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Leveraging Data Ecosystems in Model-Based Systems Engineering for Ecological, Circular Added Value

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Abstract. There are numerous initiatives and lighthouse projects around Gaia-X to create the basics of open, trustworthy data ecosystems. One of the challenges in building these data ecosystems is to convince everyone involved of the advantages of multilateral data sharing. A prerequisite is also a common understanding of the rights of use and access to the data. Data sovereignty means that the data provider decides which data with which usage and access rights he wants to make accessible to which user group. Standardised digital representations by, for instance, the Asset Administration Shell (AAS enable creation of such data ecosystems, interlinking the physical and digital space. In the paper at hand, a conceptual approach named Decide4Eco is presented with the aim to enable systematic and flexible decision-making support for product planning and development concerning the sustainability of a product and the entire value chain. Methods of sustainability assessment are expanded to include predictive AI-based effects analyses.

Keywords. Data ecosystem, Data sovereignty, Artificial intelligence, Sustainability assessment, Digital product passport, Transdisciplinary Engineering

Introduction

Manufacturing companies are increasingly seeing sustainable products as an opportunity to create unique selling points. However, products often only meet minimum ecological requirements instead of constructively and consistently implementing the requirements of the circular economy − both the ability to make decisions and to provide evidence is lacking [1]. Entire value chains supported by supplier networks as a backbone contribute to this goal where suppliers take an even larger share in the added value [2]. Modern data ecosystems following Gaia-X principles like Catena-X, Pontus-X and in the future, Manufacturing-X will enable players in the manufacturing and automotive industries of the future to have collaborative and open data ecosystems [3]. They connect players globally to create consistent value chains − easier, more secure and more independent than ever before. The aim is data sovereignty: whoever makes data available retains control and decides individually who is involved in the data exchange, how, when, where,under which conditions he gets the data and can use it. Taking advantage of

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developments for the automative industry in Catena-X, the Manufacturing-X data space shall enable this for the manufacturing industry [4]. Existing technologies and architectures of data ecosystems following Gaia-X principles need to be further extended in order to handle the multitude, complexity, and uncertainty of sustainability requirements based on data and thus realize a successful ecological transformation. The propagation of these networks should emerge in parallel, based on principle of sovereign data spaces. Complementary initiatives such as Smart Connected Supplier Network (SCSN) should be connected as well [5].

Requirements for "sustainability" and "climate neutrality" are constantly increasing in Europe and international markets and not equal world wide. This is exactly where the research comes in: Companies must also be adaptable when it comes to their own ambitious sustainability goals – taking new laws, regulations, other requirements, and CO2 targets into account. Ultimately, the reduction of energy requirements, total resource consumption, and greenhouse gas emissions as well as the creation of a closed circular economy can only be proven with data from the network of all companies involved – a task that is hardly achievable without reliable cooperation in a data ecosystem [6]. It is becoming increasingly clear that flexibility will be crucial in product engineering. This flexibility can be supported by information technology standards and trustworthy shared data [7]. This applies in the value chain including final recycling: even if your own processes can be evaluated, upstream and downstream processes remain a challenge as crucial levers for ecological transformation. Evaluability and flexibility are enabled by a targeted flow of information. The key to this is a combination of technical concepts from Product Lifecycle Management (PLM) and the collaboration of sovereign partners in data spaces and ecosystems [8]. Adopting Manufacturing-X concepts, user companies will be enabled to consciously choose ecologically sustainable solution alternatives when developing products – and to consistently track them in the material cycle.

The project Decide4Eco aims to develop a methodology that enables systematic and flexible decision support for product planning and engineering regarding the sustainability of a physical product and its entire value chain within the Manufacturing-X data space. Decide4ECO will develop standardized connectors to PLM systems, established functions of PLM systems and for product tracking, e.g. by means of a Digital Product Passport (DPP) to ensure information circularity and the basis for constantly optimized material circularity. Finally, Decide4Eco will develop methods to evaluate different aspects of sustainable design which include predictive, AI-based impact analyses [9].

In this context, the paper at hand draws an approach that enables systematic and flexible decision support for product planning and engineering regarding the sustainability of a physical product and its entire value chain in shared data spaces, by using state-of-the-art IT techniques, standardized connectors, digital product passports, and predictive AI-based impact analysis. The outline of the paper is as follows. In section 1, the background of sustainable product engineering is introduced. In section 2, the business requirements for sustainable product engineering are described. In section 3, we discuss the solution methodology that drives this engineering, followed by the presentation of expected outcomes in section 4. Integration of complementary solutions and implementation by a consortium are elaborated in sections 5 and 6. Conclusions and outlook follow in section 7.

