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Virtual Factory: Digital Twin Based Integrated Factory Simulations

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Abstract

The co-evolution problem, which is known as the concurrent evolution of products, processes and production systems, along with increased complexity and shorter manufacturing operation lifecycles, makes modelling, simulation and evaluation of such operations challenging activities for industry players. This paper presents the concept of a digital twin-based virtual factory (VF) and its architecture to support modelling, simulation and evaluation of manufacturing systems while employing multi-user (collaborative and coordinated) virtual reality (VR) learning/training scenarios. This paper also addresses how digital twin-based virtual factory can support factory lifecycle processes by demonstrating the concept in a wind turbine manufacturing plant, including preliminary evaluation by industry experts.

Keywords: virtual factory; digital twin; modelling; simulation; virtual reality; industry 4.0

1. Introduction

Forces such as innovation, competition and customer demands oblige industries to evolve continuously in three main dimensions, namely products, processes and organisations/systems [1]. Although there are different evolution rhythms for each industry, Fine [2] presented relatively universal principles of industrial evolution cycles and stated that there is no such competitive advantage forever. Ultimate core advantage, therefore, is the capability to adapt to everchanging market conditions.

In order to deal with the concurrent evolution of product, process and system domains, which is also known as the *co-evolution paradigm*, there is a need for synchronisation and simultaneous engineering of models in these three domains [1]. However, increasing complexity, shortening lifecycles and evolving characteristics of product and production lifecycle processes make concurrent engineering a more challenging task for manufacturing enterprises than ever before. Therefore, the co-evolution problem demands more active and integrated use of various methodologies, technologies and tools. Consequently, interoperability and integration between VF tools become paramount to support whole factory lifecycle processes [3].

Different VF concepts were proposed by a number of studies [4]–[7], which can be a solution for the concurrent engineering of complex manufacturing scenarios. However, the evolving nature of such complex systems requires real-time and bidirectional data integration between virtual and physical environments. For example, the lack of advanced planning capabilities of manufacturing execution system (MES), which is also called "*decision myopia*" [8], needs to be dealt with. Simulation technology together with digital twin (DT) technology promises advanced and rapid planning capabilities if they are synchronised with MES. Moreover, bidirectional data integration can also enable the capability of controlling physical systems. Additionally, such advanced systems also call for more sophisticated user interfaces, such as multi-user

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VR technology, to deal with highly complex models. Real-time integration of virtual environments with their physical counterparts has the potential to enable entirely new business cases. However, there is a need for conceptual and architectural models for such integration as well as a real-life demonstration for such artefacts. Therefore, in this paper, we propose a DT based VF concept using multi-user VR training simulations and demonstrate its use in a wind turbine manufacturing plant.

Decreasing physical builds by virtual prototyping and time-to-market by handling the *co-evolution* problem were considered the primary motivations by the case company, Vestas Wind Systems A/S (Later Vestas), during the study. Current research activities in the context of Industry 4.0 at Vestas allowed us to develop and demonstrate the concept VF proposed in this work. Nonetheless, despite the sophisticated interaction of the technologies used, DT based VF and multi-user immersive VR simulations are not turnkey solutions yet. Therefore, designing and developing such a system for industrial production remains difficult and costly processes.

Therefore, the problems of this study were identified as follows:

- Lack of artefacts for designing and developing bidirectional data integration between virtual product and production models with physical systems to achieve higher precision, accuracy and reliability in VF simulations.
- The difficulty for utilising immersive VR for complex learning/training scenarios with the capability of collaboration and coordination.
- Lack of stakeholder specific DT applications with bidirectional data integration.

The rest of the paper is organised as follows. In the second section, we review and present the relevant works and the status of relevant technologies in the knowledge base. The third section introduces the concept model and architecture. The fourth section presents the demonstration. The fifth and sixth sections cover the discussions and conclusions, respectively.

