



Demonstration and evaluation of a digital twin-based virtual factory

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Received: 21 October 2020 / Accepted: 15 February 2021 / Published online: 10 March 2021
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Abstract

Smart manufacturing, tailored by the 4th industrial revolution and forces like innovation, competition, and changing demands, lies behind the concurrent evolution (also known as co-evolution) of products, processes and production systems. Manufacturing companies need to adapt to ever-changing environments by simultaneously reforming and regenerating their product, process, and system models as well as goals and strategies to stay competitive. However, the ever-increasing complexity and ever-shortening lifecycles of product, process and system domains challenge manufacturing organization's conventional approaches to analysing and formalizing models and processes as well as management, maintenance and simulation of product and system life cycles. The digital twin-based virtual factory (VF) concept, as an integrated simulation model of a factory including its subsystems, is promising for supporting manufacturing organizations in adapting to dynamic and complex environments. In this paper, we present the demonstration and evaluation of previously introduced digital twin-based VF concept to support modelling, simulation and evaluation of complex manufacturing systems while employing multi-user collaborative virtual reality (VR) learning/training scenarios. The concept is demonstrated and evaluated using two different wind turbine manufacturing cases, including a wind blade manufacturing plant and a nacelle assembly line. Thirteen industry experts who have diverse backgrounds and expertise were interviewed after their participation in a demonstration. We present the experts' discussions and arguments to evaluate the DT-based VF concept based on four dimensions, namely, dynamic, open, cognitive, and holistic systems. The semi-structured conversational interview results show that the DT-based VF stands out by having the potential to support concurrent engineering by virtual collaboration. Moreover, DT-based VF is promising for decreasing physical builds and saving time by virtual prototyping (VP).

Keywords Virtual factory · Virtual manufacturing · Digital twin · Manufacturing planning · Optimisation · Simulation · Virtual reality · Industry 4.0

1 Introduction

The frequency of changes is increasing in markets and industries as well as associated products and processes in association with social, natural and artificial systems. One of the depictions of this change can be noticed as a shift in decision-making authority from manufacturing companies to customers. This shift pressures companies to decrease product, process and manufacturing systems lifecycles [1].

Increasing demand in customized products is resulting in higher complexity both in product models and production processes. Therefore, manufacturing companies need more constant transformations of their manufacturing systems, processes and product models. Concurrent evolution of products, processes and systems, also known as the *co-evolution* paradigm, requires synchronization and simultaneous engineering of product, process and factory models [2]. Active and integrated use of various digital factory tools, technologies and methodologies are required to deal with the co-evolution problem. Therefore, interoperability between such tools and technologies becomes paramount [3].

Despite the challenges faced in industry, emerging technologies are opening up new ways to deal with such challenges and to adapt to unpredictable environments [4]. Some of the characteristics of the future smart factories studied by the scholars are complexity encapsulation, interoperability, integration, modularity, virtualisation, intelligence, collaboration and dynamic

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reconfigurability [5]. Real-time bi-directional data integration between physical systems and digital models combined with simulation-based data analytics and VR capabilities promise viable solutions to face current and future scenarios. The virtual factory (VF) was conceptualized as a virtual representation of a real factory represented as an integrated simulation model of a factory including its subsystems [6]. VF can offer advanced decision support capacity for the evaluation and reconfiguration of new or existing smart production systems [6, 7].

The VF concept is getting attention from leading manufacturing companies like Volvo Group Global and Ford Motor Company [8]. VF simulations can support handling dynamic complexity by integrating, simulating and manipulating models from product, process and system domains concurrently and dynamically. Recent advancements in modelling and simulation (M&S) tools, digital twin (DT) technology and the interaction and collaboration capabilities of immersive VR have enabled concurrent engineering of complex models [9]. Enhancement of VF concept with bi-directional automated real-time data integration with production systems and product model enables utilizing DTs in VF tools [10]. Thus, DT-based VF concept can support bridging the gap of cyber-physical integration by achieving *faithful-mirrored* VF models corresponding to their physical counterpart in multiple dimensions by integrating data sensed from physical reality, existed in cyber space, and generated iteratively during the co-evolution [11]. Supporting concurrent modelling and engineering in product, process, and factory domains can enable virtual prototyping (VP), which can result in minimizing physical builds and time to market [12]. VF can also support efficient design and configuration of product and production systems and VR training by precision, accuracy and reliability with its capability of integration with other engineering and execution systems [13]. Together with the integration of model data across the value chain as well as real-time operations data, DT-based VF can become a system that can adapt to changes in execution and model data in real time.

In this paper, we present a demonstration of a digital twin-based VF which employs multi-user VR learning/training and its evaluation by industry experts. We draw on prior works on the design and development of the VF concept [12], multi-user VR integration with VF [13] and DT-based VF [10]. This paper extends the prior work by Yildiz, Møller and Bilberg [10] by demonstrating and evaluating the proposed concept in two different wind turbine manufacturing cases, including a wind blade manufacturing plant and a nacelle assembly line. The Related Work section of the previous study [10] is extended with recent research works, but the majority of the section is kept as the same in this article. For more details on the DT-based VF concept definition, its simulation and data integration architectures, please refer to the referenced studies.

Following the next chapter discussing the theoretical foundations of the problem, research questions are presented.

Related Works section shows some of the main concepts and technologies concerning history and the state-of-the-art. The design science research methodology's demonstration and evaluation activities are introduced and discussed in the methodology section and followed by the DT-based VF section shortly presenting the concept and architecture. Demonstration section is followed by the Evaluation and Discussions section, which gives pieces of evidence from industry experts to evaluate the proposed concept before the Conclusion section.

2 Theoretical background

The Theory of Industrial Cycles implements principles of evolutionary biology to the lifecycles of industries and enhances our interpretation of the evolving nature of industrial dynamics determined by certain forces [14]. Competition level, innovation, regulations and demography are among some of the main forces that shape the rhythm of change in industries as well as the internal domains of manufacturing enterprises. The very nature of such evolution grounds some principles including (1) there is no permanent domination for companies; (2) the faster the rhythm of evolution, the shorter the reign of domination; (3) the ultimate core advantage for the firms; therefore, is the capability to adapt to evolving industrial environments. A remarkable aspect of the Theory of Industrial Cycles for our study is that the specific rhythm of evolution for every industry takes place in three dimensions: product, process and organization [15, 16]. Here we should note that the term “organization” is used as a highly complex system of social, natural and artificial constructs. The concurrent evolution of product, process and organization/system models, which is known as the *co-evolution paradigm*, was also examined in more recent studies [2, 17]. Tolio et al. considered VF as an essential tool to handle the co-evolution problem because of its capability for the integrated use of different methodologies by supporting integration and interoperability of various digital factory tools [3]. However, understanding the integration and interaction problems of different tools and parts in a system requires us to address some basic concepts and principles of system theory.

In this regard, System Theory (General System Theory) reveals some core concepts about the interaction of different parts by defining a system as “a whole consisting of two or more parts (1) each of which can affect the performance or properties of the whole, (2) none of which can have independent effect on the whole, and (3) no subgroup of which can have an independent effect on the whole” [18]. Therefore, the fundamental properties of a system do not come from the separate actions of its parts but from the interactions. Thus, a system is “the product of the interaction of its parts” [19] which “is more than the sum of the parts,(...) that given the

properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole” [20]. Factories as natural, social and artificial systems are embedded to larger systems such as nations and industries. Therefore, factories are highly complex systems of actively interacting problems. Furthermore, increasing complexity and dynamism leads to decreasing the predictability in the domain. As a result, simplifications for complex circumstances, which are encouraged by scientific management, increasingly start to fail [21]. Consequently, problems in complex domains must be taken apart in order to understand (analyse) them, while doing the opposite (synthesis) as a complementary activity [18, 19]. Here, we should take into consideration the latest developments in modelling and simulation technologies that enable (1) digital integration across the product and production lifecycles [22]; (2) diagnostic, predictive and prescriptive analytics [8]; and (3) integrated DT and VR capabilities [23]. Thus, the DT-based VF concept enables the potential for analysis and synthesis while redesigning a complex system, its subsystems (entity), or its environment. Therefore VF can enable an experimental mode of management which is required by a complex domain [21]. The above-mentioned concepts and theories contribute to our interpretations on “what” is the external and internal nature of the problem faced in industry, namely, handling co-evolution by concurrent engineering. Nevertheless, we need to investigate another theory for the inclusive principles and concepts that interpret “how” to design a complex system that can adapt itself to dynamically changing environments.