1. Status of the research and engineering

The research approach benefits from both the results of the related research projects and the industrial engineering and initiatives. The research outcome is extracted from a systematic analysis of the literature related to the interface of data spaces, PLM, and sustainability. Moreover, the current trends in industrial engineering and the related initiatives are also presented.

1.1. *Status of the research*

At the intersection of all three research topics, only partial solutions can be found. Amongst existing approaches, some overarching ambitions can be found, but they are limited on conceptual descriptions of possible approaches (like [3]) or understand "sustainability" in the sense of long-lasting existence resp. robustness of data spaces (like [4]). Relevant to some extent are numerous contributions that make digital twins usable (see, for instance, [10][11]) or address data spaces for smart manufacturing [12]. The approach of the BOOST 4.0 project makes data available in product engineering based on a chain of Industry 4.0 standards and FIWARE technologies, but without emphasizing sustainability [13]. As part of Catena-X, among other things, approaches for decision support for the selection of circularity alternatives were developed [14][15], like using distributed data to predict CO2 emissions. Such approaches should be strengthened in terms of the planned decision-making ability through a PLM foundation and flexibility with regard to the wide range of other sustainability goals. Previous approaches based on PLM (like [7], [14], [15]) focus almost exclusively on ecology and only indicate simple approaches (e.g. by using CO2 taxes as a cost rate for CO2 equivalents). Available work on the circular economy is based on Life Cycle Assessment (LCA). The consistency of resource consumption is not considered alongside efficiency [16]. Despite some approaches [13], [15], works on deep conceptual information models are still missing.

The scientific foundation for four central approaches is available in Model-Based Systems Engineering: The modeling of causal chains in the system model [9] can be expanded to include life cycle references and sustainability parameters [17]. Impact analyzes are based on this to evaluate changes in requirements [18] and other model elements such as functions, logical, and physical elements [19]. This foundation can be extended to include sustainability requirements and the details regarding risks in the dimensions of ecology and economy. The annotation of data and information with uncertainty categories [20] also comes into play to be able to explicitly handle and eliminate uncertainty.

One track of IT evolution is the expansion of digital consistency in PLM in terms of applications for learning from product life cycle, including the recycling of products and materials, and in terms of technology in the direction of the data spaces of Gaia-X [21][22] and Catena-X [23] as well as upcoming solutions in Manufacturing-X [24]. The International Data Space Reference Architecture Model (IDS-RM) from the International Data Space Association (IDSA) is taken into account. The Data Space Support Center (DSSC) offers implementation support for data ecosystems within spanned data spaces. The Smart Connected Supplier Network (SCSN) is considered one of the lighthouse projects that enable data exchange in the value chain [5]. Huawei showed the potential of data ecosystems for sustainability transformation [25]. A study confirms that data ecosystems can form the basis for the sustainable design of supply chains by building transformation-oriented data competence [26]. In addition, data ecosystems enable optimal utilization of resources and overcome current barriers to artificial intelligence (AI) technologies [27]. AI can become a driving force for environmental and sustainability research [28].

1.2. *Scientific classification in national and international comparison*

Anchoring in the Manufacturing-X data space is central. This includes building on the basis of previous research projects such as Catena-X. It is foreseen for utilization in various domains (Table 1).

Table 1. Excerpt of related EU and national projects [21].

Project	Scope
OMEGA-X	Multi-vector data ecosystem for the energy sector
AGRI-GAIA	GAIA-X data ecosystem usable for the agricultural and food industry and to make artificial intelligence applications more easily available based on networked data.
Gaia-X4 FutureMobility	Engineering and implementation of future mobility applications based on GAIA-X.
EONA-X	Data-sharing on mobility, transport, and tourism.
FLEX4RES	Quantitative data; Based on chemical and physical characteristics; Linked to environmental impacts.

Although the list of related initiatives and projects is not exhaustive, there is still missing interoperability with PLM. No standard nor neutral implementation is known at this moment covering the entire data and information categories relevant for sustainability assessments.

2. Business requirements

An approach and a practicable solution are necessary to expand this state-of-the-art with standardizable methods and models within the Manufacturing-X data space. This ambition should be made available in a demonstrator in order to establish a new degree of flexibility in product engineering and thus new possible collaborative business models, the increase in transparency, and thus the resilience of the entire production system to uncertainties, as well as the digital traceability of products. In parallel, this should maintain the data sovereignty of all actors involved to make resource-efficient and therefore ecologically and economically sustainable production tangible.

