Virtual Factory

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BUILDING SMART FACTORIES

BY
EMRE YILDIZ

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AALBORG UNIVERSITY
DENMARK

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Emre Yıldız

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Dedicated to

Mustafa Kemal Atatürk

CV

Emre Yıldız was born in a village in Kandıra, Turkey. He studied software programming in a technical high school and completed his BSc degree in Management Information Systems at Boğaziçi University, Istanbul, in 2013. After his bachelor degree, he worked as an IT professional in Shanghai while studying Chinese at Shanghai Normal University (上海市重点大学) with a Shanghai Local Government Scholarship. In 2016, he obtained his MSc degree in Management Science and Engineering at Tsinghua University (清华大学), Beijing, China. For one year, he worked as a Business Development Specialist for a construction company in Dubai, United Arab Emirates. In 2018, he started his PhD at the Department of Materials and Production at Aalborg University. His research on Smart Factories is part of the Manufacturing Academy of Denmark (MADE) project in collaboration with Vestas Wind Systems A/S. He is currently working as a Digitalisation and Simulation Lead at Vestas.

ENGLISH SUMMARY

Constant evolution in the global manufacturing resulting from various forces like innovation, changing demands, competition, and regulations is forcing manufacturing enterprises towards more digital and smarter operations to stay competitive in their respective markets. This evolution of manufacturing towards digitalisation led to a new paradigm in the last decade, which has been called the "fourth industrial revolution" or "Industry 4.0". Yet, it is not a trivial matter for manufacturing organisations to deal with the accelerating frequency of radical changes by means of new strategies, methods, and technologies. Evolving dynamic forces have immense impacts on the digital transformation of manufacturing operations as well as the priorities of scholarly works. In its early stages, the endeavour for digitalisation of manufacturing concentrated on new technologies and their utilisation for transparency by the enhanced availability of data. However, even some of the best manufacturing companies are still struggling to leverage their competencies or develop new competencies by capturing the highest benefits from digitalisation due to challenges that have emerged within the context of complex economic, socio-political, and technological systems.

Nowadays, it is more apparent and easier to comprehend the relation between evolving market dynamics and their reciprocal consequences on products, processes, and manufacturing systems. Accordingly, manufacturing organisations must handle the initiation of change as well as its propagation, which triggers a multitude of unpredictable and complex modifications in production. This challenge is characterised as the concurrent/coordinated evolution of products, processes, and systems, in other words, "co-evolution" in scholarly works.

The Virtual Factory (VF), as an integrated simulation model of factories, including their subsystems, enables data integration across the manufacturing value chain as well as the integrated use of technologies and methodologies. Therefore, VF is recognised by scholars as a useful and effective solution to deal with the co-evolution paradigm. However, there are still significant gaps in the knowledge domain as well as empirical challenges in the application domain in terms of designing, developing, and utilising the VF concept. Particularly, recent advances in technology domains like digital twins (DTs), modelling and simulation (M&S), and virtual reality (VR) indicate the potential for extensive value in the industry. Moreover, the integrated use of such technologies enables incremental potential and value for the transformation towards smart production systems. Nevertheless, extensive utilisation and integration of such technologies within the VF concept and evaluation in actual manufacturing cases for handling co-evolution are critical but absent. Therefore, the purpose of VF research work is to address such gaps and challenges by designing and developing artefacts and frameworks together with empirical evaluations of designed artefacts in the industrial cases.

The VF research work presented in this thesis is the final outcome of a three-year-long PhD study conducted as part of a comprehensive research collaboration project named Smart Factories. The Smart Factories research project was developed in collaboration between various industrial and academic stakeholders in Denmark and has incorporated numerous scholarly works. Therefore, Virtual Factories research, as one these scholarly works, aimed to achieve both industrial relevance and academic rigour by achieving the following aims:

1) Design and develop a VF concept solution based on a real-life manufacturing case that can utilise state-of-the-art technologies including digital twin, and integrates product, process, and production system models.
2) Discover the guidelines for the actual utilisation of technologies and methodologies for simultaneous design, analysis, modelling and simulation of product and factory models.
3) Discover the enablers and barriers for designing, developing, and implementing the VF for industrial purposes.
4) Discover and evaluate the industrial value of VF.

Within the application domain, we capitalise on both descriptive (scientific) and prescriptive (technical) knowledge by aiming to contribute both the artefacts (concepts, methods, architectures) and theories. In other words, building novel artefacts and their evaluation to solve real-world problems and to explore the practical usefulness of a solution to deal with the theory and practice are the primary purposes. Therefore, the VF research presented in this thesis follows the methods, guidelines, and frameworks of design science research (DSR) in information systems (IS) that examine the generation of the artefacts required to carry out design, implementation, use and investigation of practical relevance and the pragmatic validity of a digital solution. The main empirical outcomes of the VF research incorporate overall three phases and each phase capitalises on scholarly articles. Moreover, the subsequent conduct of the study required more comprehensive and inclusive interpretations of the empirical knowledge discovered during the research, as well as a consequential extension of the concept to enterprise-level operations. Therefore, although it was not the part of the initial research plan, Paper 4 is formed to reflect on the conceptual and theoretical foundations of the DT-based VF as well as its extension to a virtual enterprise. Correspondingly, the main research questions consecutively addressed during each journal article of the study can be listed as follows:

Research Question 1. How can a VF concept that integrates the product, process, system data, as well as state-of-the-art technologies be designed and developed for an industrial case?

Research Question 2. Can DT-based VF support manufacturing organisations to handle the co-evolution of product, process, and system models by enabling concurrent engineering and shorter time-to-market?

Research Question 3. How can DT-based VF solutions support the new product introduction process by enabling virtual prototyping?

Research Question 4. What are the conceptual and theoretical foundations of the DT-based VF concept that can support the extension of the concept to the enterprise level for handling co-evolution?

The thesis on hand is the final effort to frame the three-year-long research aiming to establish a systemic design and development approach for DT-based VF, employing a collaborative virtual reality capability that can integrate product, process, and system models to support the manufacturing enterprises for handling co-evolution problems during their adaptation to evolving environments. Thus, with this final effort, this thesis is aiming to:

> *Establish comprehensive and methodical foundations for the empirical, conceptual, and philosophical discussions supporting the previously discovered and disseminated knowledge on DT-based VF employing a collaborative virtual reality capability that can integrate product, process, and system models.*

Therefore, the essential knowledge contribution of the VF research to the literature and application domain can be summarised as follows:

- Introducing a novel DT-based VF concept including design and development models based on a real-life manufacturing case
- Presenting knowledge on the practical implications and industrial value of DT-based VF
- Determining guidelines for the actual utilisation of technologies and methodologies for simultaneous design, analysis, modelling and simulation of manufacturing operations
- Discovering knowledge regarding enablers and barriers for designing, developing, and utilising DT-based VF for industrial purposes
- Elaborating on conceptual and theoretical foundations for DT-based VF.

Thus, the proposed concept solution shows signs of significant value in the application domain and is employed by the industrial stakeholder of this research project, and developments are in the course of significant progress while these lines are drawn up. Therefore, the outcome of this study provides valuable prescriptive and descriptive knowledge for both researchers and practitioners.

DANSK RESUME

Konstant udvikling i den globale produktionsindustri som følge af forskellige kræfter såsom innovation, skiftende efterspørgsel, konkurrence og nye reguleringer tvinger producenter til at kue til mere digitale og smarte løsninger, såfremt de vil forblive konkurrencedygtige i deres respektive markeder. Denne digitalisering af produktion har ledt til et paradigmeskift i det sidste årti, som er blevet døbt ”den fjerde industrielle revolution” eller ”Industry 4.0”. Det er dog ikke en triviel sag for producenter at håndtere den hyppige og radikale udvikling via nye strategier, metoder og teknologier. Udvikling af dynamiske kræfter har enorm indflydelse på den digitale transformation af produktionsløsninger såvel som prioriteten på videnskabelige værker. I de tidlige stadier var bestræbelserne på digitalisering af produktion koncentreret på nye teknologier og deres anvendelse i gennemsigtighed via øget tilgængelighed af data. Nogle af de bedste produktionsvirksomheder kæmper dog stadig for at udnytte deres kompetencer eller udvikle nye kompetencer, ved ikke at formå at fange de største fordele ved digitalisering pga. udfordringer, der er opstået inden for rammerne af komplekse økonomiske, socialpolitiske og teknologiske systemer.