Competence-Based Strategic Management Concepts also known as Competence Theory incorporates the concepts and principles of Systems Theory and Complexity Theory in a more dynamic, inclusive and systemic way [24, 25] and presents more feasible and consistent organization design concepts [26]. According to Competence Theory, an organization (a firm or a complex system) is defined with its strategic goal-seeking behaviours to respond to real-life cognitive situations. So, organizations are building and leveraging their competencies by redesigning their resources, capabilities, and coordination for strategic alignment with their environments. Sanchez [26] proposed four dimensions/cornerstones, which are *dynamic*, *open*, *cognitive* and *holistic*, to achieve competence-based strategic management of organizations by competence building and leveraging. *Dynamic* representation of an organization and its environment stems from the frequent changes in market preferences, norms, constraints and infrastructure [26]. Such changes are pressuring organizations to change their competitive capabilities in order to adapt to their environments and stay competitive. Dynamic complexity of internal and external environments, however, decreases the predictability of most future changes and their implications. In order to respond effectively to needs and opportunities arising in the future, activities and resources of organizations and their

environments need to be represented dynamically. *Open systems* are characterized by the embedded nature of organizations which receive resources (skills, materials, imagination, etc.) from their environments and provide some outputs (products, semi-products, services, etc.) [26]. Therefore, conceiving a robust open system design that can access and coordinate a changing array of inputs and outputs becomes a challenge. The *cognitive* dimension of competence theory originated from the fundamental demand for sense-making in the evolving dynamism and complexity of organizations’ internal and external nature [26]. Identifying resources and capabilities for a sustainable competitive advantage requires managerial cognition. Managerial cognition, however, is becoming a growing challenge in formulating processes for organizational sense-making and for articulating new logics to improve adaptive capabilities. The *Holistic* view emerged from the need for building organizations which can function effectively in adaptive open systems [26]. Moreover, principles of systems theory about the interdependencies of parts or subsystems of a system, which determines the properties and performance of the whole, entail a holistic view.

Sanchez also identified four key strategic environments and four types of change in response to different environments [27]. Competence theory is formulated at a high level of abstractions. So, it is applicable for all kinds of organizational processes, including manufacturing systems. Nevertheless, to the best of our knowledge, there has not been any study that attempts to implement the abstractions of competence theory in a specific manufacturing system context. Therefore, the scope of the problem is to achieve the four cornerstones of the competence theory to handle the co-evolution problem by concurrent engineering in complex systems. The DT-based VF concept is designed to support building digital system models as instantiations of the concept that can achieve four dimensions of competence theory [28]. Thus, organizations can be supported during their adaptation to dynamic and complex environments by designing, analysing, synthesizing and simulating essential changes in complex systems and improve their strategic flexibility to respond to an uncertain future.

3 Research questions

Therefore, an essential premise for the arguments in this research is that DT-based VF can support competence-based strategic management of manufacturing organizations during their adaptation to dynamic and complex environments. Hence, this paper aims to evaluate DT-based VF artefacts by developing instantiations of such artefacts in actual industrial contexts. Thus, the study aims to answer the questions below by investigating a DT based VF demo in use.

- **Research question 1:** Can the DT-based VF concept achieve the four cornerstones of competence theory, particularly, a dynamic, open, cognitive, and holistic system?
- **Research question 2:** Can DT-based VF enable concurrent engineering of products, processes, and production systems?
- **Research question 3:** Can DT-based VF support manufacturing organizations in shortening product and production life cycles?
- **Research question 4:** Are VF artefacts (concept, architecture, demo) useful, effective, simple, and consistent enough to implement VF solutions in actual manufacturing scenarios?

In the interest of research rigour, we need to clarify the distinction between DT based VF concept instantiation and demonstration and how the evaluation of data contributes to the empirical and theoretical challenges addressed above. The DT-based VF concept is a generic design solution that emerged from the context-specific problem and existing constructs in the knowledge base. The DT-based VF architecture and demo are the instantiations of the concept developed for the Vestas Wind Systems A/S (later Vestas). Demonstrations represent the actual use of the instantiations and their capabilities in particular contexts. Therefore, although the evaluations of demonstrations give knowledge about the particular, such knowledge allows experts to determine the deviations when transferring the concept into different contexts.

The novelty in the capabilities of the DT-based VF concept relies on several advanced technologies besides designed artefacts. In the next chapter, therefore, we present some essential state-of-the-art technological concepts and tools and their respective history to grasp the knowledge on which we build our work.

4 Related work

4.1 Virtual factory

In 1993, the virtual manufacturing concept, which integrates product and factory models as a critical aspect of VF, was introduced by Onosato and Iwata [29]. Although there are various definitions for VF, including emulation facility, virtual organization and integrated simulation, Jain et al. [6] defined VF “as an integrated simulation model of major subsystems in a factory that considers the factory as a whole and provides an advanced decision support capability”. Lu et al. [30] proposed a virtual environment as a factory lifecycle design and evaluation based on a real-time control system. A study [31] demonstrated virtual manufacturing is a concept that consists of several different software tools and technologies, containing VR and simulation, to support product

introduction processes. Sacco, Pedrazzoli, and Terkaj [32] introduced an integrated VF framework concept to synchronize VF with a real factory. Furthermore, the multi-resolution aspect of VF models of real manufacturing systems was presented by Jain et al. [33]. VF, as a collaborative design and analysis platform for manufacturing systems, was introduced by Yang et al. [34]. Shamsuzzoha et al. [35], however, considered VF as an environment for collaboratively monitoring business processes to integrate manufacturing companies in order to achieve some business opportunities. Some basic and legacy capabilities of VF simulations are still considered highly valuable for continuous improvement of production processes [36]. Due to different purposes and functions of simulations, the existing virtual models are considered valuable for diverse goals and various level of digital maturities. Thus, there is still a need for a set of systematic modelling methods for models integration [11]. In light of recent technological developments, the VF concept has ripened into something different than an *integrated simulation model*. This has provoked a reconsideration of the VF definition. Therefore, Yildiz and Møller considered VF as “an immersive virtual environment wherein digital twins of all factory entities can be created, related, simulated, manipulated and communicate with each other in an intelligent way” [12].

While VF has been acknowledged and demonstrated for many different business and engineering needs, various technologies and their integration were considered fundamental to developing VF, including simulation, VR, and DT. In this respect, we reviewed and present some studies about DT, simulation, and VR in the next section.

4.2 Digital twin history and present

The DT concept was introduced by Grieves in 2003 during an industry presentation, and it was revisited by NASA’s space project later on [37]. The idea of DT has become more solid since the definition of DT was made in NASA’s integrated technology roadmap [38]; in fact, this led to some other notions including experimental digital twins [39] and digital twin shop-floor (DTS) [40]. Qi et al. [41] stressed that DT should not just mirror the static physical system but should also be a dynamic simulation of a physical system. This could allow virtual models to guide physical entities or systems in responding to the changes in their environment and to improve operations [42]. Moreover, interoperability and services provided by DTs enable large-scale smart applications, especially in complex systems and flexible systems. From the system-of-systems perspective, DT is also considered as core element of complex cyber-physical production systems for design, analysis and operations [43, 44]. Interaction of virtual and physical spaces and services makes data integration an inevitable trend [41]. Implementing DT technology in manufacturing has drawn more attention among scholars;

however, there is not a common understanding of DTs. Some scholars support the concept that DT should focus on simulation [45, 46], while some others argue that it should focus on three dimensions, including physical, virtual and connection [37, 47].

A categorical literature review on DT in the context of manufacturing classifies the existing studies in terms of different integrations of a digital model (DM), digital shadow (DS) and DT [48]. They define the distinction between DM, DS and DT based on the level of data integration (Fig. 1). The study concludes that the majority (55%) of the literature is about concept development and only 18% define DT with a bidirectional data transfer. Similar results were also found in another review [49], which stressed the importance of bidirectional data integration. Holler, Uebernickel and Brenner [50] also presented a literature review focusing on DT concepts in manufacturing, and one of the research directions proposed was “industry, product and stakeholder-specific DT applications”.

DT applications in industry cover several areas including product design, prognostic health management and production. Tao et al. [51] presented a comprehensive literature review about the development and applications of DTs in industry and stated the potential value of using DTs in planning, analysing, evaluating and optimizing the production systems by utilizing self-learning and self-organizing. They also addressed the scarcity of studies on interaction and collaboration for DTs, and only two papers [45, 46] were focused on the subject. Rosen et al. argues that by compiling specific simulations used during the engineering phases together with the DT models, the consistency of the operation procedures can be validated and existing know-how can be handled and used during the design, development and execution of the production system. Simulation is also considered as a proven enabler for integrating advanced technologies and the data which will assist the transformation of product and manufacturing modelling across the manufacturing lifecycles [22]. Consequently, simulation can be used for validating operational procedures in virtual space [52]. Vachálek et al. [53] demonstrated a DT of a production line that was integrated with the real production processes using a simulation model. They argued that real-time interaction between virtual and physical spaces allows DTs to respond to unexpected changes in manufacturing processes more rapidly. Moreover, the Twin-Control project [54] under

Factories of the Future (FoF) within the European Framework Programme investigated a holistic approach for developing digital systems encompassing simulation and control systems for better controlling real-life manufacturing systems.