2. Related Work

2.1. Virtual Factory

In 1993, the virtual manufacturing concept, which is integrating product and factory models as a critical aspect of VF, was introduced by Onosato and Iwata [9]. Although there are a number of different definitions for VF, including virtual organisation, emulation facility and integrated simulation, Jain et al. [4] 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.*" A study [10] demonstrated virtual manufacturing as a concept comprising several different software tools and technologies, including simulation and VR, to support product introduction processes. Sacco, Pedrazzoli, and Terkaj [7] introduced an integrated VF framework concept to synchronise VF with a real factory. Furthermore, the multi-resolution aspect of VF models of real manufacturing systems was presented by Jain et al. [11]. VF, as a collaborative design and analysis platform for manufacturing systems, was introduced by Yang et al. [12]. Shamsuzzoha et al. [13], however, considered VF as an environment for collaboratively monitoring business processes to integrate manufacturing companies for achieving some business opportunities.

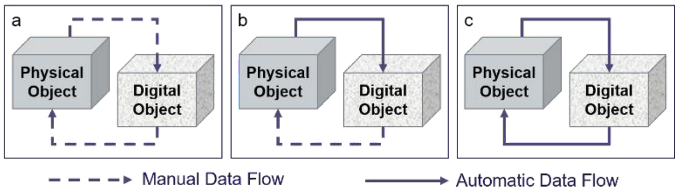

Fig. 1 Data flow in (a) Digital Model, (b) Digital Shadow, and (c) Digital Twin [23].

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

2.2. Digital Twin History and Present

The DT concept was introduced by Grieves in 2003 during an industry presentation and was revisited by NASA's space project later on [14]. The idea of DT has become more solid since the definition of DT made in NASA's integrated technology roadmap [15]; in fact, it led to some notions, including experimental digital twins [16] and digital twin shop-floor (DTS) [17]. Qi et al. [18] 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 [19]. Moreover, interoperability and services provided by DTs enable large-scale smart applications, especially in complex systems and flexible systems. Interaction of virtual and physical spaces and services makes data integration an inevitable trend [18]. Implementing DT technology in manufacturing has drawn more attention among scholars; however, there is not a common understanding of DTs. Some scholars support that DT should focus on simulation [20], [21], while some others argue that it should focus on three dimensions, including physical, virtual, and connection [14], [22].

A categorical literature review on DT in the context of manufacturing classifies the existing studies in terms of different integrations of digital model (DM), digital shadow (DS) and DT [23]. 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 work [24], which stressed the importance of bidirectional data integration. Holler, Uebernickel, and Brenner [25] 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.

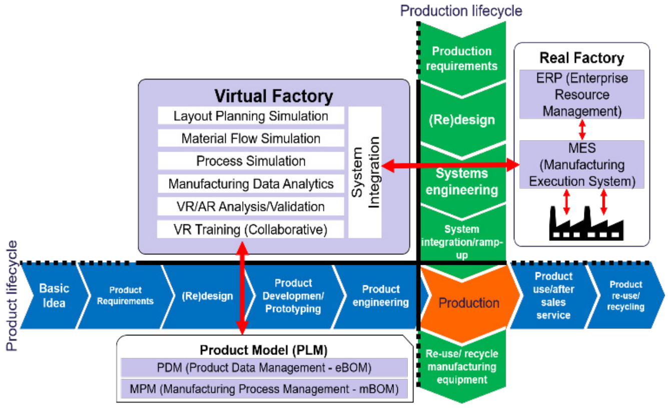

Fig. 2 Digital twin based virtual factory concept [5].

Tao et al. [26] 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 optimising the production systems by utilising self-learning and self-organising. They also addressed the scarcity of studies on interaction and collaboration for DTs, and only two papers [27], [28] were focused on the subject. Rosen et al. argues that by compiling specific simulations used during the engineering phases together with the DT models, 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. Consequently, simulation can be used for validating operational procedures in virtual space [27]. Vachálek et al. [28] 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 [29] 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.