This goal can be achieved through Manufacturing-X compatible technologies and architectures in combination with related algorithms to quantify sustainability and support decision-making. Today, only loosely coupled PLM technologies with interfaces, etc. in materials databases and LCA are used to create a methodology with open-source information models in data spaces (Figure 1). In our Decide4ECO approach, heuristics, guidelines, and simulation models need to be used methodically, data-technically, and model-based as a basis for sustainability analysis. This makes the complexity of circular value creation for materials, components, and physical products manageable and assessable in decision-making situations.

The solution should provide a comprehensive, user-friendly IT system that supports agile collaborative product engineering, learns from the past, anticipates future events, shares more data responsibly , and at the same time prevents the consequences of data misuse and fosters both decision-making ability and verifiability with respect to sustainability aspects. Decide4ECO should use standards such as the Eclipse Dataspace Connector (EDC) concept and standardized ASS models, particularly like the Catena-X “Sustainability” and “Product Lifecycle Management” AAS models, and anchor its own solutions in the Manufacturing-X data space. The necessary data must be collected and maintained across the entire manufacturing and supply chain.

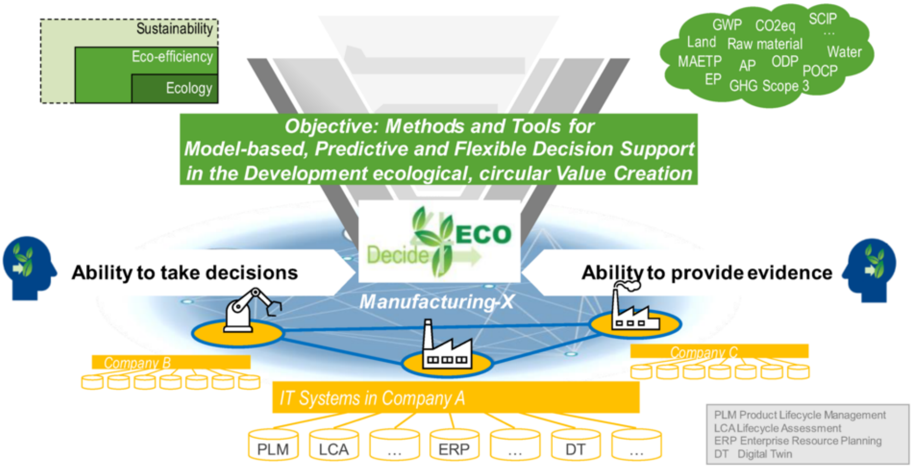

Figure 1. Decision support in the development of ecological, circular value creation based on Manufacturing-X.

3. Solution methodology

Functionally, digital preliminary products are realized for the model-based, predictive design of circular value networks. In product life, data must be obtained using Internet of Things and Services solutions and stored in the form of digital object identities, digital product passports, and digital twins. From an engineering perspective, PLM provides tools to integrate and process data. Circular business models in resilient value networks require a trusting, sovereign, and traceable exchange in shared data spaces. Flexibility is the outstanding objective in order to be able to react quickly and agile to new technological challenges, legal priorities, costs and other changing framework conditions. As a side-effect, this provides impetus for the establishment of Manufacturing-X together and within its own sphere of influence. Elements of the Decide4ECO solution are:

- the reference process model with methodological and organizational foundations for systematic and flexible decision support in the collaborative engineering process
- the extended conceptual information model as a lever for model-based and predictive decision support and the basis of the methodology
- the integrated, configurable, and decision-supporting methodology for the design of data ecosystems to enable circular value networks based on new PLM functionality and new developments in terms of digital interoperability and sovereignty

- the development of demonstrators and agile, multilateral validation with industrial partners to consistently focus on broadly enabling companies for Manufacturing-X
- the continuous improvement of Manufacturing-X standards and reference implementations for the transfer of competencies, technologies, and usage scenarios and thus for the consolidation of project results with preparation for standardization

During product engineering, it needs to be decided which footprint a product generates in the course of production, product use and return to circular value networks [29]. The forward-looking engineering of sustainable products follows, for example, VDI 2206:2021 [30] with reference to Greenhouse Gas (GHG) emission scopes and the sustainable use of raw materials/recyclable materials.