There are various patents related to DTs which were acquired by industry player in diverse areas [55]. General Electric (GE), for example, owns four patents directly related to DT, two of which are related to wind farms [56, 57]. Another four patents related to DTs were also owned by Siemens focusing human-machine interface, DT implementation method, collision detection and asset maintenance in energy-efficient way [51]. A systematic method is also invented in order to create the DT of a room by Johnson [58].

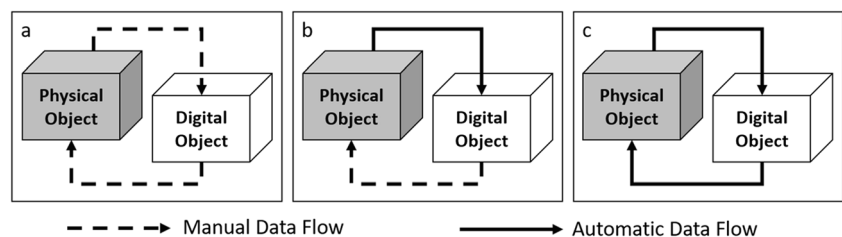
Weyer et al. [45] predicted that the next generation of simulations will be represented by DTs by which complex production processes can be monitored, optimized and quickly adjusted. Moreover, recent developments in simulation tools promise more efficient and effective methods to handle DT development considerations in a variety of industrial cases [59]. Ding et al. [60] presented a smart manufacturing shop floor, and they address the challenges for improving the fidelity of DT simulations and handling the complexity aspects of such simulations.

In this respect, VR stands out as an excellent user interface that provides more advanced interactions with such complex virtual manufacturing models. Furthermore, Mourtzis, Doukas and Bernidaki [61] conducted an investigation of simulation technologies in industry and stated that there is a gap in the use of computer-aided manufacturing systems and VR for collaboration and communication. Therefore, we will briefly review VR technology in the next section.

4.3 Multi-user VR

Since 1965, Sutherland envisioned “The Ultimate Display”, which is “a room within which the computer can control the existence of matter” [62]; it took a couple of decades to see VR technology in industry and academia [63]. After the mid-1990s, the VR knowledge base has been exploited by investigations in both industrial and academic communities. Since then, VR has been adopted for various purposes such as concept design, development and evaluation [64], training and learning [65, 66], virtual building prototyping [67] and visualizing abstract data [68]. VR is also a technology contributing

Fig. 1 a Digital model (DM). b Digital shadow (DS). c Digital twin (DT) [48]



to manufacturing simulation and modelling, especially to overcome complexity by providing advanced user interfaces [69]. Moreover, introducing immersive and interactive VR into manufacturing increases the efficiency and precision in terms of layout design, ergonomics and product and process optimisations [70]. A survey conducted by Berg and Vance with 18 engineering-focused companies shows the strategic importance of VR and a number of challenges, including a lack of environmental simulations that support understanding the interactions between virtual objects [71].

A recent comprehensive survey [72] states that 3D/VR simulations offer higher performance in model development and have rapidly become a common modelling methodology. Moreover, the study reveals that 3D/VR provides faster results in terms of verification, validation, experimentation and analysis but requires a longer model development time. Furthermore, 93% of developers and decision-makers acknowledge that 3D/VR is more effective than 2D simulations in terms of communicating to decision-makers. Another recent work also addressed synchronization between VF simulations and MES shows that access to real-time production data improves efficiency during the development of multi-user VR simulations for complex manufacturing scenarios [13].

The above mentioned scholarly works show the standalone values of M&S, DT, and VR technologies in designing evaluating, optimizing, validating and training for complex manufacturing operations. However, the gap in terms of technology and model integration and bidirectional data integration between digital and physical platforms as well as collaborative interaction with the models remain the main challenges for real-life engineering processes. Therefore, DT-based VF enhanced with multi-user VR promise opportunities to create a virtual twin of an entire factory floor which can be accessed by anyone, from anywhere, at any time. Moreover, the novelty of this study lies in the integration of the existing state-of-the-art technologies into a new solution for actual industrial challenges. Thus, the potential industrial value can emerge by utilizing available commercial tools and technologies without significant time, cost and advanced knowledge. In this regard, the methodology and objectives of DT-based VF demonstration and evaluation are discussed in the next section.

5 Methodology

5.1 Design science research

The demonstrated artefacts of this research integrate various concepts, technologies, data structures and systems of a manufacturing enterprise. Thus, an emerging challenge is that the IS which we investigate is not just a social system or a

technological system, but the phenomenon that emerges when the two interact. Therefore, the theory to understand the phenomenon links the natural world, the social world, and the artificial world built by a human [73]. Hence, the body of knowledge capitalizes on natural science, social science and which has been called “design science” [74]. Herbert Simon distinguishes between natural science and design science (the science of artificial) which can take form in constructs, methods, models and theories that match up with sets of functional requirements [75]. Therefore, design science in IS examines the creation of innovations or artefacts required to perform the design, investigation, implementation and use of IS. This research is performed on the trail of the frameworks, methods and guidelines introduced for design science research (DSR) in IS [76–78]. The article on hand covers the demonstration and evaluation activities of the six DSR methodology activities which are (1) problem identification, (2) objectives of the artefact, (3) design and development of the artefact, (4) demonstration, (5) evaluation and (6) dissemination [76].

5.2 Demonstration

Contrary to traditional experimental research approaches, DT-based VF research aims to discover the effects of interventions in a complex organization. Therefore, the generalization of the discovered knowledge in DSR demonstration and evaluation is different from conventional explanatory research where general design is discovered from data in a well-defined random sample which is similar to the whole population. Nevertheless, a generic design in DSR can be made and tested in a certain context, and it should be able to transfer into different contexts (within a certain application domain) without losing its necessary effectiveness [79]. The artefacts’ demonstration involves various activities such as experimentation, case study, simulation or proof, to solve one or more instances of the addressed problems. Thus, demonstration activity depends on knowledge that defines how to use artefacts effectively in specific contexts.

Although wind blade (large size fibreglass composite material production) and nacelle (complex and heavy parts assembly) manufacturing plants of Vestas provide unique cases, these manufacturing cases also provide highly common characteristics with other industries such as automotive, shipbuilding, and aviation. Moreover, a wind turbine manufacturing company like Vestas allows industry experts with highly diverse knowledge in different manufacturing areas to evaluate the DT-based VF demonstration. Therefore, although testing DT based VF in these two cases provides knowledge about the particular, this knowledge allows the evaluation of deviations that are unique to each context. Furthermore, it also provides general “user instructions” depending on the context which can be sufficient for experienced professionals [79].

5.3 Evaluation

Design science intends to explore the practical usefulness of a treatment in order to deal with the theory-practice gap [79]. Therefore, we aim to discover the knowledge that can be used in an instrumental way by solving practical issues with pragmatic methods of designing and implementing systems, processes or actions. In other words, DSR concentrates on practical relevance and pragmatic validity of a generic design [79]. Accordingly, the justification of designed artefact (DT-based VF concept, architecture, demo) does not concern the truth but usefulness, effectiveness, simplicity, utility, consistency and novelty [75]. Therefore, after the presentation of the DT-based VF concept and a live demonstration, evaluation activity covered three stages including (1) an open conversational interview, (2) a semi-structured conversational interview and (3) a survey. In this regard, we discuss the conversational interview method in the next section.

5.4 Conversational interviews

Conversational interviews and a survey were initially planned as a physical meeting in a VR room to allow experts to experience a DT based VF demo via VR simulations first-hand. However, due to the COVID-19 pandemic, demonstration and evaluation were performed in an online meeting. Interviewees were designated among a particular group of engineers, specialists and senior managers who have been actively involved in product and production lifecycle processes. The number of interviewees was to be limited to highly expert specialists to gain more valuable knowledge with more prolonged and intensive interviews with more penetrating interpretations. The combination of available time and resources was another reason to limit the number of interviewees. After each interview, the experts were asked for their comments on the interview methods and questions and to give advice for an expert interview. Therefore, the questions and the number of interviewees were extended slightly during the evaluation process.