Weyer et al. [20] predicted that the next generation of simulations will be represented by DTs by which complex production processes can be monitored, optimised and quickly adjusted. Moreover, recent developments in simulation tools

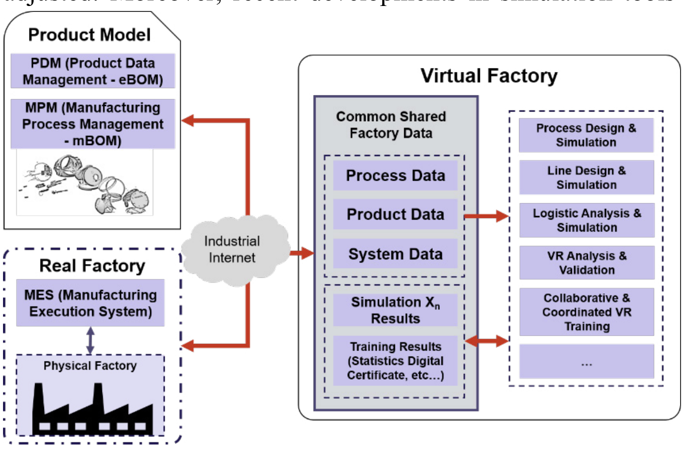

Fig. 3 VF data integration architecture.

promise more and more efficient and effective methods to handle DT development considerations in a variety of industrial cases [30]. Ding et al. [31] presented a smart manufacturing shop floor, and they address the challenges for improving the fidelity of DT simulations and handling complexity aspects of such simulations. In this respect, VR can be a better user interface providing more advance interactions with such complex virtual manufacturing models. Furthermore, Mourtzis, Doukas, and Bernidaki [8] 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.

2.3. Virtual Reality Learning/Training Simulations

Since 1965, Sutherland envisioned "*The Ultimate Display*" which is "*a room within which the computer can control the existence of matter*'' [32]; it took a couple of decades to see VR technology in industry and academia [33]. 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 [34], training and learning [35], virtual building prototyping [36] and visualising abstract data [37]. VR is also a contributing technology for manufacturing simulation and modelling, especially to overcome complexity by providing advanced user interfaces [38]. A survey conducted by Berg and Vance with 18 engineering-focused companies shows the strategic importance of VR and the number of challenges, including lack of environmental simulations that support understanding the interactions between virtual objects [39].

A recent comprehensive survey [40] states that 3D/VR simulations offer higher performance in model development and has 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 addresses that synchronisation between VF simulations and MES improves efficiency during the development of multi-user VR simulations for complex scenarios [41].

The abovementioned studies clearly show the advantages of individually using DT, VR and simulation technologies in designing, evaluating, optimising, validation and training for complex production scenarios. However, the gap in terms of technology integration, bidirectional data integration and interaction and collaboration also remain as main challenges for real-life complex production scenarios. Therefore, synchronising simulation tools with MES has the potential to deal with such challenges. Moreover, multi-user VR technology integrated with DT-based VF simulations can provide advanced user interfaces to deal with complex virtual models. In this regard, the DT-based VF system is presented in the next section.

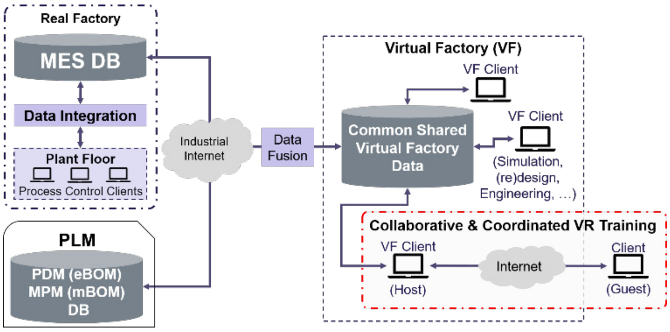

Fig. 4 VF data synchronisation architecture extended with multi-user VR.

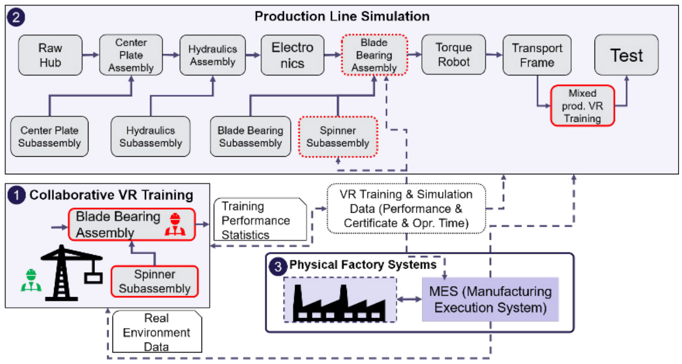

Fig. 5 Integration model for (1) VR training simulation, (2) line simulation and (3) physical factory systems.