Nu om dage, er det lettere at forstå relationerne mellem udviklende markedsdynamik og dets reciprokale konsekvenser på produkter, processer og produktionssystemer. I overensstemmelse hermed skal producenter håndtere forandring såvel som dets udbredning, hvilket bevirker et væld af uforudsigelige og komplekse modifikationer i produktionen. Denne udfordring er karakteriseret som den samtidige/koordinerede udvikling af produkter, processer og systemer, med andre ord, ”co-evolution” i videnskabelige værker.

Den Virtuelle Fabrik (VF), som en integreret simulationsmodel af fabrikker, inklusiv deres delsystemer, muliggør data integration på tværs af produktionsværdikæden samt integreret brug af teknologier og metoder. Derfor er VF anerkendt af forskere som en værdifuld og effektiv løsning til at håndtere co-evolutionsparadigmet. Der er dog stadig betydelige huller i kendskabet til VF, såvel som empiriske udfordringer i at anvende VF konceptet, ift. dets design og udvikling. De seneste fremskridt i teknologien inden for domæner såsom digital twins (DTs), modellering og simulering (M&S) og virtual reality (VR) indikerer især potentialet for omfattende værdi i industrien. Ydermere, den integrerede brug af disse teknologier muliggør inkrementelt potentiale og værdi for transformationen af teknologierne til smarte produktionssystemer. Ikke desto mindre er anvendelsen og integreringen af disse teknologier, såvel som evalueringen i faktiske produktionscases, til at håndtere co-evolution kritisk, men fraværende. Formålet med VF-forskningen er derfor at adressere disse huller i viden og udfordringer ved at designe og udvikle artefakter og rammer sammen med empiriske evalueringer af designede artefakter i industrielle cases.

VF-forskningsarbejdet, præsenteret i denne afhandling, er det endelige resultat af et tre år langt ph.d.-studie udført som en del af et større forskningsprojekt kaldet Smart Factories. Forskningsprojektet er udviklet i samarbejde med forskellige industrielle og akademiske interessenter i Danmark og har inkorporeret adskillige videnskabelige værker. Derfor har Virtual Factory projektet, som ét af disse videnskabelige værker, sigtet efter at opnå både industriel og akademisk relevans ved at opnå følgende mål:

1) Design og udvikl en VF-konceptløsning baseret på en virkelig produktionscase som kan anvende state-of-the-art teknologier, herunder digital twins, og som integrerer produkt, proces og produktionssystemmodeller.
2) Afdække retningslinjerne for den aktuelle anvendelse af teknologier og metoder for samtidigt design, analyse, modellering og simulering af produkt og fabriksmodeller.
3) Afdække aktivatorerne og barriererne i designet, udviklingen og implementeringen af VF i industrielt sammenhæng.
4) Afdække og evaluere den industrielle værdi af VF.

Inden for applikationsdomænet udnytter vi både deskriptiv (videnskabelig) og foreskrivende (teknisk) viden ved at bidrage til både artefakter (koncepter, metoder, arkitekturer) og teorier. Med andre ord, at konstruere nye artefakter og deres evaluering til at løse virkelige problemer, samt at undersøge den praktiske anvendelighed af en løsning til at håndtere både teorien og det praktiske, er de primære formål. VF-forskningen præsenteret i denne afhandling følger derfor de metoder, retningslinjer og rammer af design-videnskabs-forskning (DVF) i informationssystemer (IS) som undersøger genereringen af de artefakter krævet til at fuldføre design, implementering, brug og undersøgelse af praktisk relevans samt dets pragmatiske validitet i en digital løsning. De empiriske resultater af VF-forskningen inkorporerer i alt tre faser og hver af disse faser, drager nytte af videnskabelige værker.

Ydermere, den efterfølgende del af studiet krævede en mere omfattende og inkluderende fortolkning af den empiriske viden, der blev opdaget under forskningen, såvel som en deraf følgende udvidelse af konceptet til operationer på virksomhedsniveau. Skønt det ikke var en del af den oprindelige forskningsplan, er Artikel 4 lavet til at reflektere på de konceptuelle og teoretiske fundamenter af den DT-baserede VF, såvel som dets udvidelse til en virtuel virksomhed. Tilsvarende kan de vigtigste forskningsspørgsmål, som fortløbende bliver adresseret under hver videnskabelig artikel i studiet, opstilles som følgende:

Research Question 5. Hvordan kan et VF-koncept som integrerer produktet, processen, systemdataet, såvel som state-of-the-art teknologier designes og udvikles for en industriel case?

Research Question 6. Kan DT-baseret VF understøtte produktionsvirksomheder til at håndtere co-evolution af produkt, proces og systemmodeller ved at muliggøre samtidig konstruktion og kortere time-to-market?

Research Question 7. Hvordan kan DT-baserede VF-løsninger understøtte den nye introduktionsproces for produkter, ved at gøre brug af virtuelle prototyper?

Research Question 8. Hvad er de konceptuelle og teoretiske fundamenter for det DT-baserede VF-koncept som kan understøtte udvidelsen af konceptet til virksomhedsniveau for håndtering af co-evolution?

Denne afhandling er den sidste indsats i indramningen af den tre år lange forskning, der har til mål at etablere et systemisk design og udviklingstilgang for DT-baseret VF, der anvender en samarbejdende virtuel virkelighed som kan integrere produkt, proces og systemmodeller til at understøtte produktionsvirksomheder i deres håndtering af co-evolutionsproblemer under deres tilpasning til et udviklende industrielt miljø. Med dette sagt, har denne afhandling til mål at:

> *Etablere omfattende og metodiske fundamenter for empiriske, konceptuelle og filosofiske diskussioner som støtter den tidligere afdækkede og formidlede viden om DT-baseret VF, ved at anvende en samarbejdende virtuel virkeligheds-kapacitet som kan integrere produkt, proces og systemmodeller.*

VF-forskningens essentielle kontribution til litteraturen og applikationsdomænet kan opsummeres som følgende:

- Introduktion af et nyt DT-baseret VF-koncept, heriblandt design- og udviklingsmodeller baseret på virkelige produktions cases.
- Præsentation af viden omkring de praktiske implikationer og industriel værdi af DT-baseret VF.
- Fastlæggelse af retningslinjer for anvendelsen af teknologier og metoder for samtidigt design, analyse, modellering og simulering af produktionsløsninger.
- Afdækning af viden vedrørende aktivatorer og barrierer af design, udvikling og anvendelsen af DT-baseret VF i industrielt øjemed.
- Uddybning af konceptuelle og teoretiske fundamenter for DT-baseret VF.

Den foreslåede konceptløsning viser tegn på signifikant værdi i applikationsdomænet og er anvendt af den industrielle interessent i dette forskningsprojekt, og udviklingen af konceptet er i betydelig fremgang, mens denne afhandling skrives. Udfaldet af dette studie giver derfor et værdifuldt foreskrivende og beskrivende indblik for både forskere og praktiserende.

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This thesis is the outcome of the collaboration between the Manufacturing Academy of Denmark (MADE), Aalborg University and Vestas Wind Systems A/S. Thus, my gratitude extends to MADE for the partial funding of my PhD studies and for providing access to the network of esteemed scholars and industry experts. Correspondingly, I am thankful to Vestas for the invaluable know-how and material support. Moreover, I must acknowledge the kind assistance of the Institute for Systems and Computer Engineering, Technology and Science (INESC TEC), Porto and Multimodal Acknowledgeable Multisensory Immersive Virtual Environments Laboratory (MASSIVE Lab) team at Vila Real during my three months of research study abroad.

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Finally, I acknowledge that there are many significant individuals I could not mention here. I am extremely grateful for all those who had a part in forming my development path, leading to the successful conduct of this scholarly work.

Emre Yildiz

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Paper 2. Yildiz, E., Møller, C., & Bilberg, A. (2021). Demonstration and Evaluation of a Digital Twin-Based Virtual Factory. *The International Journal of Advanced Manufacturing Technology*, *114*, 185–203. https://doi.org/10.1007/s00170-021-06825-w

Paper 3. Yildiz, E., Møller, C., & Bilberg, A., Rask, J. K., (2021). Virtual Prototyping: Evaluating the Digital Twin Based Virtual Factory for New Product Introduction. *Complex Systems Informatics and Modeling Quarterly*. https://doi.org/10.7250/csimq.2021-29.01

Paper 4. Yildiz, E., Møller, C., & Bilberg, A. (2021a). Conceptual Foundations and Extension of Digital Twin Based Virtual Factory to Virtual Enterprise. (**Under Review/Revision**): *International Journal of Advanced Manufacturing Technology*.

