SPS2022
A.H.C. Ng et al. (Eds.)

doi:10.3233/ATDE220169

The Current and Future Challenges for Virtual Commissioning and Digital Twins of Production Lines

Anton LIDELL[a,1], Stefan ERICSON[a], and Amos H.C. NG[a]
[a] *University of Skövde*

Abstract. The use of virtual commissioning has increased in the last decade, but there are still challenges before the software code validation method is widespread in use. One of the extensions to virtual commissioning is the digital twin technology to allow for further improved accuracy. The aim of this paper is to review existing standards and approaches to developing virtual commissioning, through a literature review and interviews with experts in the industry. First, the definitions and classifications related to virtual commissioning and digital twins are reviewed, followed by, the approaches for the development of virtual commissioning and digital twins reported in the literature are explored. Then, in three interviews with experts of varying backgrounds and competencies, the views of the virtual technologies are assessed to provide new insight for the industry. The findings of the literature review and interviews are, among others, the apparent need for standardisation in the field and that a sought-after standard in the form of ISO 23247-1 is underway. The key finding of this paper is that digital twin is a concept with a promising future in combination with other technologies of Industry 4.0. We also outline the challenges and possibilities of virtual commissioning and the digital twin and could be used as a starting point for further research in standardisations and improvements sprung from the new standard.

Keywords. Virtual commissioning, digital twin, simulation, production system, literature review, interview

1. Introduction

Evaluating a production line in a virtual environment before the physical production line is constructed is generally called virtual commissioning (VC). It is based on the ability to test and validate systems against a virtual model, instead of an actual, real production system [1,2]. Closely related to VC is the emerging digital twin (DT) technology commonly referred to as one of the key enabling technologies of Industry 4.0. A DT can be defined as an evolving digital profile of the historical and current behaviour of a physical object or process that helps optimize business performance [3]. Through the integration of analytical/simulation-based models to their physical counterparts, digital twin technology can be projected to become more significant than ever in industrial applications. For production system designers, the ability to create digital twins of the desired production line system and then evaluate the performance of the system has become increasingly popular as the tools become more mature. In combination, VC

[1] Corresponding Author, Anton Lidell, University of Skövde, Sweden, E-mail: antonlidell@live.se

consists of a DT which mimics the behaviour of the target production line, including the programming code to control the model and often algorithms for handling various behaviours, for example, vision systems, is a central part of how VC can be used in evaluating and optimising the performance of the real production system.

There are many reasons for using VC and DT technologies. For example, to prevent errors and optimise the performance of the production line before any equipment is in place, thus allowing for changes to be made at a lower economical and time cost. This is due to changes in digital models mainly requiring cost in labour-time for the designer compared to material cost and labour-time for assembly and disassembly. As technology and digital tools have improved and evolved so has the possibilities for employing virtual commissioning as well, which has led to increased use of digital twins and virtual commissioning in general.

The aim of the paper is to study existing methods and standardised approaches for developing VC and DTs. The ultimate goal is to improve the utilisation of virtual commissioning models for production systems and the reliability, thus increasing cost and material effectiveness in their design process. While the virtual modelling, programming and control algorithms keep developing and improving, the knowledge and research regarding standardised and formal methods for virtual commissioning are less explored. Therefore, the focus of this paper is to concretise and summarise the current knowledge of the conditions for virtual commissioning. Through a literature review of existing research papers on methods and standardised approaches, this paper: (1) identifies important factors, such as challenges and prospects; (2) compares the identified available methods and approaches for developing VC and DTs of production systems. In addition, through three interviews with experts of various backgrounds and competencies, different views of the future about VC and DT technologies are assessed to provide insight for the industry today.

2. Research methodology

A literature review was conducted to gain a deeper understanding of VC and DTs, a rather undefined research topic, which make it a complex topic to navigate. The methodology used for the literature review was searching in the research paper database *Google Scholar*, since it includes results from other databases. Initially, the search terms mainly revolved around "virtual commissioning", "digital twins", and "simulation" in order to scout the current papers on the topic and get a wider scope of the current literature. Then, the more descriptive terms "best practices", "guidelines", "frameworks", and "behaviour models", were added to narrow down the search results according to the aim of the paper. Finally, search logic was included and the final search expression was phrased "behaviour OR behavior models "virtual commissioning" OR "digital twin" industrial production".