The determination of product properties with regard to sustainability takes place very early in the product life through a cross-disciplinary selection of functional alternatives, implementation in singular disciplines, and verification using data analysis based on PLM functionality. The strengthening of local players in international value chains in the manufacturing industry and the IT economy also takes place in networks in order to consolidate their position in the global market. This creates the prerequisites for daring business model innovations such as 100% circularity applying Cradle-to-Cradle principles [7].

4. Expected outcome and benefits

Decide4ECO is implemented in a collaborative project that aims to provide competitive advantage through the ability to flexibly quantify sustainability aspects and support the decision making process. Examples include energy and material savings, CO2 footprint, emissions reduction. Dependencies must be taken into account using multi-criteria and cross-impact analysis (Figure 2). The combination of a) domain-related, technical integration of language and metadata models based on Manufacturing-X with b) information technology approaches such as Natural Language Processing, Linked Data or Knowledge Graphs establish the basis for open, standardizable solutions. The complex search for relevant data is simplified by linking information, meaning existing information resources are used effectively and comprehensibly.

The interface for calculating profitability is made more flexible compared to a pure calculation of CO2 footprint, tax, and certificates, so that a range of target variables can be continuously varied. This specifically generates benefits in strategic planning and product engineering (Design for Environment, Design for Compliance) [1], but also supports product portfolio management with regard to changes in requirements in the product life. Focusing on different phases, it is crucial to take into account the maturity level of data. To do this, the Decide4ECO methodology must provide comprehensible information based on imprecise data. The data quality that is acquired using connectors from vendor's own IT systems or from suppliers in the data ecosystem must be explicitly and comprehensibly included [20]. Sustainability calculations converge to precise values along the product engineering process.

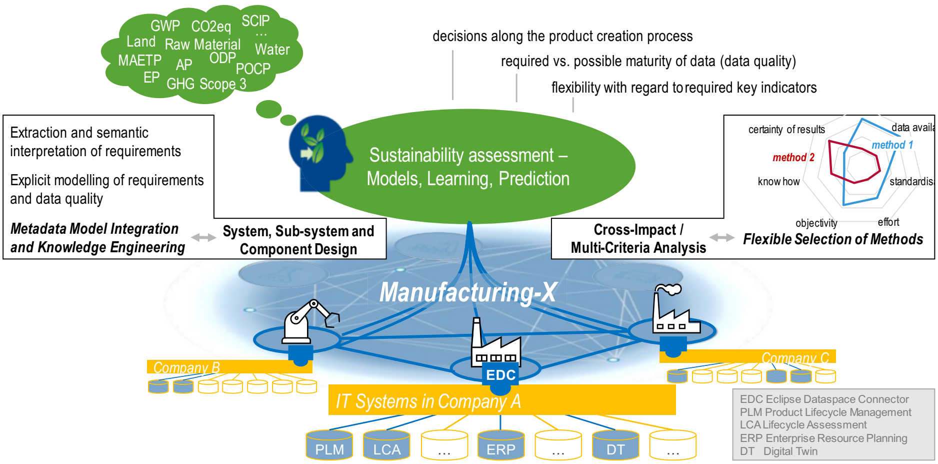

Figure 2. Innovations of the project beyond the-state-of-the-art.

Sustainability is thus implicitly determined early on and must be analyzed and predicted using selected methods. In this context, flexibility means calculating explainable statements on selectable sustainability indicators and making decisions. This means that requirements are sharpened and a verifiable sustainable system design is released. The approach will benefit both small businesses with simple, easy-to-maintain software and large businesses with dedicated PLM and ERP solutions. Decide4ECO thus addresses the challenge that, despite numerous approaches, “environmentally friendly product engineering” is still in its early stage in many respects – and helps to solve fundamental challenges. Decide4ECO enables a view of the overall context and prevents local improvements from leading to global sustainability deficits in the life cycle [31]. The network partners implement engineering functions and connectors to data spaces, thereby acquiring additional skills and thus gaining a competitive advantage.

5. Integration of complementary solutions

LCA solutions and materials databases such as openLCA, Sphera LCA (formerly known as GaBi), Campus, TotalMateria, and IT services from material manufacturers (e.g., BASF [32]) are available, can be used, and adapted for own purpose. The semantics of extremely heterogeneous data sets needs to be represented in an information model. Supposing good interoperability between systems with respect to consumption and emissions data (e.g., from Environmental Management System/EMS such as EnEffco or Ökotec) can be related to products using PLM. Moreover, corporate sustainability reports can be served and corporate life cycle assessments automated. In the next step follows the integration of the digital product passport and digital identity creation (see BMUV, DKE). Information models for digital twins are specifically expanded to include uniform data fields. In Catena-X, the sustainability assessment is viewed as a use case. For example, a Product Carbon Footprint (PCF) Rulebook is being developed as a set of rules to improve CO2 levels across vehicle manufacturing and the supply chain. It therefore represents one of the foundations for Decide4ECO, which is integrated into a data-based solution by the network and linked to other sustainability targets.