Paper 5. Yildiz, E., Møller, C., Melo, M., & Bessa, M. (2021). Designing Collaborative and Coordinated Virtual Reality Training Integrated with Virtual and Physical Factories. *International Conference on Graphics and Interaction 2019*, 48–55. https://doi.org/https://doi.org/10.1109/ICGI47575.2019.8955033

OTHER WORKS

Paper 6. Yildiz, E., Møller, C., & Bilberg, A. (2020b). Virtual factory: Digital twin based integrated factory simulations. *Procedia CIRP (53rd CIRP Conference on Manufacturing Systems)*, *93*, 216–221. https://doi.org/10.1016/j.procir.2020.04.043

Paper 7. Yildiz, E., Møller, C., & Bilberg, A. (2020a). Virtual Factory: Competence-Based Adaptive Modelling and Simulation Approach for Manufacturing Enterprise. *13th IFIP WG 8.1 Working Conference on* *the Practice of Enterprise Modelling*, *1*, 197–207. https://doi.org/https://doi.org/10.1007/978-3-030-63479-7_14

Paper 8. Yildiz, E., Møller, C., & Bilberg, A. (2021c). Demonstrating and Evaluating the Digital Twin Based Virtual Factory for Virtual Prototyping. *8th Changeable, Agile, Reconfigurable, and Virtual Production Conference (CARV2021)*, 297–304. https://doi.org/https://doi.org/10.1007/978-3-030-90700-6_33

LIST OF ABBREVIATIONS

Abbreviation	Meaning
AI	Artificial Intelligence
AR	Augmented Reality
CIE	Computer Integrated Enterprise
CIM	Computer Integrated Manufacturing
CIP	Centre for Industrial Production
CPPS	Cyber-Physical Production System
CPS	Cyber-Physical System
DES	Discrete Event Simulation
DM	Digital Model
DS	Digital Shadow
DSR	Design Science Research
DSRM	Design Science Research Methodology
DT	Digital Twin
DTS	Digital Twin Shopfloor
eBOM	Engineering Bill of Materials
ERP	Enterprise Resource Planning
FoF	Factories of the Future
IIoT	Industrial Internet of Things
INESC TEC	Institute for Systems and Computer Engineering, Technology and Science
IoT	Internet of Things
IS	Information Systems
IT	Information Technology
M&S	Modelling and Simulation
MADE	Manufacturing Academy of Denmark
MASSIVE Lab	Multimodal Acknowledgeable Multisensory Immersive

	Virtual Environments Laboratory
mBOM	Manufacturing Bill of Materials
MES	Manufacturing Execution System
MPM	Manufacturing Process Management
NPI	New Product Introduction
PDM	Product Data Management
PLM	Product Lifecycle Management
PTC	Parametric Technology Corporation
QR	Quick Response
R&D	Research and Development
RMS	Reconfigurable Manufacturing System
RTO	Research and Technology Organisation
SME	Small and Medium Enterprise
VF	Virtual Factory
VP	Virtual Prototyping
VR	Virtual Reality
WTG	Wind Turbine Generator

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CHAPTER 1. INTRODUCTION

Without a doubt, the significant advances in modern manufacturing that materialised in the twentieth century had an immense impact not only on the way we live and do things on a personal level but also on demographic, geographic, socio-economic systems around the globe. In fact, such remarkable advances in industrial production and their impact on society were labelled as an “industrial revolution”. Each industrial revolution enabled additional advances for better, faster, and cheaper manufacturing which fulfilled the needs of the new society shaped by the very revolution of the industry (Colli, 2020). During industrial revolutions, manufacturing companies attempt to exploit technological innovation to leverage their competencies or develop new competencies by means of effective and efficient use of their tangible and intangible assets to stay competitive in their strategic environment.

Historically, the subject matter of innovation has been the invention of crucial new technologies and their dramatic influence on the complete transformation of societies from feudal to industrial. The revolutions provoked by the force of scientific technologies were ruthless, called a “technology imperative”, and no society could resist (Betz, 1998). Therefore, each industrial revolution emerged from and materialised on a certain technological catalyst. These catalysts, from the first industrial revolution to the fourth revolution taking shape at the present, can be defined as water/steam engine, electricity, automation, and cyber-physical systems (CPSs) (Betz, 1998; Wee et al., 2015).

Thus, the advances in various enabling technologies such as the internet of things (IoT), cloud computing, augmented reality, big data, simulation, additive manufacturing, and system integration were among the main initiators for Industry 4.0. Yet, it is apparent that CPSs are dependent on the advanced integration between systems, data, and methods to achieve more agile, flexible, resilient, and smarter manufacturing systems. In fact, the changeable (reconfigurable) manufacturing paradigm promises significant value and is gaining prominence among industrial and scholarly communities (Andersen, 2017).

Thus, during the last decades, the momentum of manufacturing technology evolution was exponentially accelerating and mainly driven by maximizing economic utilities, developing sustainable environments, and enhancing human experiences (Gill & Hevner, 2013). Therefore, it is the role of scientists to understand why and how these newly formed IT artefacts work the way they do. It is apparently a continuous and endless endeavour within the vast domains of science to perform the duties of such a role.

This dissertation is the outcome of a three-year-long PhD research that aims to construct the abstract forms of information technology (IT) artefacts, including concepts, models, and methods to address various challenges within the manufacturing domain. The study was able to contribute to the knowledge base by being given the opportunity to study the proposed solutions in a relevant real-world application context by developing and demonstrating various demos. Therefore, the discovered knowledge aims to be part of an enormous scientific endeavour that contributes to the acceleration of technological advances and to support the deeper understanding and generalisation of these advances.

Within the application domain, we exploit both descriptive (scientific) and prescriptive (technical) knowledge by aiming to contribute both technology (artefacts) and science (theories). Although both activities are significant, building novel artefacts and their evaluation to solve real-world problems and explore opportunities were the primary purposes. This was because the research aims were focused on the activities for discovering the impacts of interventions in a (manufacturing) organisation and exploring the practical usefulness of a solution to deal with the gap between theory and practice.

Therefore, there is a need to introduce the context of three-year PhD project. The project context is presented and discussed in the next section to respond to this need.

1.1. PROJECT CONTEXT

As a result of the association between product, process, and system domains, together with the advances in computing technologies and tools, manufacturing systems are becoming a fusion of a wide range of different tools and processes related to each other. For a long while, the product, process, resource, and system models associated with manufacturing operations have been handled in a digital environment, and a huge volume of data related to these entities has already been stored in digital platforms. Therefore, emerging technologies, different tools and platforms related to manufacturing are getting more and more integrated. Thus, changing demands, regulations and innovations have led to the need for agility, modularity, scalability, flexibility, and knowledge-based decisions that are generally incorporated by the scope of the Smart Factory concept (Radziwon et al., 2014).

As a reflection of the abovementioned transformation in the manufacturing industry and evolving requirements, Aalborg University (Center of Industrial Production (CIP)), the Manufacturing Academy of Denmark (MADE)[1], and Vestas Wind Systems A/S[2] (later Vestas) initiated a Smart Factories project under the MADE

[1] https://www.made.dk/

[2] https://www.vestas.com/

Digital Program[3]. The Smart Factories project aims to provide new knowledge for designing, implementing, and operating Smart Factory solutions. Furthermore, the project focuses on building Smart Factory infrastructure by closing the planning loop, integrating systems, and building digital infrastructure. Virtual Factory (VF) research work is among numerous research works developed and conducted under the Smart Factories project. Therefore, the project objectives, main stakeholders, and their motivations set the primary stage to form the research work. Thus, it could be illuminating for the reader to introduce the main stakeholders of the Smart Factories project. The three main stakeholders of the project are 1) Aalborg University, 2) Vestas, and 3) MADE, as shown in Figure 1 Main stakeholders of the Smart Factories project.