3. Proposal for Digital Twin-based Virtual Factory

3.1. *Concept*

The main VF concept (Fig. 2) used in this study is adopted from [5] since it conceptualises the product, process and production system domains more distinctly in the concept design. Segregating product, process and system domains can also increase the understanding of the link between product design, production system design and process planning. Such a concept is also more suitable for the organisational structure of our case company. Data integration of the original concept design changed from one way (real factory to VF) manual data flow to bidirectional automated data integration, which is the main function that allows us to develop DTs in VF simulations. As many scholars in Section 2 show, bidirectional automated data integration has the potential for handling high complexity, flexibility, and controlling the real-life manufacturing systems. Moreover, it improves efficiency during DT development and improves the fidelity of virtual simulation environments.

3.2. *Architecture*

The data integration architecture in Fig. 3 shows the integration between product, process and system, which are equivalent to the product lifecycle management (PLM) system, VF and MES, respectively. VF mainly uses two types of common shared factory data; 1) data from real systems containing product, process and system data and 2) data generated by simulation systems. Real system data can only be used by VF simulation, and it can be manipulated in the simulation environments for required engineering scenarios. However, the results of VF simulations can be reused multiple times for multi-resolution modelling and simulation scenarios. Integrating simulations can increase the efficiency for multidisciplinary analysis, and decrease the time for modelling, validation and computing resources [42], [43]. A high-resolution change in a machining process, for example, can be simulated with a specific simulation tool. The results of new process simulations can be input for lower-resolution simulations, such as line simulation.

Fig. 4 shows the data synchronisation architecture of MES, PLM and VF, including multi-user VR simulation. The details of the synchronisation architecture are not disclosed to prevent potential conflict of interest between stakeholders. Common shared factory data is synchronised with MES to update production execution data in real-time. Multi-user VR technology allows guest connections to VF simulations via the Internet, which enables collaboration in a virtual environment without physical boundaries.

4. Demonstration

A proof-of-concept DT-based VF system integrated with multi-user VR simulation was designed and developed in close collaboration with shop floor workers and engineers at Vestas. A real manual assembly scenario (Fig. 6), which requires the collaboration of two workers in one operation while one of those workers has to coordinate his time between other tasks, was chosen in the hub assembly line. To prove the concept of “integrated” simulations, line simulations of the hub assembly and full factory layout were also developed in another simulation.

The Unity 3d™ game engine was used to develop the collaborative and coordinated VR training scenario. Photon networking packages from Unity were used to enable multiplayer VR simulation. The FlexSim simulation tool was used to design and develop the 3D factory simulation, mainly because of its relatively easy drag-and-drop user interface and embedded VR function. Two head-mounted VR glasses were used for immersive simulations.

Fig. 5 shows the integration model between VF simulations and physical production systems. First, the multi-user VR training simulation synchronised data with MES. The latest operation times of previous and next operations were imported from the real production system and shown to VR users during the simulation. This allows them to know whether their performance causes a block or hunger in the line during the simulation while they are performing the VR training scenario shown in Fig. 6. VR trainee performances were recorded in a VF local SQL database. Second, the production line simulation synchronised operation data with MES. The latest execution

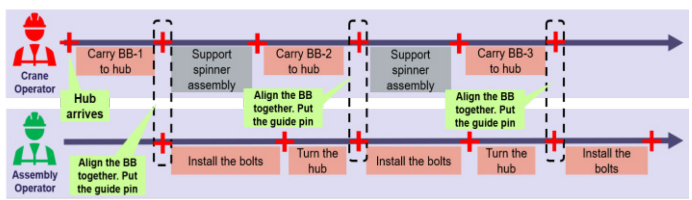

Fig. 6 Collaborative and coordinated VR training scenario.