The guidelines provided by Kvale [80] for designing interviews were followed during the design of the conversational interview. Since the interviewer is the primary research instrument to obtain knowledge, this makes the quality of knowledge dependent on his/her experience, empathy and craftsmanship. Therefore, the interviewer obtained certified online training by MITx [81]. It is believed that this training contributes to decreasing the context-sensitivity and effects of the interrelationship between interviewee and interviewer on the knowledge gained. The purpose of the interview was to obtain data (1) to evaluate DT-based VF artefacts (Concept/Architecture/Demo) in scale of solving the problems defined by application domain with well-grounded evidence and arguments and (2) to evaluate the DT-based VF concept in the context of the four concepts of competence theory, namely,

dynamic, open, cognitive and wholistic system, by exploring industry experts' perspectives and interpretations.

The interviewer aimed to explore the potential impact of the DT-based VF concept in different domains of manufacturing as unknown territory roaming freely as intertwined phases of knowledge construction. This was because the field of product and production lifecycle processes covers a broad area, and the interviewees had diverse backgrounds and experiences. The evaluations by the interviewees critically examined the empirical value of DT-based VF by the conversational, narrative, and inter-relational nature of knowledge to gain specific grounded and precise shreds of evidence and examples. In other words, the interviewer is intent upon instigating a process of reflection that leads to new ways of understanding the proposed artefacts as well as uncovering previously taken for granted values and knowledge in the knowledge base.

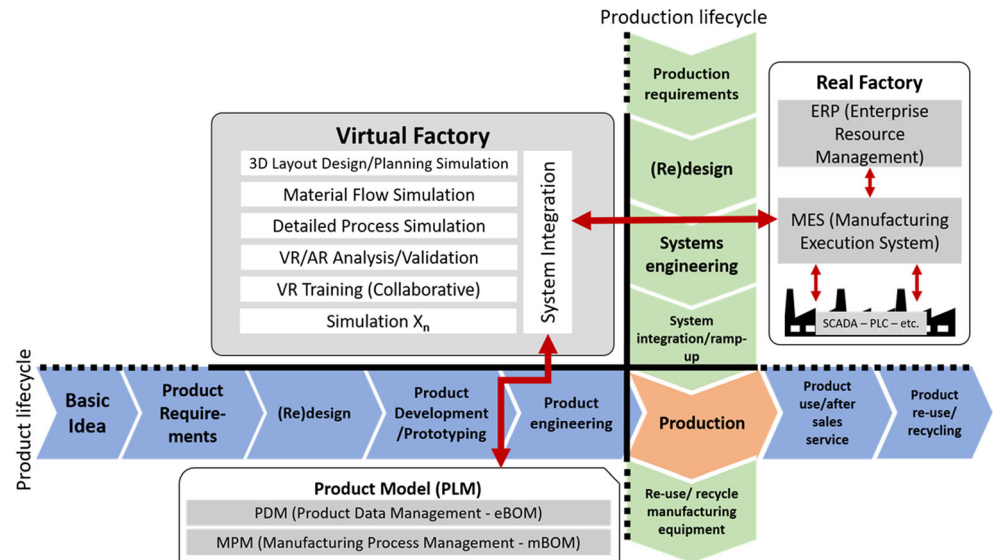
Before presenting the demonstration and evaluation results, the DT-based VF concept is shortly presented and discussed in the next section.

6 Digital twin-based virtual factory

6.1 Concept

The VF concept proposed by Yildiz and Møller [12] is extended with DT and multi-user VR capabilities [10]. The proposed concept in Fig. 2 stands out for its distinction of product, system (factory) and process domains. Such segregation enhances the perception of the link between process, system and product models. Moreover, the concept intends to demonstrate the VF simulations as a virtual environment where production and product lifecycle processes can have a rendezvous. Such a rendezvous is considered to be an enabler for concurrent engineering of product, process and production system models. The initial concept [12] is extended with automated real-time bidirectional data integration and multi-user VR capabilities. Such extensions enable the development of DTs in VF simulations as well as collaborative design, development, validation and training/learning functions. Thus, DTs of factory entities in terms of physical objects, systems and processes can be created, related, simulated and manipulated in the VF simulations, and the determined parameters can be sent back to shop floor via MES layer. As a result, DT-based VF simulations can decrease complexity while increasing flexibility, accuracy and reliability. Real-time data integration between physical systems and engineering platforms enables DT-based VF to represent changes in a product and a real factory simultaneously in VF simulations. Tests performed during the DT-based VF demo development, for example, a 3D discrete event simulation (DES) of a particular production line that produces a certain product model, did not run due to a pause for the production of such a product in the line.

Fig. 2 DT-based VF Concept as a rendezvous between product and production lifecycle (adopted from [10])



Accordingly, DT-based VF enables an open system that can be embedded in other systems by creating new connections with its evolving habitat.

Dynamic representations of product, process and manufacturing systems in 3D DES decrease the cognitive load both vertically and horizontally for diverse experts. Integration of different simulations enables co-simulation of complex systems in different resolutions and more holistically.

6.2 Architecture

Figure 3 shows the data integration architecture between system, product and process models which are represented as a real factory (via MES), product lifecycle management (PLM)

and VF, respectively. Data utilized by VF, as common shared factory data, can be grouped into two categories: (1) actual product, process and system data imported from actual engineering and execution systems and (2) data created by VF simulations. Data imported by engineering and execution systems can only be imported into simulations and manipulated but cannot be changed. Simulation results, however, can be consumed by simulations multiple times and be sent back to PDM or MES platforms. Such integration of data can facilitate increased efficiency and effectiveness for multidisciplinary design, analysis and validation.

Data synchronization architecture between MES, PLM and VF extended with multi-user VR simulation is shown in Fig. 4. Therefore, DT-based VF simulations enable the interaction and

Fig. 3 DT-based VF Architecture (adopted from [10])

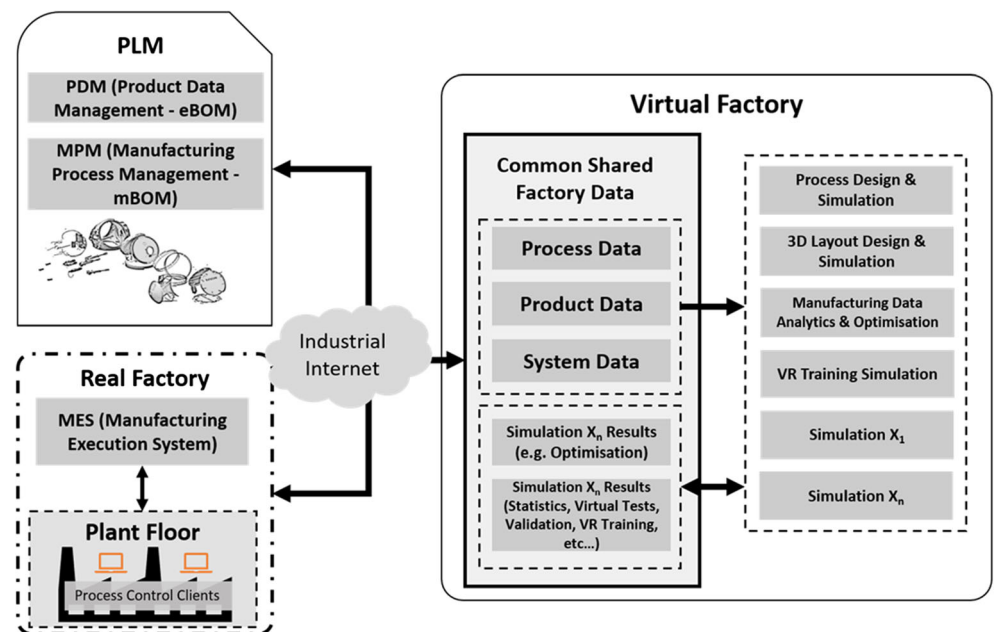
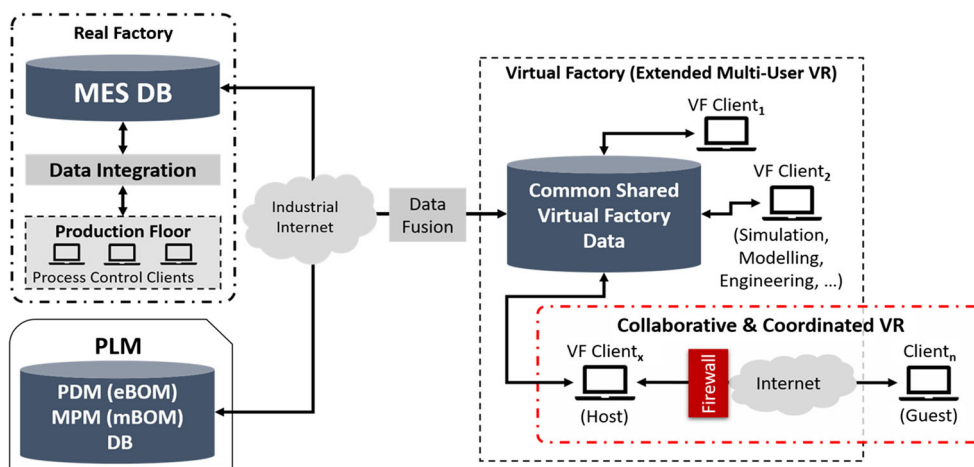


Fig. 4 Data synchronization architecture of DT-based VF extended with multi-user VR (adopted from [10])



training with DTs in immersive VR environments. Due to a potential conflict of interest, the detailed elements of the synchronization architecture are not disclosed. Multi-user VR simulation is developed with the Unity™ development platform with Photon Unity Networking packages. This method allowed guest connections to DT-based VF simulations via the Internet, which enables collaboration in a virtual environment without physical boundaries.