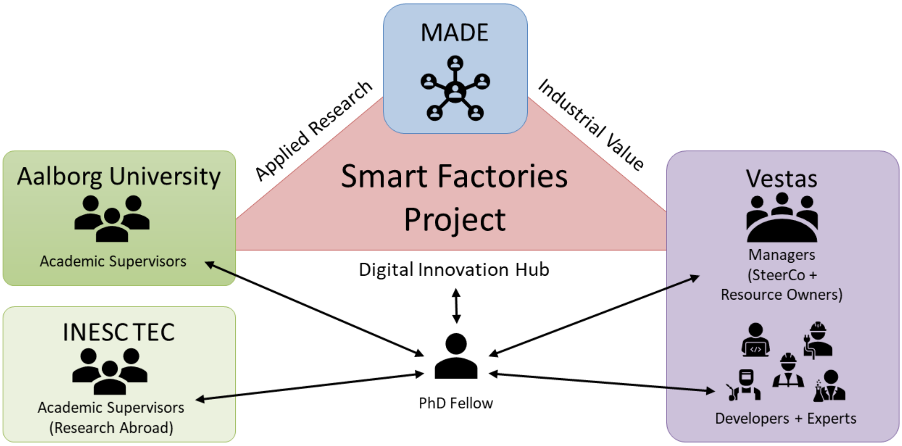

Figure 1 Main stakeholders of the Smart Factories project

MADE is a *"Danish national innovation and research platform for the manufacturing industry in Denmark"*, acting as an independent association. It aims to enable greater competitiveness for the Danish manufacturing industry globally by facilitating the development of innovative manufacturing solutions through establishing strategic partnerships between academia, research, and technology organisations (RTOs) and industry partners. Therefore, it secures and supports applied industrial research projects together with various innovation and education activities through the implementation of state-of-the-art technology in the manufacturing industry.

Aalborg University, as the main academic stakeholder, maintains the environment, resources and regulations for supervising and auditing the execution of the research

[3] https://www.made.dk/digital/

project to train researchers. Academic supervisors are responsible for ensuring that the PhD fellow conducts the research within the highest standard of scientific methodology while fulfilling the academic requirements, including but not limited to completing required PhD courses, performing teaching activities, knowledge dissemination, and active participation in the international research environments.

As a part of the active participation in the international research environment, a research activity abroad was conducted under the Institute for Systems and Computer Engineering, Technology and Science[4] (INESC TEC). INESC TEC is a private non-profit research institution that is committed to scientific research and technological advancement and transfer in Porto. Three months of research activity abroad (4th October 2018 to 30th January 2019) was conducted as part of the subject research at the Multimodal Acknowledgeable Multisensory Immersive Virtual Environments Laboratory (MASSIVE Lab[5]) of INESC TEC at Vila Real, Porto.

As an industrial partner of the project, Vestas provides the application context to develop and demonstrate the designed solutions and required resources and industrial expertise for the evaluation of the implications. A line manager and an industry supervisor were responsible for the main administrative tasks under a steering committee (SteerCo). SteerCo comprised the company’s relevant senior and executive managers to provide resources and evaluate the research activity. Four SteerCo meetings were held within the three years for initiation, guidance and evaluation, and project closure. More than fifty industry experts and developers have actively participated in developing, demonstrating, and evaluating the solution. The experts’ feedback was the primary information for the evaluation and discussion presented in the outcomes of the research work.

The author of this dissertation, who holds the PhD Fellow role under the Smart Factories project, was responsible for the planning and execution required to conduct the high-level academic research activity. These responsibilities mainly cover determining the research topic, scope, and objectives within the framework of project expectations, as well as managing the collaboration between industry and academy stakeholders. Therefore, various activities were performed to secure the alignment between the main stakeholders, including regular Trilateral Meetings involving the PhD Fellow, industrial experts and academic supervisors. Table 1 Project stakeholders summarises the main stakeholders as well as their requirements and contributions to the research project.

[4] https://www.inesctec.pt/en/institution#about

[5] https://massive.inesctec.pt/

Table 1 Project stakeholders

Stakeholder	***Motive & Requirements***	***Contribution***	***Activities & Deliveries***
Aalborg University	• Contribution to the knowledge base • The successful conduct of the research	• Supervising • Teaching • Funding	• 2-month, 11-month plans • 6-month portfolio submissions • PhD dissertation • Monthly trilateral meetings
Vestas	• Information value-add • Discovering barriers and enablers for digitalisation • Proof-of-concept	• Application context & cases • Funding • Equipment Support	• Development • Demonstration • Evaluation • Intranet publishing • Monthly trilateral meetings • Annual SteerCo meetings
MADE	• Industrial potential of the implementation of the research • Cooperation between industry and research partners	• Funding • Collaboration • Dissemination	• MADE conferences • Industry & academic workshops
INESC TEC	• The successful conduct of research • Publication	• Supervision • Development support	• Demonstration • Evaluation • Dissemination (publishing)

Since this dissertation is the outcome of an industry-based PhD study, the industry partner focused on the pragmatic validity and value of the research. In contrast, the academic partners focused on the scientific contribution to the state-of-the-art literature. Therefore, it is imperative to present the scope of the research project.

1.2. PROJECT SCOPE

The scope of the Smart Factories research project is simplified and shown in Figure 2 Scope of the Smart Factories project[6]. The research project is scoped into two iterative phases: 1) Idea generation and 2) Proof-of-concept. In the first phase, problems of the application context that are introduced and discussed in the following sections were planned to be examined while taking into account the state-of-the-art knowledge in the literature for problem identification and defining the objectives of a solution. A concept solution is planned to be designed based on the requirements defined by the problem domain while employing the relevant existing artefacts in the knowledge base. The essential outcome of the project, for both the academic domain and the application domain, is incorporated in the second phase. Designing the technical artefacts, development of a demo solution and demonstration is performed with the support of industry partners and expertise. The evaluation is conducted based on the assessment performed by the industry experts. We should note, however, that the final evaluation contributed to the knowledge base incorporates both empirical and theoretical arguments.

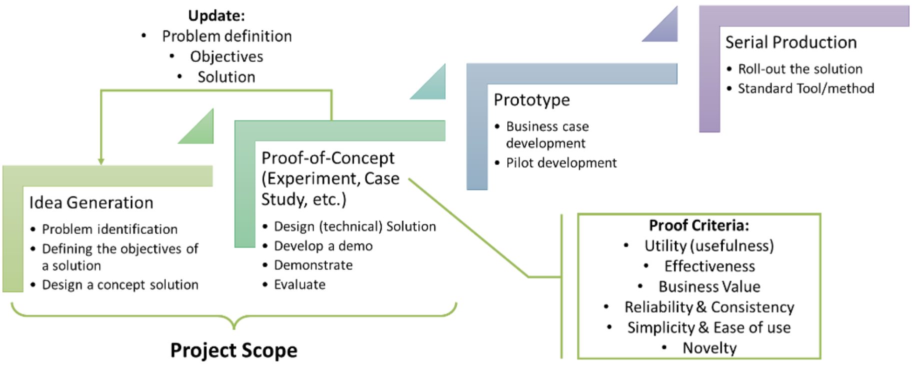

Figure 2 Scope of the Smart Factories project

The outcome of the second phase activities provided the empirical evidence for the required improvements or revisions during the second iteration. Such adjustments and revisions may concern redefinition of the problem, the objectives of a solution or redesign of the solution.

The third and fourth phases are shown in Figure 2 Scope of the Smart Factories project, to make it easy to interpret the long-term expectations of the project's

[6] The illustration is developed based on various drawings presented by MADE in early phase meetings.

industry partner. Although the project scope does not cover prototyping or business case development tasks to prove the industrial implications of the designed solution, it is anticipated that the knowledge discovered during the first and second phases will provide sufficient evidence for the industry partner to pursue the development of a full-scale solution.

Vestas provides the application context that encompasses the problems, requirements, opportunities, and motivations as inputs for our research, and designates the acceptance criteria for the eventual evaluation of the research results. The research activity engages real-life problems to create knowledge by solving practical matters with pragmatic methods. Therefore, the knowledge we aim to discover should be used in an instrumental way to design and implement actions, systems, or processes. In particular, we aim to study digital solutions to improve the operations in a manufacturing enterprise. Accordingly, the body of knowledge we aim to build on is social science, natural science and "design science" (A. R. Hevner et al., 2004). Therefore, design science research (DSR) is considered more suitable to discover the effects of interventions in a manufacturing organisation to explore the practical usefulness of a solution to close the gap between theory and practice (van Aken et al., 2016). However, there is a need for more inclusive articulation and discussion on the requirements of the application domain (problems, opportunities, motivations) before diving into the empirical foundations in terms of the existing knowledge (related works, methods, concepts, and knowledge gaps).

1.3. PROBLEMS AND CHALLENGES

1.3.1. EVOLVING INDUSTRIES

It is not a trivial matter for the global industry to deal with the increasing frequency of more radical changes that pressure manufacturing enterprises to adopt new methods, technologies, and strategies. Here we should note that the terms organisation, enterprise, firm, and company are used as synonyms in this thesis, since they incorporate similar characteristics like openness to larger systems and goal-seeking strategic behaviours as social, artificial, and natural systems. Since manufacturing enterprises are embedded in their respective industry via their supply chain systems, as well as the markets via sales operations, the transformation occurring in their environments governs their survival for manufacturing organisations. Therefore, adaptation to ever-changing environments for manufacturing firms becomes the ultimate core advantage. A senior manager of Vestas expressed this challenge as follows:

> *"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"* (Yildiz, Møller, & Bilberg, 2021c)

Increasing competitiveness, changing regulations and demands within the context of highly complex socio-political, economic, and technological dynamics have immense impacts on the operations of manufacturing companies as well as the research priorities of scholars (Tolio et al., 2010). Although it is possible to define various other dynamics that have an impact on the evolution of industries, technology and innovation, the level of competition, evolving demands and regulations are listed among the major forces (Fine, 1998).