6. Implementation

An interdisciplinary team of project partners (a research institute, IT companies, user companies, an association and lawyers) who are stakeholders at every stage of the value chain created the conceptual framework. The solution is being developed using a contemporary, integrated approach of user-centered design. A modified version of the V-model forms the framework in which the solution is built and implemented in an agile manner. Each of the work packages primarily contributes to one of five project goals and three exploitation goals.

The starting point is an extended data and information model which creates the basis for model-based and predictive decision support. This method can be used for supplementing established PLM functionality with the newly developed Eco-Design functions to deepen the Manufacturing-X data space. The result is an integrated, configurable methodology for the trustworthy and legally secure design using and sharing information in data ecosystems

The incremental implementation using requirements analysis, demonstrators, and validation in user tests enables continuous adaptation to the needs of the project partners and a consistent focus on the needs of companies to achieve ecological transformation using the Manufacturing-X data space.The methodology will be implemented and validated in an agile manner with three industrial projct partners to consistently focus on the broad empowerment of companies. Decide4ECO provides demonstrators and contributions to the standardization of information models and AAS-submodels and functionality for value creation in networks with small and large companies.

The creation and exchange of a DPP in a collaboration scenario will be the first application of the proposed approach (Figure 3). In accordance with the European Green Deal, the majority of industrial products in the EU must supplement a DPP [11]. DPP is meant to provide details regarding a product's reusability, maintenance, and repair in addition to pertinent information about it along the relevant supply chain. To do this, information from several sources (PLM, ERP, ALM, etc.) must be gathered, combined into a single document, and updated in case of a change. This implies that all of a product's components – from raw material extraction through production and usage to disposal or reuse – as well as its composition and place of origin will be recorded in the future. A gap in the collaborative product engineering will be filled by exchanging DPP.

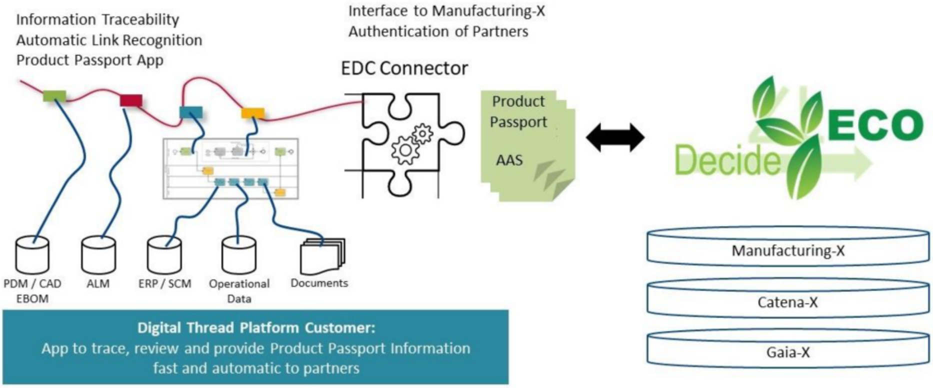

Figure 3. Exchange of the Digital Product Passport among the partners by using an EDC connector.

7. Conclusions and outlook

Digital technologies such as PLM are an important instrument to enhance the efficiency and sustainability of products and procedures [17]. Digital platforms can also be used to link sectors and industries and benefit from mutually reinforcing impacts [6].

This paper provides an initial introduction to sustainability-centric, systematic, and flexible decision support for product planning and engineering of a physical product and its entire value chain. The main outcome is an demonstrator for this purpose based on data spaces, by using IT techniques, standardized connectors, creating product passports, and provide predictive AI-based impact analysis. The developed modules offer a clear foundation for quicker and better judgments. This will facilitate the development of sustainable products ans thus the ecological transformation.

Moreover, sustainability is a typical transdisciplinary, superordinate objective with social and societal impact [33]. Supplier evaluation and selection are important elements for building an efficient sustainable innovative supply chain [34]. Approaches like this described here provide criteria for a systematic supplier evaluation and selection based on sustainability innovativeness [35].

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