7 Demonstration

Since the DT-based VF concept can be implemented with a high variety of simulation tools, functions and capabilities, a short presentation of the concept and artefacts is performed to give the interviewee an understanding of the DT-based VF vision. A DT-based VF demonstration video is shown after the presentation. We strongly recommend the readers of this article to access the simplified demonstration media in the reference to discover the work performed with rich visual data [82]. The media file, which is publicly shared, does not cover, unfortunately, the demonstration of nacelle production due to the non-disclosure agreement between the stakeholders of this study.

Figure 5 shows the collaborative and coordinated manufacturing scenario, which is adopted from real manual assembly tasks performed by two VR users. During the multi-user VR training, the remaining time data, which represents the actual time of the previous operation, is shown on the wall. That allowed the trainees to know if they caused a block or hunger in the production line. Moreover, the concept of developing DTs in collaborative VR simulations is validated. After the multi-user VR training was performed, the performance data (duration of completing the task) is exported to a local SQL database. 3D DES of the whole factory is developed in the FlexSim™ simulation tool due to its easy drag-drop user interface as well as the embedded VR function. The latest operation time data for each operation in the factory is imported from MES except for two operations which are simulated in the multi-user VR simulation. Collaborative VR training performance data is used for respective operations in the factory simulation. This enabled analysing the effect of collaborative trainee performance on the production line level automatically. Line simulation which represented twins of the most operations was also manipulated by embedding a mixed production VR learning scenario. A VR user followed a training scenario for product grouping based on their colours

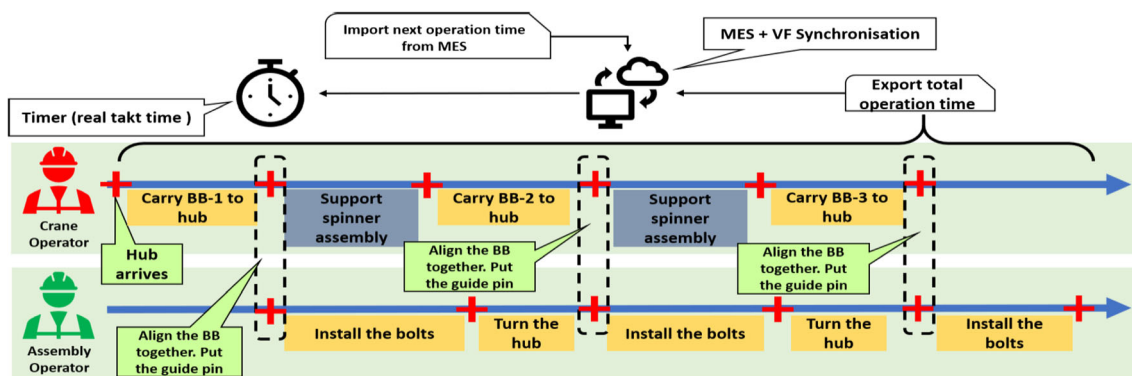


Fig. 5 Collaborative and coordinated VR training scenario (adopted from [10])

and performed a crane operation to more semi-product to next operations. The performance of VR trainees as well as their learning curve was observed and analysed in real time. VR trainees learning performance and its effect to assembly line were exported automatically when the simulation ends. Except manipulations like mutli-user VR training and mixed production VR training, all operations of the hub assembly line represented the real production and product data, including the layout, product CADs as well as simplified process models. Basic manufacturing data analytics were performed while the line simulation was running. Moreover, layout changes were performed during the simulation is running, and the real-time effects of such changes were observed. When the discrete event simulation is ended by the user, some main operations data were extracted to a local VF SQL DB. It was ensured that the simulation results were automatically be imported by the MES solution of the case company.

Demonstration of the DT-based VF is followed by the evaluation activity covering the conversational interview and a short survey. The results of the industry expert's evaluation are presented in the next section.

8 Evaluation and discussions

Thirteen industry experts from Vestas participated in the DT-based VF demonstration, and they were interviewed afterwards for the evaluation. Please refer to the appendix for more information about the interviewee's department, responsibilities, etc. with concealed personal data. Comments from the interviewees are referenced to the respective interviewee number in the appendix. Interviewee number 3, for example, is referenced as (Int. 3). The evaluation process includes a semi-structured interview, a structured interview and an online survey. The evaluation took 93 min per interviewee on average. Interviewees were chosen from vertically diverse positions including a production worker, senior vice president, production engineer, senior specialist and senior manager. The average years of experience of participants was 11 years and ranged from a minimum of 3 years to a maximum of 30 years. Interviewees' responsibilities cover a broad spectrum of tasks such as optimizing a production line, regional production engineering, technical support, quality, building factories, digitalisation and concept selection. Industry experts were selected by taking into consideration their roles in new product introduction (NPI) processes in order to cover major and critical processes of NPI. The reason for focusing NPI processes was apparent, because it is the primary domain implementing changes to both product and production lifecycle processes. Figure 6 shows digital tools that the interviewees worked with directly or indirectly while they are performing their tasks.

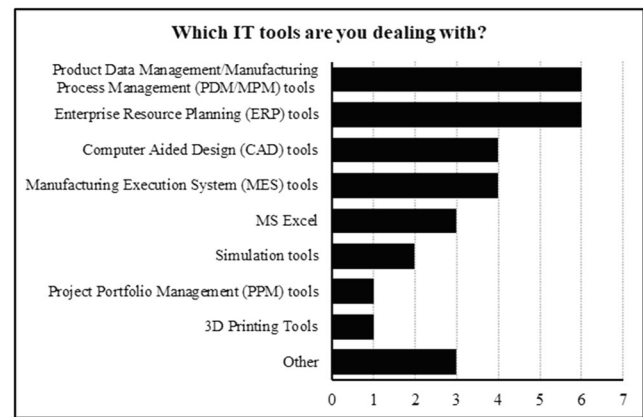


Fig. 6 Familiarity with IT tools

Only two out of the 13 experts stated that they are using simulation tools while they are performing their tasks. Table 1 presents a summary of the discussions to provide a fast glance. The questions in Table 1 were not asked as a direct question but analysed based on experts' interpretations or asked for validation at the end of the discussion.

In the next section, we present the challenges addressed by experts in the context of the evaluation and digitalisation of their tasks. Following the challenges, the evaluation data as a response to the Research Question 1 is presented in (1) Dynamic Representation, (2) Open System, (3) Cognitive System and (4) Holistic System sections. The Concurrent Engineering section provides the arguments to respond Research Question 2. The Time Saving, Virtual Prototyping, and Collaborative VR sections show the discussions as a response to Research Question 3. Lastly, the DT-based VF Artefacts sections introduce the survey results as a response to Research Question 4.