The search yielded over 8.000 results, where the first 20 result pages were reviewed, and of this 81 papers were selected based on the titles. First, the abstracts and introductions of the 81 papers were briefly read to get a sense of the papers relevance, thus 42 papers were included and 39 were excluded. The reference lists of the found high impact factor papers were examined as well as their citations to add five new papers. Next, the 47 papers were read deeply, along with marking up interesting sections in order to categorise the papers to sort the papers in which ways they were useful. After reading the articles more thoroughly, 26 of the initially included papers were excluded due to not being suitable to the aim of this paper. This left 21 papers left to be used in the literature review.

Interviews were held to broaden the understanding of VC and DTs and the related challenges and prospects, as well as providing a qualitative aspect of the topic. It is suggested to design an interview guide including a formal introduction, interview questions, as well as a concluding part [4]. Therefore an interview guide was designed as an aid for the interviews. The interview questions should be open-ended and not be more than 15 per interview. Ten open-ended questions related to VC and DTs were formulated, such as “your background?”, “your description of the topic?”, “troubles regarding terminology?”, and “current limitations and opportunities”. Another complementary method of preparing for an interview that was used, is to conduct a test interview in order to practice and evaluate the interview questions.

The interviewees were found and selected partly using information found during the literature review search process, such as research programme responisbles, researchers, and company representatives that had been involved in VC and DTs. A list of 14 possible interviewees was made, of which three accepted the interview invitation. The background of the interviewees was intentionally varied in order to find different perspectives. The background of one interviewee was as product manager of a robiotics company but also as a senior advisor the University of Skövde, while another interviewee was a simulation specialist and senior advisor at a global and broad company, and the final interviewee was a senior lecturer and head of division at the University of Skövde.

During the interviews quick notes of key words were taken to not interrupt the natural flow of the conversations. The key words were then written out in full text directly after the interviews, before any details of the interviews were forgotten.

3. Literature review

The literature review was conducted to gain a deeper understanding of VC and DTs, a rather undefined research topic, which makes it a complex topic to navigate. The literature review consists of found attempts to define VC and DTs, as well as existing frameworks, along with some examples of use cases.

3.1. Defining virtual commissioning and simulation

Already in 2010, Hoffman et al. reviewed approaches to and presented concepts for VC of manufacturing systems [1]. According to the authors, the purpose of VC is identifying errors earlier in the process and presents some necessary requirements for VC to be adopted more widely. In a white paper a by Siemens AG and Pforzheim University, the definitions, current and future use of simulation were reviewed [5]. It was found that most of the participants saw VC as a way of validating automation systems control logic. Lechler et al. define the term VC as “the early development and validation of PLC code using a simulation model.” and reviews its use cases [6]. The authors use **Figure 1** to show the difference between employing VC and not during the engineering process. A complete comparison of the papers can be seen in **Table 1**.

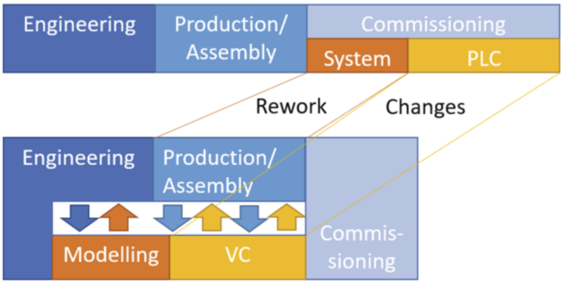

Figure 1. Engineering with and without virtual commissioning by Lechler et al. [6]. The figure exhibits the benefit of employing VC in shortening the real commissioning time through parallelising the process of automation evaluation with the engineering and production process. Thus, the total time from start to finish of a production line project is reduced.