Fig. 7 (1) VR trainee (assembly operator) connected in Portugal, (2) Collaborative and coordinated VR training simulation, (3) VR trainee (crane operator) connected in Denmark.

time data for each operation in the hub assembly line simulation was imported from the real production system (MES), except for two operations, which were simulated in the multi-user VR training. Blade bearing and spinner subassembly execution times (Fig. 5) were synchronised with the performance data from VR training simulations. This integration allowed us to analyse the effect of trainee performance on the line. A simple mixed production VR learning scenario for grouping the products based on their colour with a crane operation is also embedded in VF line simulation (Fig. 8). VR training performance and learning curve analysed in real-time and exported at the end of the simulation. In the line, all operations represented the real product and production data, including the 3D layout, product CADs and simplified process models. While line simulation was running, basic data analytics and layout changes are performed, and the effects of layout changes observed real-time. When the simulation is stopped or reset, some critical operation data were extracted to local VF SQL DB and be imported by the MES.

For the initial demonstration, multi-user VR training users were in the same physical room; however, a distant connection is also performed by developers. Fig. 7 shows the collaborative and coordinated VR training simulation with a distant connection. More comprehensive demonstrations and evaluations for remote connection are under development.

5. Evaluation and Discussion

A vice president, a senior director of production systems, two senior specialists in digitalisation, two highly experienced engineers and two scholars in immersive VR simulations constructed the preliminary evaluation team. Unstructured interviews were performed, and the significant comments are summarised below:

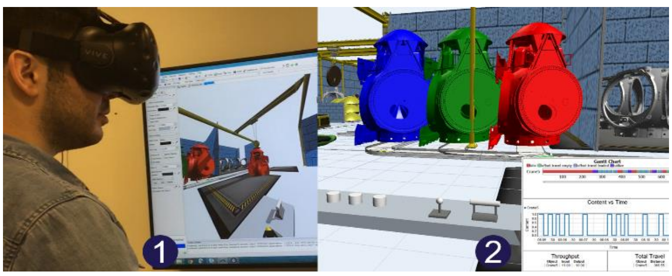

Fig. 8 Line simulation integrated mixed production VR training (refer Fig. 5)

- Data integration can also enable utilising DTs in immersive VR training. This also increases "*the feeling of seriousness and responsibility to finish the task on time*"[41] and the precision, accuracy and reliability of VF simulation models.
- While local content (distributed production) projects are increasing, multi-user VR learning/training can provide more easy, effective and efficient model-based engineering and knowledge sharing for engineers located in different countries.
- Data integration between virtual models and physical systems can be more effective for more data-intensive product and manufacturing engineering.
- Bidirectional data integration between VF tools and MES can allow manufacturers to make more comprehensive time studies in the earlier phases of product introduction processes.
- DT based VR training can support the development of modular VR training systems in the future.
- Utilising multi-user VR with VF is promising for decreasing the design and development time, not just for product, process and VR training simulations.

This study extends the VF concept developed by Yildiz and Møller [5], with real-time bidirectional data integration between VF and physical systems as well as multi-user VR training simulation. Preliminary evaluation shows that the multi-resolution/multi-level simulation capability of the proposed solution has potential to support (re)design, validation verification and optimisation of product development/prototyping, system integration and other system and product engineering processes. DT capability enables the development of smart applications for complex systems. The precision and reliability of the MES data were out of the scope of this work. The number of industry experts who evaluate the demonstration was limited due to geographical constraints.

6. Conclusion

The study presented in this paper focuses on the integration of DT, simulation and multi-user VR technologies to handle the increasing complexity of digital/virtual models in product, process and production system domains. We presented the DT-based VF concept, data integration and synchronisation architecture as well as their demonstration for a wind turbine manufacturing plant. Preliminary evaluations show that the proposed approach has potential for more efficient and effective engineering in product, process and systems. More comprehensive demonstrations and to industry experts' evaluations in more specific product and production lifecycle processes such as virtual prototyping are planned for future works.

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