8.1 Challenges

Although the challenges addressed by the experts differ based on their tasks and responsibilities, it is possible to observe similar patterns of adaptation to the new conditions by handling concurrent changes in product, process, and system domains caused by changing demands, increasing complexity and shortening lifecycles. Due to the increasing size of products in an increasing frequency, space constraints and optimisation of shop floor space were among the challenges mentioned by experts who are working close to the shop floor. The major challenges addressed were the complexity and the lack of a dynamic representation of product, system (layout) or process models in PLM and ERP systems, as well as the lack of a capability to test what-if scenarios of the future by using MES, which is known as *decision myopia*. The lack of dynamic model representation and the capability to test what-if scenarios with legacy engineering tools is argued by saying "I

Table 1 Interview results summary

<i>Do you see VF as a dynamic system?</i>	Yes	Yes	Definitely	Definitely	Yes	Definitely	Yes	Definitely	Yes	Yes	Definitely	Yes	Yes
<i>Do you see VF as an open system?</i>	Yes	Yes	Yes	Definitely	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Is VF a cognitive (sense making) system?</i>	Yes	Yes	Yes	For VF user-yes / for VF developer-not sure	Yes	For VF user-yes, for VF developer not sure	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Is VF a holistic system?</i>	Yes	Yes	Not sure	Definitely	Yes	Yes	Yes	Yes	Absolutely	Yes	Yes	Yes	Yes
<i>Can VF help save time during new product introduction (NPI)?</i>	Yes	Yes	Absolutely	Definitely	Yes	Yes	Yes	Yes	Absolutely	Yes	Yes	Yes	Yes
<i>Can VF support concurrent engineering?</i>	Not sure	Yes	Yes	Yes	Yes	Definitely	Yes	Yes	Exactly	Yes	Yes	Yes	Yes
<i>Can VF enable virtual prototyping?</i>	Yes	Not sure	Yes	Some of it, definitely	Not sure	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Can virtual prototyping in VF help decrease physical builds?</i>	Yes	Yes	Yes	For big changes in product-yes/ for small changes no	Not sure	Yes	Yes	Yes	Yes	Probably	Yes	Yes	Yes

can see how the system will look like with the current tools, but I cannot see how it will work” (Int. 2). The missing link between digital models and physical models are addressed as a challenge “since there are ad-hoc minor improvements as a result of continuous improvement on the line” (Int. 7). Concept selection experts who are dealing with the challenge of translating the design requirements, design concepts and ideas into consequences for manufacturing in terms of processes, lead times, manning, tools, layout, etc. stressed the lack of interoperability between different systems. They stated that “There are a lot of errors through various information translation steps from different systems and mindsets. And, that information is given further down to the value chain and probably not updated in the system. So, that information is decoupled from a lot of other information when it gets to the next level” (Int. 4).

The above mentioned, relatively technical challenges were emphasized in a broader sense by the senior project management level: “Products are changing more often. Consequently, we are constantly changing the production layout, but we are not adapting the way we produce to the development of the products. There are a lot of IT tools for handling products, items, and materials but not a lot of tools for layouts and processes (factories)” (Int. 11). As a result of this, “Time to market is a constant challenge. Collaboration aspects across the full value chain, which could be design for manufacturing, design for service or design for transport, need to be considered in very early phases. Otherwise, we see huge challenges later on in the projects that need to be managed” (Int. 10). The scope of the difficulties in the industry is well summarized by the vice president level; “The challenge is our agility in terms of adapting to changing environments and securing that adaptation fast enough to maintain our competitiveness in the market” (Int. 13). Instigation to discover experts’ reflections on challenges they are facing naturally leads to their interpretations on how the DT-based VF concept could support manufacturing operations to deal with such challenges. Most of the experts addressed the advantage of dynamic model representation of DT-based VF simulations as the initial benefit.

8.2 Dynamic representation

Dynamic model representation of VF simulations is considered as “exactly the strength that we can use data to simulate and manipulate the future” (Int. 13). Some experts acknowledged the dynamism as an enabler to see more details in terms of the interaction of materials and tools with processes. Moreover, the ability to analyse constraints, capacities and collisions which cannot be analysed in PDM solutions is an advantage. Static process models are not suitable for drawing each process step in a detailed way. “That is why until you test it (process model), you do not know if there are going to be any problems. I believe VF can show such errors in advance” (Int. 2). Using 3D VF simulations for the design for manufacturability in very early stages is addressed as highly beneficial (Int. 3). Some (Int. 5) considered the dynamism as the synchronization between live production data and simulation rather than 3D animations in DES; while another expert (Int. 7) considered using existing production data as a prerequisite for dynamism. The comparison between VF and legacy engineering platforms can be summarized as “PDM and MPM are more static programs. They do not have the time factor. Then the MES and ERP systems do not have the design data.” (Int. 9). As a result, experts stressed the importance of the realistic results “to measure how efficient the future model will be” (Int. 7) by manipulating complex simulation models for testing assumptions. Therefore, dynamic model representation stands out as a valuable capability when it is synchronized with actual engineering and execution data. Thus, “we can actually use VF as sort of seeing the future, looking at bottlenecks, constraints, and resource planning, because I cannot do that with PDM” (Int. 8). Such synchronization requires openness to establish flexible connections with other systems. Therefore, arguments for DT-based VF as an open system are shortly presented in the next section.

8.3 Open system

The openness of DT-based VF for integration with actual engineering and execution systems is argued as the main desire for updating parameters based on reality to increase

accuracy and trust to DT-based VF models as well as saving time (Int. 7, Int. 8). The significance of openness for new integrations has become apparent, especially during NPI processes. Lack of qualified data from the beginning and continuous change of data during the progress are central considerations for this capability. Being “open” to set up new connections with other systems while the dynamic complexity of the environment is evolving does not just save time, it enables “actually simulating the real world not just numbers that you put in. I think that is extremely important” (Int. 11). Openness to integration can provide value in capturing requirements early and in design phases “that we can simulate all our decisions across the value chain as we make the decisions. Because that is really what will create the benefit for us and monetarily reduce our time to market” (Int. 13).

8.4 Cognitive system

Visual capabilities of VF simulations and dynamic 3D models together with VR have been stated as the primary contributors to sense-making and increased visual data for communication. When it comes to the “sense-making” aspect of the VF models, all experts agreed to the ease of judgement in the first glance as a user; however, a few argued that it could be highly difficult to understand the calculations behind the DT based VF models. Experts in the concept selection department argued that “It is a new type of skill set that is needed compared to what we are doing today” (Int. 5). Accordingly, they state the strategic importance of the new competencies by saying; “it is very important that you do not end up having like a task force with ten people or this one guy as the only one who understands what is going on” (Int. 4).

The difference between VF models and legacy engineering platforms in terms of communication and sense-making was also argued. “The tools that we are using today to develop a new production facility get so specialised that you are actually not able to present it very well. Virtual Factory represents a huge amount of communication (data)” (Int. 11) “PDM and MES just show data and things have been done. But in VF, I can see why this is like this. Why is this happening? What was the problem?” (Int. 1). Collaborative VR capability is considered to be highly useful for learning, training analyses, verification and validation or for finding errors and problems. Utilizing the DT-based VF for knowledge dissemination during the global expansion of production is also addressed “A lot of our Russian colleagues were not able to travel to Denmark to understand and see how we should assemble the turbine. If I could do that upfront by showing them at least virtual reality, then the understanding and the preparation of these new operators who have not seen a turbine before will definitely be much better” (Int. 6).

How to achieve a cognitive representation of highly complex and dynamic engineering models seemed “a core

question because there is a tipping point between showing off and facilitating an innovative thought process. VF is definitely something that helps on the creative part of the way things can be illustrated and simulated, but we should also make sure that it does not become a show of (virtual) reality that we will never materialise” (Int. 13).

8.5 Holistic system

The benefits of a holistic system approach seemed quite obvious to the experts from the shop floor since they stated, “we can optimise the line better when we get information about the other related systems (material handling, maintenance, etcetera)” (Int. 2). Production engineers gave several historical examples that they faced due to lack of a holistic view. A holistic view is essential to analyse the impact of a change to “understand how everything works together. In current systems, if I change something, it can be quite hard to understand what effect it has. And remember, small changes in one place can affect a lot of other places as well” (Int. 6). Moreover, DT-based VF is also considered to be a better solution to analyse and understand a system than the current engineering platforms for a specific factory that will shift to a mixed production soon (Int. 9). The potential role of VF among the legacy engineering tools is summarized in the following statement. “These tools (PDM, PLM) are product related. They do not have other data. If you are doing a change in a PDM link, you do not see the consequences on the production line. MES also does not have the product data. We need more integration between our legacy engineering systems. I think VF can support this integration. We can create simulations for each factory, and it could help determine which factory is the most suitable factory for producing that specific product. It can also get data from shipping and be extended to higher-level supply chain simulation” (Int. 9).

A senior manager considered “the holistic understanding of how a certain idea or design impacts the value chain is the big benefit” (Int. 13). He also stressed that assumptions are good at a detailed level, but integrating assumptions and organizational knowledge into a model and simulating it repetitively is a real advantage (Int. 13).

8.6 Concurrent engineering

A majority of the experts agreed that DT based VF could support concurrent engineering by enabling independent teams to access and work with the same integrated simulation models. Some stated that it could support not just manufacturing operations inside the organization, but it can also support engineering tasks coordinated with suppliers as well as alignments with customers. Some experts also stressed the increasing importance of concurrent engineering with collaborative VR due to the COVID-19 pandemic. A senior manager

stressed the limited engagement across the value chain with the design and requirements gathering process. The capability of visualizing the impacts of a design decision across the value chain considered that “it makes it much easier for the entire value chain in a company like Vestas to engage themselves into the design process” (Int. 13). “As soon as we start to have a blade shape, we actually understand the effect across the value chain. In one simulation, for example, we would actually be able to simulate the whole transportation route through the strategic markets for which the product is designed. And by that, we will engage in those discussions much earlier than we have ever done before, and we do not need to have the discussion just before it hits the market” (Int. 13).

