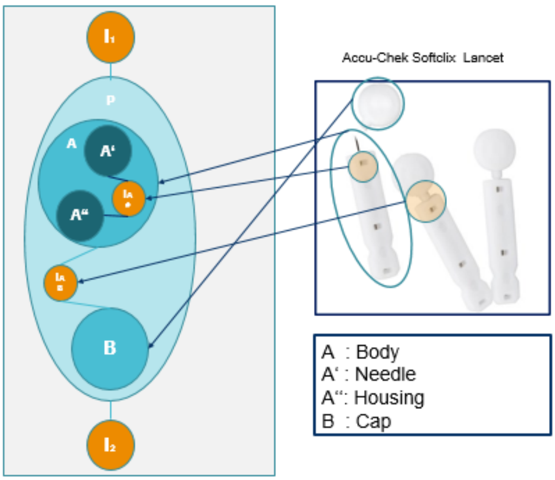

Figure 2. MIEM Applied to Accu-Chek® Softclix

Performing the MIEM iterations delivers useful information about the product that complements the product requirements and needs. This information is used to create a functional achitecture that lists the expected functionalities of the product, the relationships within functions and the assignements of these to an entity or interface. The functional architecture makes sure the interfaces and interactions of the product are clearly described including the import and export of infromation and energy as seen on Figure 3. Once the functional architecture is built, a risk assessment can be performed and the risks assigned to the individual entities and interfaces of the model. The risk values are derived from the known information from the product requirements as a function of the relationships defined in the functional architecture. This architecure sets the stage for a collection of risks assessemnts at the level of functions independent of the future proposed solutions that can be used in a cumulative manner to produce the risk assessemnt for a specific product [23] in a later stage of the development process. The details on how the MIEM was applied to the Accu Chek ® Softclix device, the definition entities and interfaces, their raltionship, how a functional architecture was constructed out the MIEM and the information gained from it, are throughtly described in a previous paper [22]

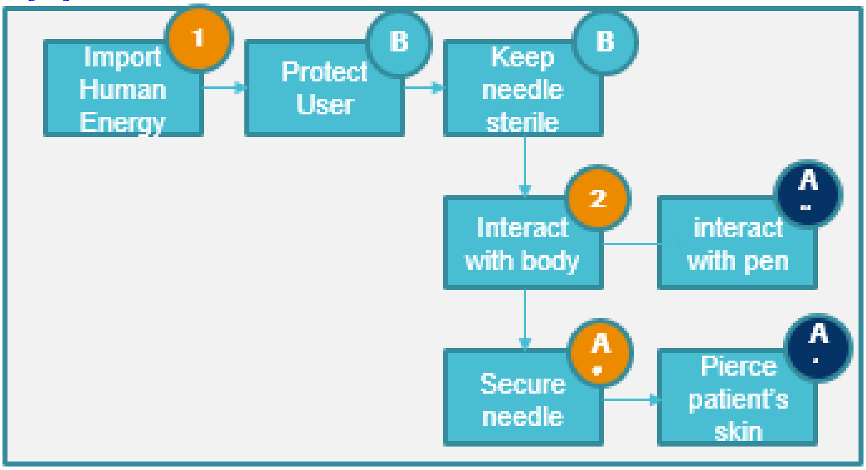

Figure 3 Creating a functional architecture of the product and assigning the functions to the MIEM entities

Keeping in mind the goal to reflect this information in a PLM environment the MIEM and functional architecture deliver the first steps to organize data in structures and concatenate information and create meaningful traces of information. At this point the designers have the possibility to create the Defintion View in PLM tracing requirements, functions, entities and interfaces, and risk vectors that include the risk description, evaluation and controls. This structure is free of any solution bias and shall give enough information if the product is viable and the next milestone of the product development can be started.

In order to reach our goal to take our existing product and have a framework to be able to define modules and re-usable assets. Modules are a set of functionalities that can have several technical solutions and can be re-used in several product configurations. To achieve this, the designers should create a logical architecture that provides a detailed description of the modules without defining the module's technology but clearly defining to which entities or interfaces of the MIEM it belongs as well as the inputs and outputs for, for example, energy or information. Having this view of the product allows the risk managers to create a new level of the product risk analysis. Being that a module is the sum of several functions, the risk assessment of the module is the cumulation of the risks associated to each function plus the risk analysis of the module itself as a function of clustering done for the module.