Table 1. Summary of articles exploring virtual commissioning. The summary includes all three analysed articles and highlights the main similarities and differences. The common parameters of which the articles are compared are the focus area, definition and description of VC, challenges to further usage of VC, key tools and enabling technologies for VC, as well as some other conclusions by the authors.

	Hoffmann et al. 2010 [1]	**Lechler et al. 2019 [6]**	**Bruckner et al. 2020 [5]**
Focus	Review of approaches and concept of VC	Define term VC and review use cases	Survey of use, definitions, and future for simulation
Definition	To test manufacturing systems and the control programs using simulation before the real commissioning	Early development and validation of PLC code using a simulation model	Validation of automation systems through modelling logic signals
Description	Real commissioning	Use cases: logistics, process simulation, and automation systems	Use cases: product design optimisation, early design, and VC
	Hardware-in-the-loop Software-in-the-loop	Reduced real commissioning time	Level of detail: subsystems, unit, complete plant, and last single component
	Full VC		Low use of standards and not knowing what standards exist
Challenges	Requires high expertise Requires high effort	High costs of implementation Complexity of VC	Simulation too expensive Too much effort Missing skilled personal
Tools	Off-shelf or developed	Software programming	FMI and FMU
	Standard model libraries	Communication platforms	STEP
Enabling technologies	AutomationML and CAD	DTs	Open-source tools
Conclusions	Improved detail in modelling libraries required	Need for component manufacturers to provide extended models	Simulation to become more important throughout lifecycle
	Standardisation for data and data structure formats required	Lifecycle of VC models to be expanded through DTs	Simulation should be integrated with learning and training

3.2. Defining digital twins

Kritzinger et al. conducted a categorical literature review and classification of Digital Twin in manufacturing [7]. Three categories of DTs were determined: Digital Model (DM), Digital Shadow (DS) and Digital Twin (DT). These categories are often incorrectly used interchangeably which can cause confusion. A DT includes data streams in both directions between the physical and virtual objects. Biesinger and Weyrich compare various characteristics of DTs in the automotive industry and note that the amount of publications on the subject is increasing [8]. The authors also describe different types of DTs as well as some example descriptions and applications.

Lim, Cheng and Chen performed a state-of-the-art review of DTs in perspective of PLM through a literature review of 123 research articles along with 22 other references to concretise the survey [9]. In the paper, techniques for DT creation and how they are stacked on top of each other is presented as well as a review of other authors' definitions of DTs, over time. A thorough review by Liu et al. surveys DTs in terms of concept, technologies, and industrial applications [10]. Here, an increased interest in the term DT is also identified, along with the fact that most literature regards the applications and frameworks of DTs. The authors conclude with a suggestion to define a systematic research architecture for DTs. In **Table 2**, a summary and in-depth comparison of the articles can be found.

While the need for standardising the definition of DTs, there is a standard by ISO currently in progress that should cater to this need [11]. The standard has passed the approval stage and is, as of October 2021, in the publication stage, which means that it should be soon become available in its entirety.

3.3. Virtual commissioning frameworks

During the literature review, some high-level frameworks for VC were found, see **Table 3** for a thorough summary. Schneider et al. aim to create a platform for use in VC and focus on scenario-based test specifications to simulate both expected and unexpected system behaviour [12]. The authors suggest a two-part test specification where the application scenarios are specified first, next the failure scenarios are specified. VC is described as the modelling, realisation, and evaluation to simulate behaviour when setting up a production system. Scheifele, Verl and Riedel presents a real-time co-simulation platform for VC of mechatronic systems [13]. The concept of real-time co-simulation is presented as partitioning the full simulation model into smaller model blocks to parallelise the simulation calculations and maintaining the time determinism through lossless and clock-synchronised communication. Finally, Albo and Falkman aim to classify different levels of detail in VC in the perspective of production lifecycle specification strategies for new production systems and predicting future challenges for existing systems [14]. A hierarchical framework consisting of five levels, from automation systems to communication, behaviour models, resource models, and interconnected systems, is presented. The authors conclude that VC requires proper cooperation between the different disciplines involved, such as mechanical engineers and PLC programmers.