Another depiction of the evolution in the markets can be recognised in the shift of the decision-making power from manufacturing organisations to customers. That means that products, their functionality, quality, and performance are determined by evolving market forces. Accordingly, rising demands for customised products result in increasing product variances and complexities, and thus associated production processes and systems.

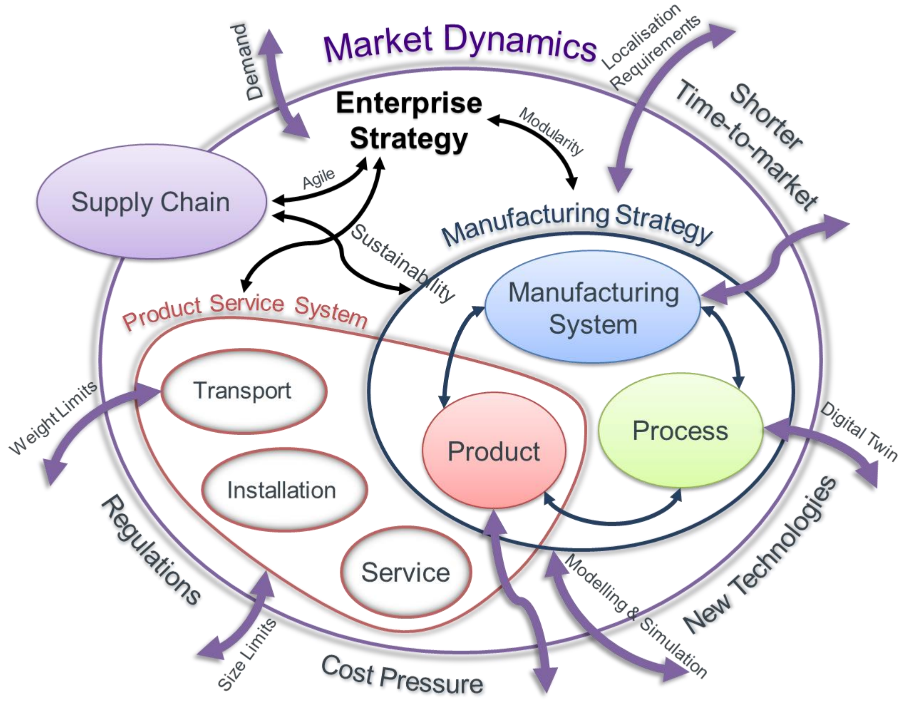

Figure 3 Manufacturing dynamics for wind turbine generator manufacturing [adapted from (Tolio et al., 2010)*]*

Figure 3 Manufacturing dynamics for wind turbine generator manufacturing [adapted from (Tolio et al., 2010)] shows a simplified illustration of the complex relationships between internal and external dynamics with the product, process, and system domains for a Wind Turbine Generator (WTG) manufacturing company like

Vestas. It is not difficult to comprehend the relation and reciprocal consequences of product, process, and system models with the enterprise strategy as well as external driving forces. The evolution of external forces and internal requirements increasingly calls for approaches and concepts such as modularity, reconfigurability, flexibility, cognitive adaptability (Zäh et al., 2009), self-diagnosis and self-resilience (Prakash et al., 2009) for product, process, and system models. Therefore, the introduction of a change and its propagation triggers a multitude of unpredictable and complex change scenarios that manufacturing firms have to deal with to stay competitive. This challenge is described as the concurrent/coordinated evolution of products, processes, and systems, in other words, "co-evolution" in the knowledge domain (Tolio et al., 2010).

Therefore, co-evolution, initiated by dynamic forces, constructs the main challenge for operations management and manufacturing engineering (Algeddawy & Elmaraghy, 2010). The next section will briefly discuss the co-evolution paradigm that has to be addressed to secure the evolution of manufacturing enterprises.

1.3.2. CO-EVOLUTION

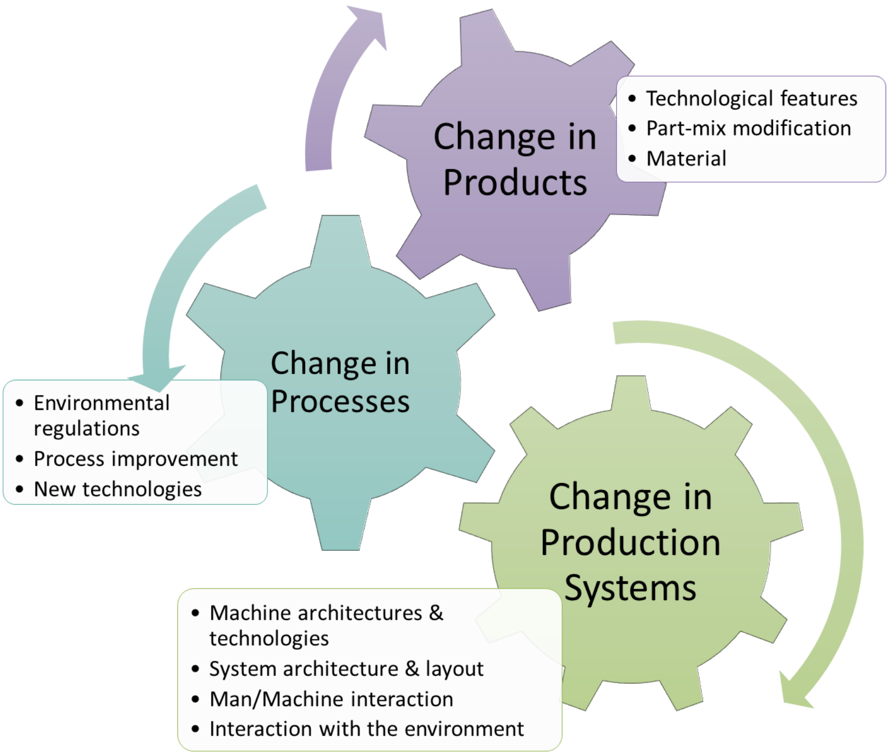

Figure 4 Co-evolution paradigm [adapted from (Tolio et al., 2010)*]*

The co-evolution paradigm shown in Figure 4 Co-evolution paradigm [adapted from (Tolio et al., 2010)] depicts the competence to manage the propagation of engineering changes within the product, process, and system domains of an organisation to achieve competitive advantage by responding to the external market and industry dynamics (Tolio et al., 2010). Recently, more and more industrial firms are being increasingly challenged in relation to the co-evolution problem. Companies need more synchronisation and simultaneous engineering of process, product, and factory models to deal with the challenges forged by the co-evolution paradigm. Therefore, digital tools to support both production and product lifecycle engineering processes are becoming more crucial. However, when considering the product design, process, and manufacturing system engineering, most of the available digital tools are traditionally designed and developed to focus on more specific issues instead of the whole due to obvious complexity issues. This situation is becoming more critical, considering the communication, collaboration and knowledge management required for concurrent engineering (Mottura et al., 2008). Therefore, the integration, interoperability, and harmonisation of knowledge, methodologies, tools, and technologies are critical requirements. Accordingly, one of the most relevant challenges for manufacturing engineering is developing more innovative approaches to integrate the product, process, and system (manufacturing system, factory, supply chain, etc.) domains to achieve more holistic, flexible, modular, and scalable operations (Azevedo & Almeida, 2011).

Despite the momentous developments regarding digital tools and manufacturing solutions, the inefficiency of such tools within highly dynamic environments is still significant. Product Lifecycle Management (PLM) tools are acknowledged to support designers, suppliers, manufacturers, and sales partners to manage product information throughout the entire product lifecycle, from the concept stage through engineering, prototyping, verification, manufacture, service, and disposal. Although the PLM tools encompass the requirements for being a shared platform to exchange, represent and capture a wide range of data, the boundary between the digital tools for product and process design and the tools for manufacturing and the required system design is still strong (Prakash et al., 2009). Another reflection of this issue is the weak link between product design and manufacturing, for example, process planning. This is because of the high complexity of integrating information on the production process and physical equipment design and its performance. The weakness of the link between product and production models is more apparent, especially when we consider the dynamism of models in the product, process, and system domains. Therefore, holistic tools, strategies, methods, and approaches are paramount to handle the co-evolution problem.