With well defined modules, designers can start proposing solutions that fulfill the modules in a layer called the generative architecture with the end goal to describe the set of all components of a logical architecture and defines the technology of each component. For each defined module, there could be several solutions. This creates a network of possible combinations of solutions where all possible solutions of a module could theoritically be matched with all solutions of a further module linked in the logical architecure. Some of these combinations are incompatible and should be promptly ruled out. For the remaining possible combinations, the designers have now the possibility to create a risk assessment for each pairing. The risk vector at this point is not associated to the module A or to the related module B but to the link between modules A and B. This exercise will give the designers the chance to create a layer of physical products in the physical architecture. The possible products are a product of the possible combinations between modules given they are compatible. At this point the cumulative risk assessment across the architectures shall give the designers which module combination describes the product with the lowest risk (Figure 4).

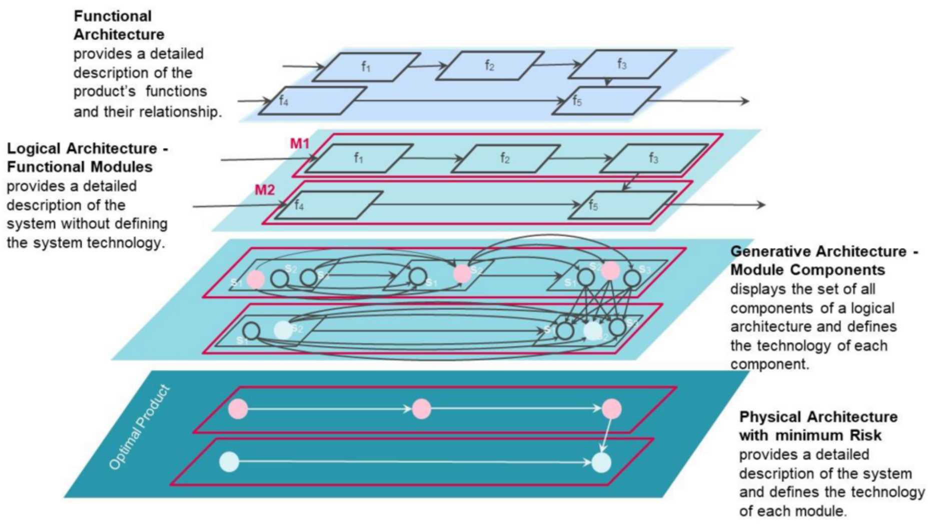

Figure 4 Multi-layered Architecture Approach

Just as the different layers of architecture deliver the traceability from the requirement to the function to the module to the products, the information can be reflected in PLM structures using views that serve for orientation and traceability of the content. Out of the functional architecture an as defined structure of the product can be created. The logical architecture gives an overview of which configuration items are needed in the design structure and the generative architecture can be represented as 150% product structure where viable configurations can be destiled through the variant configuration management process as seen on Figure 5. Here, the logical architecture provides the information of the configuration items (CI) that the as-designed product structure will have. The CIs will then be the structural parent of the possible solutions to these modules.

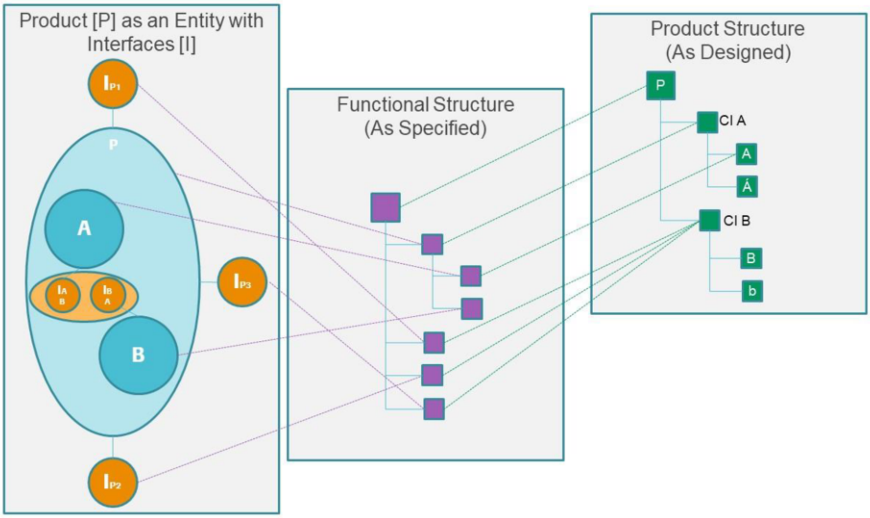

Figure 5 Creating PLM Views as an Output of the MIEM and the Derived Architectures