Table 2. Summary of articles exploring the digital twin. Included in the summary are all four articles used to analyse the current definitions of DT. The common parameters used for comparing the articles are the focus area, definitions of the DT, some examples of enabling technologies, and some general conclusions by the authors.

	Kritzinger et al. 2018 [7]	**Biesinger and Weyrich 2019 [8]**	**Lim, Zheng and Chen 2020 [9]**	**Liu et al. 2021 [10]**
Focus	Defining DTs	Compare characteristics of DTs	Review of DTs in perspective of PLM	Review of DT concept, technologies, and applications
Definitions	DM: representation of object with no data exchange	ABB: for PLM, design, behaviour, maintenance, and 3D visualisation Airbus: digital model for cyber security Daimler: integration twin for VC, maintenance, and prototyping	Grieves: "Virtual representation of what has been produced" Söderberg et al.: "Using a digital copy of the physical system to perform real-time optimization"	DM: virtual model without self-driven data flow
	DS: representation of object with data exchange to virtual representation	GE: component twin, asset twin, process twin, or system twin for prediction, simulation, and optimisation Siemens: PLM simulations and digital models for prediction and optimisation	El Saddik: "Digital replications of living as well as non-living entities that enable data to be seamlessly transmitted between the physical and virtual worlds"	DS: virtual model with self-driven unidirectional data flow
	DT: representation of object with data exchange to both virtual representation and physical object	Engineering twin: for robot simulation and VC Control twin: DTs focused on automation and control	Xu et al.: "Simulates, records and improves the production process from design to retirement, including the content of virtual space, physical space and the interaction between them"	DT: virtual and dynamic model with bidirectional data flow
Enabling technologies	DES, CS, communication protocols, and Industry 4.0 technologies	Digital models, position data, 3D-scanning, and real-time communication	Data exchange protocols, computational processing, and machine learning and analytics	Data technologies, hi-fi modelling, and model-based simulation
Conclusions	No common definition of DTs	DTs will be important data sources for AI	Continuous evolution of DTs requires understanding and definitions	Concept of DT need clarification
	Most research focus on DS	Currently data lacking quality for AI, interconnecting DT	Future directions: increase DT flexibility, increase interoperability, improve real-time simulation, and improve system communication	No standardised creation process DTs to be individualised, high-fidelity, real-time, and controllable

Table 3. Summary of articles defining frameworks for VC. All three articles used as a foundation for the analysis of the current frameworks for VC are compared through common parameters. The first parameter is core, or essence, of the presented framework. Other parameters are challenges and the focus area of the article, as well as some conclusions and suggested areas for further research to improve the frameworks of DTs.

	Schneider et al. 2014 [12]	**Scheifele, Verl and Riedel 2019 [13]**	**Albo and Falkman 2020 [14]**
Core of framework	Platform for VC	Platform for VC	Hierarchical framework of 5 levels
Highlighted issues	Steady increase in system complexity	Lack of standardisation (tool chain and model exchange standards)	Need of wide framework of technological standards and disciplines
Focus area	Test specification: Application scenarios, failure scenarios	Real-time co-simulation Need of model-integration interfaces (ex. FMI)	Differences for green- and brownfield scenarios
Conclusions	Test specifications can support verification in VC	Platform increase significance of DTs and therefore VC	Standardisation is key for Industry 4.0 and interconnectivity Improve communication of OT and IT Reduce cost/improve efficiency through standardised frameworks
Suggested further research	Procedure model for VC (detail design)	Investigating partitioning, parallelisation, synchronisation, and data exchange	Verify financial justification Impact of correlating factors

3.4. Behavioral models for Virtual commissioning

Throughout the literature review, the importance of accurate Behaviour Models (BMs) was made clear. Thus, the creation and improvement of BMs were explored as well. Süß, Strahilov and Diedrich present a concept procedure for component manufacturers to provide BMs in a standardised way as well as how to apply it in VC [15]. The authors suggest that the component manufacturers should provide BMs along with their products. Though, the challenge of providing accurate BMs without sharing too much information that could be confidential, or sensitive, was acknowledged as well. Süß et al. propose a new approach to behaviour simulation, as well as automatised testing [16]. The authors report that standardising BMs in a model description format is necessary for the VC process. The suggested approach enables the association of control program variables to BM variables through AutomationML and to explore the distribution of manufacturer BMs.