The scientific community has given particular attention to a holistic approach for the integrated representation of manufacturing-related models throughout the last decades. VF (Onosato & Iwata, 1993b) was introduced as a critical aspect of virtual manufacturing, integrating the factory and product models. Later, it is defined *"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."* (Jain et al., 2001). The European Project titled the "Virtual Factory Framework" (Sacco et al., 2010; Tolio et al., 2013) extended the integration framework to enable the synchronisation between virtual models and physical systems. Therefore, the existing knowledge base in the scholarly literature and the challenges faced at Vestas oriented the direction of attention towards the VF concept in this study.

In regard to the wind industry, WTG manufacturing contains a wide range of diverse manufacturing operations, including *"heavy metal manufacturing (towers), large-size fibreglass composite material production (blades), complex and heavy parts assembly (gearbox, nacelle, generator, etc.), and electrical & electronic systems manufacturing (control and grid infeed systems)"* (Yildiz, Møller, Bilberg, et al., 2021). Therefore, the engineering of product, process and system models is becoming more challenging for WTG manufacturers like Vestas. Moreover, the tendering processes for wind energy projects are formed around the cost per megawatt, which has created significant pressure on WTG manufacturers to improve the output performance of their products. Undoubtedly, this results in more regular changes in WTGs in terms of redesigning the products and, therefore, their production processes and systems, including manufacturing, IT, supply chain, transportation, and installation systems.

Moreover, such changes oblige manufacturing organisations to shorten the lifecycles of their products, processes, and systems (Azevedo & Almeida, 2011). Thus, manufacturing organisations need to re-engineer their ever more complex products, processes, and system models within ever shorter times to deal with the co-evolution problem. Therefore, the challenges in terms of complexity and shorter lifecycles will be discussed in the next sections.

1.3.3. INCREASING COMPLEXITY

It is becoming apparent that the recent developments in digital solutions are disrupting the social, sociotechnical, economic, and operational nature of industries. In addition to the impact of innovation in society and on business models, products are also getting smarter and more complex, with new technologies like the Internet of Things (IoT), Digital Twin (DT), Virtual Reality (VR), cloud computing, artificial intelligence (AI), and machine learning. Although replacing combustion engines with electric engines in vehicles seems a transition to simpler systems from a mechanical perspective, electric vehicles are much more complex considering the information and communication systems such as the IoT sensors, radars, DT and AI algorithms that are needed for autonomous driving. The same applies to the aerospace industry. Especially considering that the success and reliability of Space Exploration Technologies Corporation's (Space X) launch vehicles' vertical landing significantly depends on the avionics, navigation, guidance, and control systems, increasing complexity becomes more noticeable[7]. Similar to the automotive and aerospace industry, the wind energy industry is being challenged by the increasing complexity of WTGs over time.

Together with increasing product variances, modularity mainly imposed by increasing size, weight and regulations extends the impact of complexity from manufacturing to the supply chain, transportation, and installation operations. One of the latest WTG of Vestas, for example, has a 236 meter diameter rotor with a 115 meter long single wind blade[8]. Even though the wind blade is among the lightest of the main components of a WTG, its weight reaches 70 metric tonnes per unit for transportation[9], resulting in significant complexities for production operations as well as transportation and installation. Such complexities require synthesis between a great variety of engineering processes during New Product Introduction (NPI) operations and pose a threat of serious delays and quality issues.

Although new technologies provide opportunities for improved performance and higher profitability, considering that the speed of evolution in complex systems depends on the level of stability/maturity of the intermediate forms (Jacobson, 1955; Simon, 1962, 1996), we can argue that there is a need for greater maturity in such technologies. Therefore, more complex, and interdisciplinary, decisions are required to be made by organisations to accommodate the vital long-term impacts for enterprises (Souza et al., 2006).

1.3.4. SHORTER LIFECYCLES

While manufacturing organisations are improving their product performance and quality as well as associated production systems and processes by utilising novel technologies, accomplishing such improvements as fast as possible is strategically vital to secure a competitive advantage. Between 1979 and 1989, for example, Vestas manufactured seven different WTGs in 10 years, compared to 21 different WTG models between the years 2004 and 2014[10]. Although there have been significant improvements in engineering tools and technologies since the early 1980s, when we consider the corresponding increase in WTG complexities, this data provides valuable evidence of the increasing pressure on manufacturing organisations to introduce new products within shorter times.

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[7] https://www.spacex.com/media/falcon_users_guide_042020.pdf

[8] https://www.vestas.com/en/products/offshore%20platforms/v236_15_mw#!

[9]https://www.vestas.com/en/products/4-mw-platform/v136-_3_45_mw#!technical-specifications

[10] https://www.thewindpower.net/manufacturer_en_14_vestas.php

This challenge also demands higher complexity in production, including mass customisation as well as the operations, while reducing the time-to-market (Azzi et al., 2012; Cohen et al., 2019). It is visible that such pressure will inevitably require similar complexities to be handled in all of the product lifecycle stages such as supply chain, service, and maintenance. As a result of this, integrating digital tools and models along all the whole product lifecycle is becoming more pivotal to prevent delays, uncertainties, and to ensure successful product introduction. Therefore, executing continuous transformation in the product, process and systems domain while preserving faster, feasible and profitable co-evolution is paramount.

Despite the abovementioned challenges, there have been significant developments in recent technologies, concepts, and approaches for the next generation industry, namely Industry 4.0, for increased flexibility, higher quality, mass customisation and shorter time-to-market (Zhong et al., 2017). Vestas, together with its various manufacturing facilities and operations that constitute the application context for our research, is a global leader in sustainable energy solutions and maintains relatively advanced digital products, capabilities, processes, and manufacturing systems. Therefore, we will discuss the opportunities and motivations of the application domain further on.

1.4. OPPORTUNITIES

1.4.1. EMERGING TECHNOLOGIES

Although innovation and technology are among the major dynamics that are forcing industries to evolve faster, emerging technologies like IoT, DT, AI, VR, cloud computing, blockchain, etc., are opening up novel ways to handle co-evolution and to adapt to unpredictable conditions (Napoleone et al., 2020; Qu et al., 2019), with smaller, cheaper, and smarter sensors, better connectivity, and cloud computing-enabled IoT solutions, as well as their industry-specific applications and new notions like the Industrial Internet of Things (IIoT) (Gilchrist, 2016). The big data of physical entities provided by IoT solutions provide much-needed fuel to run predictive and prescriptive analytics in advanced simulation tools and enabled DTs. DT enables digital mirrors of physical objects, systems and environments, with advanced data analytics and simulation capabilities. It enables predictive and prescriptive studies in manufacturing for planning, evaluating, analysing, and optimising the production systems (Tao et al., 2019). Such advances in DT solutions enable the development of Cyber-Physical Systems, which are also called Cyber-Physical Production Systems (CPPSs) in the manufacturing context. CPPSs are also considered among the building blocks for the Smart Factories of the future by enabling adaptability to unexpected changes (Cheng et al., 2018; Monostori et al., 2016; Xu et al., 2018).

Developments in VR technologies have provided immersive virtual environments for visualising abstract data, designing, verifying, and analysing models, as well as advanced learning training (Cote et al., 2008; Dam et al., 2000; Mobach, 2008; PWC, 2016). Although real-time collaborative optimisation of multiple subsystems remains a challenge (Qu et al., 2019), recent developments in modelling and simulation (M&S) tools provide viable solutions to integrate the data across all manufacturing value chain stages (Mourtzis, 2020). Moreover, using advanced M&S solutions in manufacturing operations is also considered one of the important steps in achieving Smart Factories (Weyer et al., 2016). Some of the main characteristics of Smart Factories have been determined as interoperability, modularity, complexity encapsulation, intelligence, virtualisation, collaboration and dynamic reconfigurability (Napoleone et al., 2020). Moreover, recent advances in M&S tools with 3D modelling and embedded VR capabilities that allow more advanced analysis and interaction with the models provide viable solutions for advanced communication and collaboration.