4. Discussion

In this paper, a conceptual solution for the integration of product risk management in a comprehensive PLM approach for highly configured, modular medical devices is explored. In this way, the standard PLM system is being enhanced by an additional capability as an intelligent collaborative and distributed platform for assessment, maintenance and monitoring of each product capability during the product lifecycle. Thus, the proposed, generic solution has the potential to fulfil the demand of the continuous, software-aided risk assessment and to provide the appropriate user-friendly support within PLM system. Finally, the resulting risk management process looks as seamless as possible, with the purpose to provide a basis for the software solution to achieve the desired goal: identifying, assessing, prioritizing, or monitoring risk like other summative properties (e.g. the cumulative weight of the configured product) are examined in an assembly.

Methods implemented by software solutions simplify the daily work of risk engineers and managers that all risks which are accompanied with a product configuration are properly considered and minimize the subjectivity of subsequent human risk assessments. Although the risk values do not provide the absolute results, their comparison is a valuable basis for reproducible risk assessment. This generic methodology can be used for all types of product risk assessments, not dependent on the domain, the type and the genesis of the risk. Risk assessment emerges while the product emerges during its product lifecycle. The uncertainty remains only through little human assistance and judgment. However, the comparison stabilizes this activity too. The proposed solution can also facilitate that the effects of cognitive biases are documented within the risk matrix.

The approach to map the function structure in the design architecture is just the first step, followed ba a comprehensive definition of the risk model. In that way, a methodology can be defined which is valid for the entire product lifecycle. Assumed a performant software implementation, the method monitors the potential technical risks in a systematic manner at each moment in the product lifecycle. In particular, a standardized risk assessment is beneficial in case of product change.

5. Conclusions and outlook

Focusing cumulative risk management methodology, we investigated the usage of the Multi-interfaces Entity Model (MIEM) integrated with a summative risk management concept that allows an incremental risk analysis, as the entities in the MIEM are refined. After a certain degree of maturity, the risk assessment of the product a design architecture of the product is generated where the risk analysis validated confirming the gate for the next step in development. Within the design structure the same principle is applied the sum of the risks of the component and the interfaces will define the risk assessment of the product. This approach does risk management not only at the global (top down) or component (button up) level but at the modular level. The modular approach can be scaled up to large component clusters down to design elements and features of the PDM system at any level where re-use is possible. Perfomring a risk assessment at the functional level provides a new dimension of risk management of components or modules as a parmeter of the function they provide. Further from this paper, if this assessment is validated the next step is to create a configured design structure, applying recursively the same cumulative properties of the risk assessment where a new configuration would create new interfaces. The configured structure describes the product in the design view and should create the next level of traceability from the requirement to the function over to the solution. This enables a holistic risk assessment based on reused components, systems and modules of the product as family of variants. The intention is to create further views of the product to asess the risk of later life-cycles also at the the module level but as a function of their manufacturability, commerciability, recycle-ability amoing others. This, supported with a PLM integrated risk management as described in previous papers, can be automated to make sure the risk assessment is complete, re-usable and configurable.

The next steps are the implementation in this concept with the PLM architecture and make it possible to support further views of the products for the nest lifecycles: production planning, production, assembly, usage, maintenance and recycling. With this approach the intention is to avoid having a very heavy risk management at the definition and design phase that is later left to a lower plane in the life of the product.

In this way, the product risk assessment can be established a an inherently transdisciplinary engineering process[24].

References

[1] J. Stark, *Product Lifecycle Management (Volume 4): The Case Studies*, Springer Nature Switzerland AG, 2019.