8.7 Time-saving

All interviewed experts considered that DT-based VF can save time during the introduction of a new product to market. Shop floor engineers considered DT-based VF simulations to be a more practical engineering tool to integrate 3D factory and product models while simulating the processes for analysing, validating and optimizing. Project managers addressed the value on risk aversion, increased readiness for operations execution and organizational alignment.

A regional production engineer addressed the problems that they were facing during the introduction of a new windmill blade mould and stressed that many of those problems would not be faced if they had VF models. “Last week, for example, we moved a crane and found that there is an issue in the layout. Now we have to wait four weeks to change it again” (Int. 7). An expert from the project management office listed some time-saving scenarios for having a full-scale DT based VF solution: “1) We are spending a lot of time on building some early representations. A business case for a VF would be very helpful in removing some of those early builds. This would have a huge impact on the timeline and reduce time to market. 2) If the VF replaced or removed one or two design prototypes or the mock-up builds in blades, that would significantly reduce the time to market. It would also have a huge cost reduction impact. 3) In a technology transfer project, if we could have the VF for every single factory that we have around the world, then we could do virtual factory tours without sending a lot of people to these actual factories and spending many days on that. 4) We have many iterations in the projects that look into the layout and the flow, and these are constantly being revised. VF could remove some of those iterations as well” (Int. 10).

Senior managers consider that it is a capability of integrated simulation to enable parallel work for different operations in product and production lifecycles. It is also stressed that the gains of DT-based VF in terms of time to market can be extended with the simulations of other parts of “the value chain from supply chain to manufacturing to transport to

construction on site” (Int. 13). Thus, “whenever we have done with the design (of a product), we can have the full knowledge about what the impact will be and how we can use that knowledge across the design process to make the right decisions in a timely manner. If we can gather all that knowledge and have those sprints in the design phase, then we are actually ready when the design is done instead of having a design done and then making ourselves ready, as we do today” (Int. 13).

8.8 Virtual prototyping

Before presenting the discussions on VP by utilizing a DT-based VF solution, we should note that there are mainly three types of prototypes performed at Vestas. These are design, process and 0-series prototypes. While design prototypes focus on capturing design requirements and finalizing the bill of materials, process prototypes focus on capturing assembly processes. 0-series prototypes focus on capturing serial production requirements.

Although the majority of experts agreed that DT-based VF could enable VP, some stressed that there will always be a lack of trust for the virtual models. A few also stated that some prototypes are needed for physical material tests or to verify physical material quality supplied by a supplier. It is considered that simulation of new products in DT based VF utilizing actual production data can save time and cost by capturing conflicts and bottlenecks in advance. Some also considered that DT based VF can enable VP of new products by extending the production line models with toll usage, material handling, and warehouse models. “Today, we have virtual design prototypes where we are sure that parts do not collide. We also have an idea on the assembly sequences, but it does not include the factory environment and tools. Including the factory would be the correct approach” (Int. 6). Some considered that VP can support investment decisions by ensuring the capacity and unveiling the bottlenecks in early phases, while some address that it can reduce the number of early builds and accelerate the ramp-up.

Some experts argued that decreasing physical builds requires highly detailed simulation models and a high level of trust for such models. A few experts argued that similar trust problems were faced with CATIA composite modelling, but increasing familiarity with the virtual engineering models in time resulted in decreasing physical builds. Therefore, DT based VF tools can gain trust by increasing expertise and familiarity in time and, “when we start seeing trust for them (VF Simulations), the impact will be reducing the physical builds” (Int. 13). A few stated that decreasing physical builds with VP is more useful when there is a significant change in the product introduction processes due to more unpredictable scenarios that could be analysed in VF simulations. However, most of the experts agreed that the DT-based VF solution would support decreasing physical builds. “We have around

700 findings (during prototyping) where we need to change something when we do the assembly. We have some risks, errors, and some corrections; others are mainly improvements. By reducing these numbers using VF, we can decrease physical builds” (Int. 6). Some experts considered process prototypes and 0-series prototypes to be more suitable for decreasing physical builds by VP due to the more mature design of a product. Nevertheless, some others state that VP with DT based VF can be more useful in decreasing early design prototypes. “In some projects, because there are so many changes and so many things discovered through the design prototype, we end up building many more design prototypes. Some of those changes or errors or validations could be done in the VR environment of a VF” (Int. 10). Some assumptions were made by experts for gains in VP in VF too. “We are building six nacelles before we are going for a process prototype and most of them are built to be sure about the design. With VF, maybe we should be building four instead of six. But for sure, there are 20 0-series productions and maybe that number could be, let us say, 10 or 5. So, I think we can go straight to running production instead of using a (long) time for 0-series production” (Int. 1). “We can really earn some money by decreasing the number of errors caused by developing the wrong tools. We spend at least half of the time to develop new tools and for modifications. These delays could often be a week or two; the worst case is months of delay and hundreds of different problems that we are mitigating during the introduction of a new product. For X converter, we found around 200 errors, and I would guess that we could have spotted 15 to 20% of those earlier by having a (VF) simulation” (Int. 11).

8.9 Collaborative VR

Experts were provoked to discuss and explore potential use cases for utilizing multi-user VR capability. Although a few experts stated that there is some training which may require a physical training environment, all agreed on the importance of virtual collaboration and stressed the increase in the emergence of such technology due to Covid-19. The statement explains the effect of shortening manufacturing lifecycles on training as follows. “Training is getting increasingly difficult because we are ramping-up so many factories at the same time. A couple of years ago, we were first building (a new line) in X factory and people from other factories were travelling for learning before they ramped-up in other factories. But now, we need to ramp-up as fast as possible and do full production. At the same time, we may be rolling it out to a number of factories around the world. They cannot just travel out to three different sites at the same time to do training. And, there is also Covid-19. So, there are many challenges to the whole concept of conventional training” (Int. 10). Wind blade manufacturing, which typically relies on the craftsmanship of workers, seems to be a promising high-value case for VR

training. “When we built the blade for the first time, we really needed good blade builders (craftsmanship). If we could have two week virtual training sessions that would allow them not to be completely green once they hit the shell moulds. It would be absolutely perfect. I know it is going to be virtual, but they are going to have a basic understanding of what they need to do and how they need to do it. I think that would be super beneficial. It does not have to be the most difficult part, just a basic understanding which prevents us from having a lot of mistakes” (Int. 8).

Besides the apparent cases promising value for collaborative VR such as remote support and training, other cases like training design and evaluating various standard work setups were also proposed as a beneficial. Recording best practices in a collaborative VR for designing training instead of a predefined standard work instruction stands as a promising idea. Using VR for training/learning is also considered as standing out with a decrease in the cognitive load compared to 2D documents. VR training technology is also considered to be a “competitive advantage in the workforce market” (Int. 7) by motivating a younger generation of workers.

8.10 DT-based VF Artefacts

Figure 7 shows the results of the survey, which was conducted for the evaluation of DT-based VF artefacts, including concept and architecture. The DT-based VF concept is ranked relatively high in terms of utility, simplicity, consistency, novelty and handling complexity. When it comes to effectiveness, reliability, and ease of use, however, it is ranked lower. Experts stated that, although the high level of concept design increases the consistency of DT-based VF implementation into different contexts, it also decreases the ease of use and effectiveness. Because the DT-based VF integrates a number of technologies, systems and data across the value chain, the reliability is stated as dependent on IT infrastructure and the data quality of the organization implementing the concept.