3.5. Similar approaches to virtual commissioning

In parallel to VC, some similar and novel approaches can be found. Logo and Fantuzzi present an example of simulation for virtual design and optimisation of industrial production lines using the IMPROVE project's framework [17]. The approach enables user support functions in self-diagnosis and self-optimisation possible for Small and Medium-sized Enterprises (SME), as the latest technologies often are not affordable for SMEs. The foundation of the approach is using a mix of Discrete Event Simulation

(DES) and System Dynamics (SD) to get the advantages of both methods when modelling industrial production plants. An approach to testing safety logic virtually through using the Input-Output Conformance (IOCO) as the validation criteria is presented by Khan, Falkman and Fabian [18]. The approach is a stepwise commissioning and can, for example, be testing sensors and actuators in simulation first and then replacing them with the physical hardware, then moving on to the next subsystem. IOCO also helps in involving the engineering staff in the process of PLC programming.

3.6. Digital twin frameworks

DTs have been found to be an important part of VC and the level of simulation details in which the state-of-the-art VC is focusing on. While no articles reviewing concrete methods in details have been found, some articles attempt to define a common approach or framework for creating DTs, see **Table 4**. Bao et al. propose a framework for the modelling and operations of DTs in the manufacturing industry [19]. The authors describe DTs as the convergence of the virtual and physical world and suggest dividing into product DTs, operation DTs, and process DTs. Barbieri et al. find it fundamental to define the necessary steps for developing DTs and propose a method based on VC [20]. The authors note an increasing demand for the current production systems due to the shift to mass customisation and shorter product lifecycles. The presented methodology for guiding the user in developing DTs is described and aims to fully integrate the DTs in the manufacturing system.

Table 4. Summary of articles defining frameworks for the digital twin. The two analysed articles are compared through some identified common parameters. The parameters are the concept core of the presented framework, highlighted issues which the framework should resolve, the focus area of the article, and conclusions and suggested further research by the authors.

	Bao et al. 2019 [19]	**Barbieri et al. 2021 [20]**
Core of framework	Approach to modelling and operations of DTs	VC based approach for developing DTs
Highlighted issues	Data communication between parts of the DTs Only static models	Lack of methods for design, integration, and verifying DTs
Focus area	DTs for convergence of virtual and physical space Process DTs	Synchronise DTs, MES, and PLCs Guiding user in DT Development
Conclusions	Provide method for constructing process DTs Creating platform for integration and intercommunication	Fundamental to define architectures for stepwise development of DTs Fundamental to define architectures for integrating DTs into manufacturing systems
Suggested further research	Integrating DTs and AI/Big Data for predictive manufacturing Construct DT method focused on workshops modelling and operations	Further validation of proposed concept in real case Improve learning through VC Integrate failure detection in concept

3.7. Expansions of digital twin

The concept of DTs has been expanded by multiple authors. This section highlights some examples of the current width. Martínez et al. address the shortcomings of Simulation-Based DT by combining existing implementation methods [21]. Regular DTs only use measured data, which means that they can only predict what is given by that input data, and not foresee other occurrences. The authors introduce an approach to Automatic Model Generation (AMG) to simplify the DT development process.

Booyse, Wilke and Heyns propose a solution to the dependence of historical data and focuses on the use of a Deep Digital Twin (DDT) for system health and for predictive maintenance [22]. The DDT is defined as a DT developed using deep learning from operation data, physics models, digital models, data models, and probabilistic models. Pérez et al. present a novel method for process automation design, implementation enhancement, and real-time surveying in the creation of a DT in the manufacturing process [23]. The method is creating a DT of a manufacturing system with a Virtual Reality (VR) interface to simulate and analyse layout; this approach can aid in decision making. Mykoniatis and Harris describe a Digital Twin Emulator (DTE) to be used in mechatronic automation systems to enable real-time data exchange [24]. The approach combines DES and Agent-Based Modelling (ABM) to capture both product flow and production stations accurately in order to overcome the limitations of the individual simulation approaches. Key Performance Indicators (KPI) are also essential in capturing the variability of the DT.