[2] S. Manz, *Medical Device Quality Management Systems. Strategy and Techniques for Improving Efficiency and Effectiveness*, Academic Press, London, 2019.
[3] M. Leimeister and A. Kolios, A. A review of reliability-based methods for risk analysis and their application in the offshore wind industry, *Renewable and Sustainable Energy Reviews*, 2018, Vol. 91, 1065–1076.
[4] X. Zhao and X. Bai, The Application of FMEA method in the risk management of medical device during the lifecycle, *2010 2nd International Conference on E-business and Information System Security*, 22-23 May 2010, DOI: 10.1109/EBISS.2010.5473713, pp. 455-458.
[5] T. Aven, Foundational Issues in Risk Assessment and Risk Management, *Risk Analysis*, Vol. 32, No. 10, 2012, pp. 1647-1656.
[6] J. Hatcliff, E.Y. Vasserman, T. Carpenter and R. Whillock, Challenges of distributed risk management for medical application platforms, *2018 IEEE Symposium on Product Compliance Engineering (ISPCE)*, 14-16 May 2018, DOI: 10.1109/ISPCE.2018.8379270.
[7] D.C. Hall, Making Risk Assessments More Comparable and Repeatable, *Systems Engineering*, Vol. 14, No. 2, 2011, pp. 173–179, DOI 10.1002/sys.20169.
[8] B. Pongrac, T. Majić, Business Risk Management, *Technical Journal*, Vol. 9, 2015, No. 1, pp. 94–98.
[9] M.N. Teferra, ISO 14971 - Medical Device Risk Management Standard, *International Journal of Latest Research in Engineering and Technology (IJLRET)*, 2017, Vol. 3, Issue 3, March 2017, pp. 83-87.
[10] T. Aven and E. Zio, Foundational Issues in Risk Assessment and Risk Management, *Risk Analysis*, Vol. 34, No. 7, 2014, pp. 1164-1172.
[11] J. Oehmen, B. Dick, U. Lindemann and W. Seering, Risk Management in Product Development – Current Methods, *International Design Conference - DESIGN 2006 Dubrovnik - Croatia*, May 15 - 18, 2006, pp. 1551-1558.
[12] E.D. Smith, W.T. Siefert and D. Drain, Risk Matrix Input Data Biases, *Systems Engineering*, 2009, Vol. 12, No. 4, pp. 344–360.
[13] M.S. Kirkire, S.B. Rane and J.R. Jadhav, Risk management in medical product development process using traditional FMEA and fuzzy linguistic approach: a case study, *Journal of Industrial Engineering International*, 2015, Vol. 11, pp. 595–611.
[14] R. Riascos, T. Majić, E.Ostrosi and J. Stjepandić, Modular Approach to Technical Risk Management in Product Lifecycle Management, *Advances in Transdisciplinary Engineering*, 2019, Vol. 10, pp. 380-389.
[15] J. Stark, *Product Lifecycle Management (Volume 2): The Devil is in the Details*, 3rd edition, Springer International Publishing AG, 2016.
[16] M. Rusu, The configuration management requirements for aviation, space and defense organizations, *INCAS Bulletin*, 2019, 11(1), pp. 239-253.
[17] J. Stjepandić, E. Ostrosi, A.-J. Fougères, M. Kurth, Modularity and Supporting Tools and Methods, in: J. Stjepandić et al. (eds.): *Concurrent Engineering in the 21st Century: Foundations, Developments and Challenges*, Springer International Publishing Cham, 2015, pp. 389–420.
[18] D. Flood, F. McCaffery, V. Casey, R. McKeever and P. Rust, A roadmap to ISO 14971 implementation, *Journal of Software: Evolution and Process*, 2015, Vol. 25(5), pp. 319-336.
[19] B. He, H. Xue, L. Liu, Q. Pan, W. Tang and E. Ostrosi, Rigid-flexible coupling virtual prototyping-based approach to the failure mode, effects, and criticality analysis, *International Journal of Advanced Manufacturing Technology*, 2019, Vol. 100(5-8), pp. 1695-1717, DOI: 10.1007/s00170-018-2641-2.
[20] J.K.Keski-Rahkonen, Probabilistic framework for product design optimization and risk management, *IOP Conf. Series: Materials Science and Engineering*, 2018 ,Vol. 351, 012007.
[21] B. Fontem, B. Keskin, S. Melouk, C. Vaughn, An exact decomposition algorithm for a chance-constrained new product risk model, *Operations Research Letters*, 2019, Vol. 47, Issue 4, pp. 250-256.
[22] R.A. Riascos, T. Majić, E. Ostrosi, J.-C. Sagot, j. Stjepandić, Multi-interfaces Entity Model for Summative Risk Management of Medical Products, *IFIP 18th International Conference on Product Lfiecyle Management,* 11-14 July 2021,, Curitiba, accepted, in press.
[23] H.P.L. Bruun, N.H. Mortensen, U. Harlou, M. Wörösch and M. Proschowsky, PLM system support for modular product development, *Computers in Industry*, 2015, Vol. 67, pp. 97–111.
[24] N.Wognum, C. Bil, F., Elgh, F., M. Peruzzini, J. Stjepandić, W.J.C. Verhagen, Transdisciplinary engineering research challenges, *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 753-762.
[25] *Council Directive 93/42/EEC of 14 June 1993 concerning medical devices.* eur-lex.europa.eu.

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