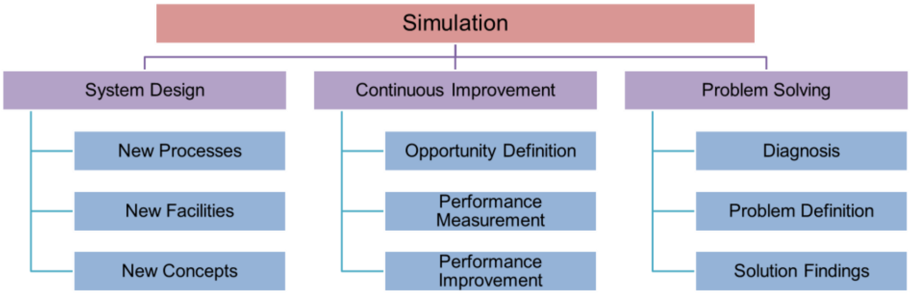

Figure 5 Simulation capabilities in manufacturing operations [adapted from (Mourtzis, 2020)*]*

Figure 5 Simulation capabilities in manufacturing operations [adapted from (Mourtzis, 2020)] illustrates the capabilities of modelling and simulation tools within the context of manufacturing operations. Recent studies also show that 3D Discrete Event Simulation (DES) tools, together with VR capabilities, provide better performance in model development (Akpan & Shanker, 2019). Moreover, 3D DES with VR enables faster experimentation, verification, validation, and analysis.

Therefore, virtual models of manufacturing systems that utilise the data from real factories and integrate the product models from PLM tools can provide decision-support solutions for smart production systems by enabling simulation-based data analytics from design to manufacturing (Lin & Fu, 2001). Thus, extending the VF concept with DT technology can respond to the need for cyber-physical integration by enabling faithfully-mirrored VF models equivalent to their physical counterparts in various dimensions during the co-evolution (Cheng et al., 2018). Accordingly, utilising the abovementioned digital solutions together with the long-established VF concept *"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"* (Jain et al., 2001) can provide feasible solutions for manufacturing organisations to handle co-evolution. In addition, *"for some initiatives, the Smart Factory is the practical implementation of the VF concept and, possibly, the manifestation of the Industry 4.0 initiative being pursued"* (Turner et al., 2016; Yildiz & Møller, 2021). Moreover, various initiatives and developments in the application domain (Vestas) of this research are also aligned with the abovementioned advances in the emerging technology domains.

1.4.2. APPLICATION CONTEXT

As mentioned earlier, Vestas provides the application context that encompasses the requirements, problems, as well as opportunities and motivations. When we initiated our research activity, Vestas was at the early stages of an all-comprehensive Manufacturing Execution System (MES) deployment. Vestas installed the DELMIA APRISO solution from Dassault Systems[11] , which can provide real-time traceability for manufacturing processes, warehouse, quality, maintenance, labour, and to some extent, shopfloor machines. This is provided with a feasible platform to access real-time manufacturing execution data across all factories worldwide in real time.

Vestas is also among the limited number of global manufacturing organisations that can afford all-comprehensive PLM and Enterprise Resource Planning (ERP) solutions. Elsewhere, Parametric Technology Corporation's (PTC) Windchill PLM software[12] is in use for PLM operations. Windchill also provides Product Data Management (PDM) and Manufacturing Process Management (MPM) solutions. While the PDM solution utilises the Engineering Bill of Materials (eBOM), the MPM solution manages the Manufacturing Bill of Materials (mBOM), which is created by restructuring eBOM. Although the MPM solution was under deployment at the initial stage of the research project, the PDM platform makes it possible for us to access reasonably mature product models. SAP solutions[13] for ERP operations have been acquired by Vestas, and provide relatively easy access to comprehensive data regarding enterprise operations. Such digital platforms, in short, provide quite mature and advanced data across the manufacturing value chain. But there is still a lack of an integrated and dynamic representation of production operations incorporating both product and system models. Thus, the current situation and digital setup in the application domain provides a suitable environment to research a VF solution.

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[11] https://www.3ds.com/products-services/delmia/products/delmia-apriso/

[12] https://www.ptc.com/en/products/windchill

[13] https://www.sap.com/index.html

Besides, ongoing development works across Vestas to utilise more DT technology and extensive capabilities for IoT solutions also provide practical resources in terms of the data, development capabilities and skills required for the Smart Factories research. Moreover, Vestas is conducting research and development (R&D) works to utilise immersive VR and augmented reality (AR) to support product development, production, and training operations. Therefore, the empirical evidence on the industrial demands and developments also aligns with the potential advances of the VF concept addressed by scholars.

Although the diversity of the Vestas manufacturing operations, such as large-size fibreglass composite material production, heavy metal manufacturing, complex and heavy parts assembly, and electrical and electronic systems manufacturing, is recognised above as a challenge, it can be considered as an opportunity to test the designed artefact in various industrial cases. This also means that the experts in the WTG manufacturing enterprise potentially have diverse skills and experience in various manufacturing operations. Such diversity enables rich data for the evaluation of industrial demonstrations.

Within the context of the challenges as mentioned earlier and opportunities, the scholars and Vestas experts considered an empirical study on the VF concept more valuable and feasible for both the application and knowledge domains. Although the VF was not a new concept, the scholars and experts considered that extending the old-established VF concept with emerging technologies like DT, VR, and 3D DES has the potential to exploit its implications as well as to discover knowledge, closing the gaps in the knowledge base addressed by scholars. It is also worth mentioning that some of the leading manufacturing firms, including Volvo Group Global and Ford Motor Company, are also implementing the VF concept (Jain et al., 2017). All in all, Vestas provides a viable research context with various convenient cases and favourable resources and the capabilities required for rigorous theoretical and empirical study.

1.5. MOTIVATIONS

Although the research presented in this dissertation is not a business case-oriented study, there are sound expectations for exploring new knowledge during the research study that can provide adequate evidence to the industry partner to capture business value. These expectations originated from the conventional motivations of a manufacturing enterprise as depicted in Figure 6 Value convention of application context.

Value capture comprises two main processes, namely, 1) the cost reduction of production operations by supporting the existing production operations and transformation of manufacturing systems as well as risk mitigation and 2) the value added by decreasing the time-to-market and servitisation. However, value creation for the products and solutions for service are not covered by the current research project.

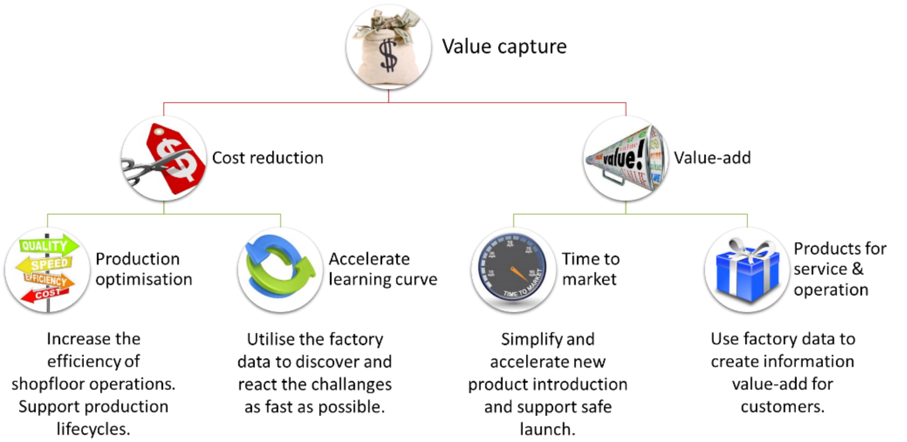

Figure 6 Value convention of application context

Capturing value by supporting existing manufacturing operations by developing VF solutions that integrate real-time production data from MES as well as PLM solutions is considered relatively more apparent. Moreover, performing prototype building by utilising VF solutions, particularly Virtual Prototyping (VP), potentially promises significant business value for decreasing the physical builds, which have significant costs due to the nature of the materials and operations involved. In addition, utilising the VF concept for planning, designing and training for complex manufacturing operations is considered significantly valuable to accelerate the learning curve. This motivation is complementary to decreasing the time-to-market during NPI operations. Moreover, decreasing the time-to-market has the potential for strategic competitive advantage in terms of gaining a stronger position to win cost per megawatt-oriented tenders by introducing higher performance WTGs to the market.

Overall, the research project maintains the motivation to explore the opportunities for utilising the existing product, production, and system data to improve the long-term impact of decision-making processes within the context of complex operations. Accordingly, the objectives and goals of the Smart Factories research project will be introduced and elaborated in the next section.