Other recent articles include [24] and [25], in which the authors outline two promising but currently under-explored application areas of DTs: dispatching optimization and operational control. Specifically, in [26], a DT-enhanced dynamic scheduling methodology is presented. The case study shows that the proposed method can reduce the makespan and total tardiness by 14.5% and 87.1%, respectively, and increase the average utility rate by 14.9%. The results from this study shed light on the application of DTs to dynamic dispatching and operational control as a promising research direction. In [25], they conclude that despite the rapid growth, DTs remain a rapidly evolving concept and there are still many pressing issues to be addressed to enhance its viability in practice, e.g., a unified DT modeling method.

4. Interviews

The first interviewee is mainly connected to the business world, while still influenced by the academics through working with the University of Skövde. According to this expert, the most common practice is not using VC and that a DT is a precise replica of a physical object. Another highlighted obstacle for the development and use of VC is related to the cultural and social aspects of implementing new technologies and work methods. Some other interesting thoughts raised by the interviewee are the paradox of using VC efficiently and reducing the real commissioning time, and thus working more in the office can fool the customers to think that the assignment is easier than they are paying for.

In the second interview, where the interviewee is completely in the business world and focused on marketing. This expert views VC as a standard procedure for at least two or three companies working with system integration. The interviewee was very clear with not being too interested in VC anymore since he thought the process was adequate and wanted to focus on the rest of the lifecycle of the DTs. As in other business areas, the interviewee suggested that there could be organisations to certify the VC process of companies in order to harmonise approaches and verify the VC process. Finally, a possibility from using VC is improving the social sustainability of the workplace. By increasing the time spent in the office and for normal work hours while reducing the time needed for the real commissioning, the work conditions of the employees of system integrators are improved. Some are forced to quit due to the private life clashing with the work of real commissioning on site.

The third and final interview, in which the interviewee is purely academic and therefore could not give very detailed or specific answers regarding VC technology and methods. The interviewee notes that in some companies it is not the engineers who drive the use of VC, and therefore the approaches and methods in those cases can often be ad-hoc or improvised. Another interesting issue raised by this expert regards the role of higher education as the rate of the technological and digital evolution increases. In addition, the shift in competence demands from process knowledge to competences in technological and digital tools, which can create a competence gap in the labour market. A short summary of these three interviews can be seen in **Table 5**.

Table 5. Summary of the three interviews held with people of various background but understanding of the topic. The comparison highlights the similarities and differences described by the interviewees. In total, the interviewees' answers are consistent with each other.

	Interview 1	**Interview 2**	**Interview 3**
Description of VC	Use case for DTs	Use case for DTs	Use case for DTs
Use of standards	In practice similar approaches	Modelica, FMI	Local "standards"
Standardisation of DTs and VC	In need of standardisation	In need of standardisation	In need of standardisation
Other improvements from VC	Collaboration between disciplines	Collaboration between disciplines	Collaboration between disciplines
Errors not detected through VC	Process related (spray paint, weld)	Small details (last 5 percent)	Not specified
Obstacles	Culture/Social	Culture/Social	Culture/Social
Future of VC	Prolonging lifecycle (AR, VR)	Prolonging lifecycle (AI, VR)	Prolonging lifecycle (VR)

5. Conclusions and future work

The topics of VC and DTs have seen an increased significance and interest in recent years, but little has been done in terms of classification. Overall, in both the literature and interviews, the need for standardisation was made clear, not only in defining the terminology but also for standardised approaches to the design of VC and DTs, as well as for data exchange and communication protocols. This discrepancy creates challenges in forming a cohesive description of VC and DTs. In this regard, as identified clearly by the thorough analysis of the papers reviewed in the current paper, the ISO 23247-1 standard could bring some much-needed clarity and definition to DTs. Before the standard and its content is published, it is hard to completely predict the entirety of the outcomes. But to speculate, the standard should allow for a widely accepted definition of DTs as well as data exchange protocols for interconnectivity and automated dataflow. All these aspects and technologies for simplifying and improving the use of VC and DTs in specific are also important for increasing the use of virtual tools and methods in general.