8.11 Discussions and limitations

This research work achieved (1) demonstrating the DT-based VF concept and demo, (2) evaluating the DT based VF artefacts and demo, and (3) exploring the potential implications of the concept in wind blade and nacelle manufacturing cases. Nevertheless, a design science approach in complex and dynamic organizations which contain human factors has the possibility to lead to internal validity confusion [83]. Due to difficulties in isolating highly complex environments and a large number of interdependent variables consisted in such environments, it was not possible for us to design an experimental or quasi-experimental research approach for such an evaluation. It must be kept in mind that the work presented in this article covers the second half of a comprehensive research project

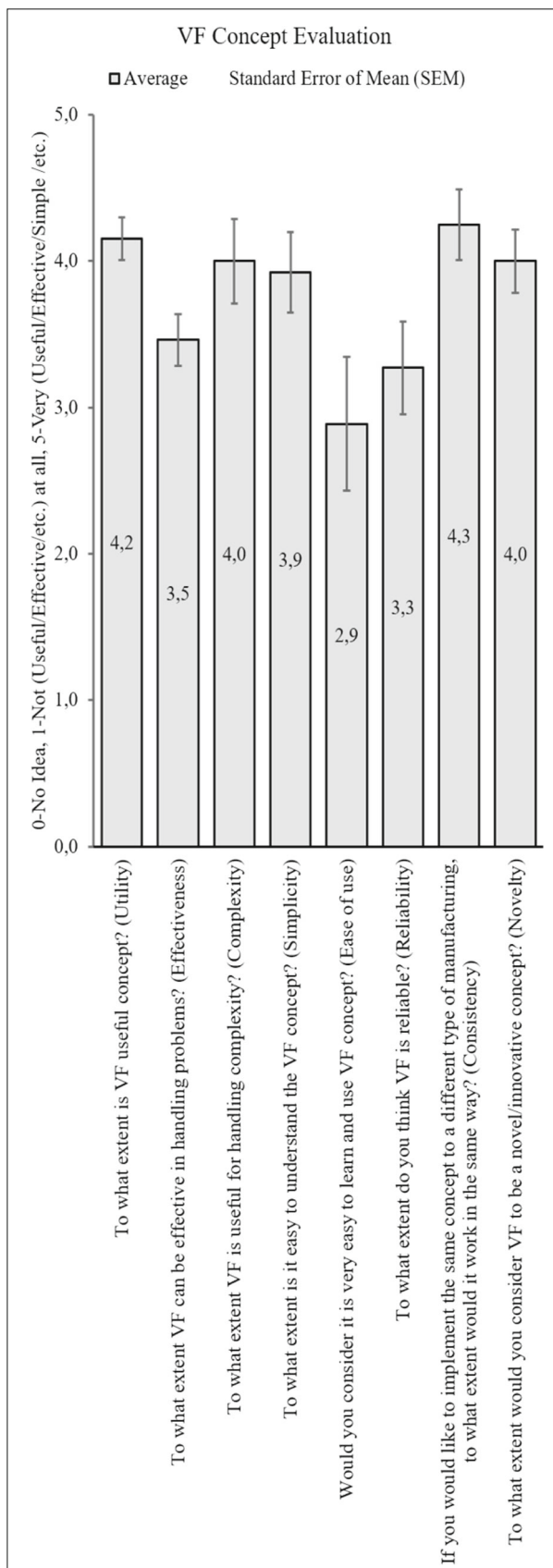


Fig. 7 VF artefacts evaluation

[12]. The gap between the claim of the subject research, which is the design and development of DT based VF artefacts, and implementation and evaluation presented in this article is covered in previous studies.

It is believed that the evaluation of industry experts and arguments provides valuable data to answer previously addressed research questions. DT-based VF is considered to be a dynamic, open, cognitive and holistic solution by industry experts. Experts' discussions, arguments and pieces of evidence about how DT-based VF can support saving time, concurrent engineering and VP were also presented. Potential use cases for utilizing collaborative VR in the manufacturing industry were explored and presented. The artefacts were evaluated as useful, effective, simple and consistent to implement a DT-based VF solution. Although there can be various simulation tools and technologies as well as data integration approaches, the artefacts can provide context dependent on general user instructions, which can be sufficient for competent professionals.

Open conversations allowed us to collect the information provided by respondents with well-grounded evidence and examples from real-life industrial cases and well-defended arguments. This led us to identify some implementation issues, namely, (1) highly detailed DT-based VF simulation and trust are needed to decrease physical builds and (2) reliability of the DT-based VF simulations is dependent on the data provided by the legacy engineering platforms.

Although there are a great variety of values from promising use cases for the concept, VP stands for a highly promising industrial use case. Therefore, more particular use case evaluations are required for future studies. New use cases for utilizing collaborative VR, namely, designing process work instructions or VR training/learning scenarios, could also be considered for future research. Particularly, due to Covid-19 pandemic, the significance of collaborative VR capabilities in VF simulations is raised.

9 Conclusion

DT-based VF is promising for enabling a virtual environment for integrated representation of product, process and system models to design, evaluate, validate, optimize and interact with such models. Such integration has potential for enabling a rendezvous for product and production lifecycle processes. Therefore, DT-based VF can support concurrent engineering of product, process and manufacturing systems. Recent developments in M&S, DT and VR technologies exploit the potential value of the VF concept. Although each of these technological concepts promises a significant benefit, integration of such technologies exponentially increases the value to industry. Easy to use user interfaces of M&S and integration possibilities enable faster development cycles for 3D simulation

models. Embedded VR functions and the decreasing cost of VR tools are attracting the industry to utilize such technology more. There are a number of studies covering either very specific implications of the distinct technologies or highly conceptual work. Therefore, this study aims to close the theory-practice gap by demonstrating and evaluating the DT-based VF concept with multi-user VR capability in wind blade and nacelle manufacturing use cases.

Experts' evaluations show that the DT-based VF concept can achieve dynamic, open, cognitive and holistic system concepts of competence theory. Therefore, it has the potential to support manufacturing enterprises for competence-based stra-

tegic management. DT-based VF is promising as a viable solution to support manufacturing organizations during their adaptation to changing conditions by designing, analysing, validating, simulating and optimizing product, process and system models.

Ongoing research will be devoted to combining here shown theory for the application of DT-based VF concept as a more comprehensive Cyber-Physical System for enterprise-level operations. This will include (1) extending the DT-based VF concept to virtual enterprise, (2) more contextual simulation integration architecture and (3) more tangible case studies such as virtual prototyping in wind blade manufacturing.

Appendix

Table 2 List of Interviewees

Int. No.	Interview date and time	Interviewee title	Years of experience	Department	What is your responsibility?
1	11-05-2020 14:06	Process Technician	3	Process Excellence (PEX)	Complexity reduction in running production line.
2	12-05-2020 10:50	Production worker	5	PEX	Optimizing production line
3	11-05-2020 09:43	Team Leader	11	Technical Support (TS) & Quality (Q)	Team lead for quality and technical support in production and logistics
4	11-05-2020 15:56	Specialist	11	Concept Selection	Production specialist in PEX in the manufacturing
5	13-05-2020 10:59	Lead Production Engineer	10	Concept Selection	How we should set up our systems and our production floor set in accordance with new products in our factories around the world.
6	14-05-2020 14:39	PE, TS & Q Developer	3	Regional Production Engineering (PE), TS & Q, Europe Middle East and Africa (EMEA)	Production engineering as a developer
7	22-05-2020 15:43	PE, TS & Q Developer	6	Regional PE, TS & Q, Americas region (AME)	Regional Production Engineering, Technical Support & Quality, Americas Region
8	25-05-2020 15:52	Senior Manager	7	New Product Introduction (NPI) & Test line	Senior manager for production, specifically building blades for the first time (NPI).
9	07-05-2020 10:18	Project Manager	15	Production Engineering (Projects & Tasks)	Production Line: Tools, process flow, process work instructions, control plans
10	20-05-2020 11:09	Senior PMO Specialist	10	Project Management Office (PMO)	Executing projects in manufacturing related to developing and rolling out new products as well as rolling out those internal and external factories around the globe.
11	25-05-2020 09:38	Senior Technical Support Manager	12	Technical Support	Responsible for all layouts, operation times, building facilities, item allocation
12	11-06-2020 15:35	Chief Specialist, Digitalisation & Capability Dev.	30	Business Development	Focusing on the digitalisation, and business improvement roadmap in different areas like PLM, engineering.
13	11-06-2020 15:35	Senior Vice President (SVP), Industrialisation	26	Industrialisation & Vestas Power Solutions Excellence	Heading up industrialisation in power solutions and blades

Funding The research presented in this article was funded by the Manufacturing Academy of Denmark (MADE) and Vestas Wind Systems A/S, including equipment support (Grant: 6151-00006B). This work was also partially supported by the “*Virtual Environments for optimisation and training in industry 4.0 (VESTAS 4.0)*” project financed by the North Portugal Regional Operational Programme (NORTE 2020–01/SI/2018) (Grant: POCI-01-0247-FEDER-038524). The authors of this article also would like to thank FlexSim for supporting our research by providing the licence free of charge.

Availability of data and materials Part of the research data is subject to financial/intellectual interest of the Vestas Wind Systems A/S and therefore, covered by the provisions given to the industry partner by the research collaboration agreement.

Declarations

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee or comparable ethical standards.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent to publish The participants provided informed consent for publication of their statements.

Disclaimer The use of the commercial software systems identified in this paper to assist the progress of design, development and understanding does not imply that such systems are necessarily the best available for the purpose.

Conflict of interest No potential conflict of interest was reported by the authors and the stakeholders.

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