When summing up the collective knowledge of the literature review and interviews, some conclusions in regards to the definitions of VC and DTs could be made. First, VC is defined, rather harmoniously, as the validation of automated industrial production systems before any physical commissioning is made. If any definition of DTs should be made, it could be as a virtual model of a physical industrial production system being constantly updated and updating the physical object through a real-time and bidirectional data exchange. Even if the incomplete types of DTs, such as DM and DS described in some of the literature, are useful, it is the fully automated and bidirectional dataflow of the DT which makes the concept really interesting.

The increased use of VC and DTs is important for many reasons, such as increasing safety for operators through minimising harmful situations and correctly validating safety systems, as well as allowing improved working conditions, as described in the second interview. Furthermore, increased use of VC and DTs should also make the process of designing and developing production systems more cost-effective. More use of VC and DTs could also minimise wastes, such as ordering wrong components and machines, and to optimise the resource and energy usage through simulations and using DTs.

Whereas several other articles have made similar state-of-the art reviews of VC and DTs separately, this paper presents the topics side-by-side in order to differentiate them. It gives a recent outlook on the challenges and prospects of the topics because the field is still fairly new and thus the knowledge is rapidly expanding. While similar review-based papers might have a greater technical depth regarding the various technologies underlying the implementations of VC and DTs, given the limited space, this paper stands out in using interviews as a complement to the literature review and thereby obtaining information from some first-hand sources.

A theme of this paper has been the need for standardisation, which could be applicable to most new technologies and techniques. The focus of this paper has been VC of production systems. Still, some of the results, such as the ISO standard could also result with simplifications and improvements to VC and DTs of, e.g., products and operations. This kind of close generalisation can also be made regarding extending the lifecycle of the DTs for products and operations.

References

[1] Hoffmann P, Schumann R, Maksoud TMA, Premier GC. Virtual commissioning of manufacturing systems a review and new approaches for simplification. Proc - 24th Eur Conf Model Simulation, ECMS 2010. 2010;2(Cd):175–81.

[2] Lee CG, Park SC. Survey on the virtual commissioning of manufacturing systems. J Comput Des Eng. 2014;1(3):213–22.

[3] Parrott A, Warshaw L. Industry 4.0 and the digital twin. Deloitte Univ Press [Internet]. 2017;1–17. Available from: https://dupress.deloitte.com/dup-us-en/focus/industry-4-0/digital-twin-technology-smart-factory.html

[4] McGrath C, Palmgren PJ, Liljedahl M. Twelve tips for conducting qualitative research interviews. Med Teach [Internet]. 2019;41(9):1002–6. Available from: https://doi.org/10.1080/0142159X.2018.1497149

[5] Bruckner L, Oppelt M, Urbas L, Barth M. The current and future use of simulation in discrete and process industries. Siemens AG. 2020;

[6] Lechler T, Fischer E, Metzner M, Mayr A, Franke J. Virtual commissioning – Scientific review and exploratory use cases in advanced production systems. Procedia CIRP. 2019;81:1125–30.

[7] Kritzinger W, Karner M, Traar G, Henjes J, Sihn W. Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine [Internet]. 2018;51(11):1016–22. Available from: https://doi.org/10.1016/j.ifacol.2018.08.474

[8] Biesinger F, Weyrich M. The Facets of Digital Twins in Production and the Automotive Industry. 2019 23rd Int Conf Mechatronics Technol ICMT 2019. 2019;

[9] Lim KYH, Zheng P, Chen CH. A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives. J Intell Manuf. 2020;31(6):1313–37.

[10] Liu M, Fang S, Dong H, Xu C. Review of digital twin about concepts, technologies, and industrial applications. J Manuf Syst [Internet]. 2021;58(PB):346–61. Available from: https://doi.org/10.1016/j.jmsy.2020.06.017

[11] ISO/TC 184/SC 4 Industrial data Committee. ISO/FDIS 23247-1 Automation systems and integration — Digital Twin framework for manufacturing — Part 1: Overview and general principles [Internet]. https://www.iso.org/standard/75066.html. 2021 [cited 2021 May 18]. Available from: https://www.iso.org/standard/75066.html

[12] Schneider M, Gausemeier J, Schmüdderrich T, Trächtler A. Approach for scenario-based test specifications for virtual commissioning. Proc Int Des Conf Des. 2014;2014-Janua:1339–48.

[13] Scheifele C, Verl A, Riedel O. Real-time co-simulation for the virtual commissioning of production systems. Procedia CIRP [Internet]. 2019;79:397–402. Available from: https://doi.org/10.1016/j.procir.2019.02.104

[14] Albo A, Falkman P. A standardization approach to virtual commissioning strategies in complex production environments. Procedia Manuf [Internet]. 2020;51:1251–8. Available from: https://doi.org/10.1016/j.promfg.2020.10.175

[15] Süß S, Strahilov A, Diedrich C. Behaviour simulation for Virtual Commissioning using co-simulation. IEEE Int Conf Emerg Technol Fact Autom ETFA. 2015;2015-Octob(October).

[16] Süß S, Magnus S, Thron M, Zipper H, Odefey U, Fassler V, et al. Test methodology for virtual commissioning based on behaviour simulation of production systems. IEEE Int Conf Emerg Technol Fact Autom ETFA. 2016;2016-Novem.

[17] Longo CS, Fantuzzi C. Simulation and optimisation of production lines in the framework of the IMPROVE project. IEEE Int Conf Emerg Technol Fact Autom ETFA. 2017;(November):1–8.

[18] Khan A, Falkman P, Fabian M. Testing and validation of safety logic in the virtual environment. CIRP J Manuf Sci Technol [Internet]. 2019;26:1–9. Available from: https://doi.org/10.1016/j.cirpj.2019.07.002

[19] Bao J, Guo D, Li J, Zhang J. The modelling and operations for the digital twin in the context of manufacturing. Enterp Inf Syst [Internet]. 2019;13(4):534–56. Available from: https://doi.org/10.1080/17517575.2018.1526324

[20] Barbieri G, Bertuzzi A, Capriotti A, Ragazzini L, Gutierrez D, Negri E, et al. A virtual commissioning based methodology to integrate digital twins into manufacturing systems. Prod Eng [Internet]. 2021;(0123456789). Available from: https://doi.org/10.1007/s11740-021-01037-3

[21] Martínez GS, Sierla S, Karhela T, Vyatkin V. Automatic generation of a simulation-based digital twin of an industrial process plant. Proc IECON 2018 - 44th Annu Conf IEEE Ind Electron Soc. 2018;3084–9.

[22] Booyse W, Wilke DN, Heyns S. Deep digital twins for detection, diagnostics and prognostics. Mech Syst Signal Process [Internet]. 2020;140:106612. Available from: https://doi.org/10.1016/j.ymssp.2019.106612

[23] Pérez L, Rodríguez-Jiménez S, Rodríguez N, Usamentiaga R, García DF. Digital twin and virtual reality based methodology for multi-robot manufacturing cell commissioning. Appl Sci. 2020;10(10).

[24] Mykoniatis K, Harris GA. A digital twin emulator of a modular production system using a data-driven hybrid modeling and simulation approach. J Intell Manuf [Internet]. 2021;(0123456789). Available from: https://doi.org/10.1007/s10845-020-01724-5

[25] Tao F, Zhang H, Liu A, Nee AYC. Digital Twin in Industry: State-of-the-Art. IEEE Trans Ind Informatics. 2019;15(4):2405–15.

[26] Zhang M, Tao F, Nee AYC. Digital Twin Enhanced Dynamic Job-Shop Scheduling. J Manuf Syst [Internet]. 2021;58(PB):146–56. Available from: https://doi.org/10.1016/j.jmsy.2020.04.008