1.6. THESIS CONTEXT AND OBJECTIVES

Since the Smart Factories project has been developed through the collaboration between industry and academic stakeholders, the objectives of the project concern the appropriate execution (empirically relevant & academically rigorous) of the overall tasks illustrated under the project scope (in Figure 2 Scope of the Smart Factories project). The industrial domain mainly focuses on the practical relevance and validity of the study and the pragmatic outcomes of the work. The academic domain, however, concerns the rigour of the research in terms of the relevance and validity of the research questions, the methodology and the contribution to the knowledge base in terms of theoretical contributions, as well as closing the knowledge gaps. Since the project has been initiated and framed with generic expectations required to develop the Smart Factories of the future, we used the term "project" to refer to the overall work performed during the three years, with the active involvement of all stakeholders. Therefore, we would like to take the opportunity to stress the difference between the scopes of the Smart Factories Project and the VF research. While the first one encompasses the overall objectives of the industry and academic collaboration for research and development, the latter incorporates particularly the scholarly work on the VF subject. Thus, the Smart Factories project aims to solve the abovementioned empirical problems, by

1) designing artefacts (concepts, models, methods, architectures, demo, etc.) that can guide the industry experts to solve empirical problems,
2) developing and demonstrating the demos within the industrial cases,
3) evaluating the designed solutions based on empirical demonstrations, and
4) disseminating the discovered knowledge.

Recent developments in emerging technologies, the challenges, opportunities, and motivations within the application domain, as well as existing artefacts and research gaps in the knowledge domain, were considered together with the industrial and academic stakeholders of the project. As a result, a research activity that is extending the existing VF concept (Jain et al., 2001; Sacco et al., 2010) with a DT and VR capability to enable the development of virtual replication of manufacturing operations (Grieves, 2014) is considered a promising solution in which product, process and system models can be developed, simulated, optimised, and manipulated concurrently to handle co-evolution. Thus, the VF research work under the Smart Factories project is framed to focus on the design, development, demonstration, and evaluation of the novel DT-based VF concept within industrial cases to establish a systemic design and development approach. The new knowledge discovered in each phase of the study was disseminated in scholarly journals and formed the foundation of this PhD dissertation. Therefore, the objective of this thesis can be expressed as follows:

> *Establishing comprehensive and methodical foundations for the empirical, conceptual, and philosophical discussions supporting the previously discovered and disseminated knowledge on DT-based VF employing a collaborative virtual reality capability that can integrate product, process, and system models.*

The research work aims to ensure both the rigour of the study by designing a novel VF concept based on existing artefacts and theories in the knowledge base, and the relevance of the study by actively participating in/executing the development and demonstration of VF processes in the application environment. Thus, this thesis aims to support the rigour of the research by presenting the three-year-long study in a holistic and confined way by aggregating and linking the research phases, questions and methodology. It is expected that the design, development, and evaluation of demonstrators will produce essential outcomes as valuable knowledge both for manufacturers from the application domain and for scholars from the academic domain.

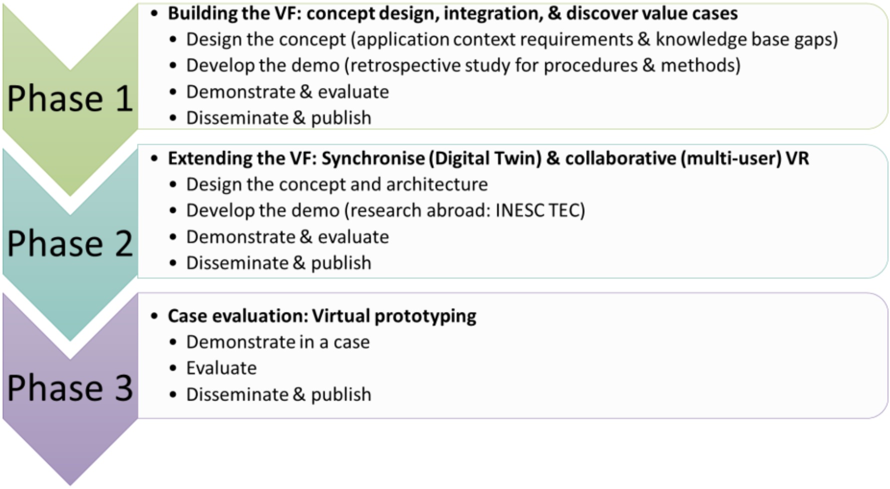

Figure 7 Research phases (work packages)

The research project is planned to be executed in three phases (also called Work Packages), each of which represents the iteration of two phases of the project scope (1- Idea Generation, 2- Proof-of-Concept). Figure 7 Research phases (work packages) illustrates the three phases of the overall research project. Phase 1 is focused on the VF concept design, demo development, integration (product, process, system models), and exploring the value of promising cases. Since the intended solution covers a wide range of data, models, and technologies, the initial stage of the project aims to focus on constructing meta-artefacts and solutions; moreover, it aims to discover the future research and development directions for both application and the academic domain. Phase 2 focuses on extending the demo with bidirectional data integration between the shopfloor (via MES) and the simulations (DT) and collaborative and coordinated VR training (Multi-user VR) capabilities. The research period of Phase 2 overlapped with the collaboration with MASSIVE LAB, which accommodates capabilities for multi-user VR development. In order to take advantage of such expertise and capabilities, the research abroad/collaboration period was dedicated to extending VF with DT and multi-user VR capabilities.

Phase 3 concentrates on evaluating the DT-based VF in a high-value promising industrial use case (VP case). The outputs of each phase provide inputs for the next iterations/phases. The demonstration and evaluation of the concept and demo during the first and second phases by experts and scholars, for example, provided the data to determine the evaluation case of Phase 3, which is VP in NPI operations.

Each phase aimed to contribute to the knowledge base by disseminating the discovered knowledge during the study with a minimum of one (peer-reviewed) publication in a relevant and respected international scholarly journal. In total, eight peer-reviewed scholarly articles, including conference and journal papers, were generated, five of which were employed within this dissertation content.

Therefore, the structure of the thesis and utilisation of the papers are discussed in the next section.

1.7. CONTENT AND STRUCTURE

This dissertation is written as a collection of papers, each of which addressed various transdisciplinary empirical studies. Moreover, due to the interdisciplinary and transdisciplinary nature of the study, various dissemination activities were performed in terms of participating in and publishing at scholarly conference events. Thus, some of the journal papers used in this thesis were extended from and/or built upon previously published conference papers. Although the essential scholarly contributions are mainly incorporated in the journal papers, the conference papers also consolidate the original and authentic content. Therefore, this thesis is built upon a collection of four journal and one conference papers, each of which addresses some of the empirical challenges as well as gaps in the knowledge base. Meanwhile, the other works are also appended as a reference for the reader.

Figure 8 QR Codes for 1) DT-based VF simulations, 2) collaborative VR simulation, and 3) outbound supply chain simulation

Since the visual contents are potentially capable of containing and conveying extensive knowledge, we would strongly advise the readers of this thesis to review the publicly available videos on 1) integrated VF simulations (Yildiz, 2020a), 2) collaborative VR training (Yildiz, 2020b), and 3) outbound supply chain simulation work (Yildiz, 2022) as part of extending the VF concept to enterprise-level operations, before diving into the content of this dissertation. To maintain adaptability in the age of mobile technologies, the Quick Response (QR) codes to access the abovementioned media contents are provided in Figure 8 QR Codes for 1) DT-based VF simulations, 2) collaborative VR simulation, and 3) outbound supply chain simulation.

Table 2 Overview of papers covered in the thesis summarises the papers incorporated in this thesis.

Table 2 Overview of papers covered in the thesis

Paper 1: ***Building a Virtual Factory: An Integrated Design Approach to Building Smart Factories*** The purpose of this paper is to introduce a novel design approach for VF that integrates product, process, and production system models to support concurrent engineering of such models. Moreover, the paper also presents the actual development and demonstration of the proposed VF concept in a wind turbine manufacturing plant (Hub assembly line). Design Science Research methodology (DSRM) is followed, since it is more suitable to discover the effects of an intervention in the operations of exploring the generic design's practical usefulness as instrumental knowledge. The VF concept, architecture and its demonstration are presented and evaluated in the context of improving the performance in the reconfiguration and evaluations of new or existing manufacturing plants, reducing the design and ramp-up times, as well as supporting the management decisions.
Paper 2: ***Demonstration and Evaluation of Digital Twin Based Virtual Factory*** The purpose of this paper is to introduce the VF concept extended with DT and multi-user VR capabilities, as well as the demonstration and evaluation of the concept for supporting manufacturing companies to adapt to complex and dynamic environments by concurrently reforming and regenerating their product, process, and system models. The demonstration is performed in two different cases of WTG manufacturing, including a nacelle assembly line and wind blade manufacturing. Thirteen experts with diverse backgrounds and expertise participated in demonstrating and evaluating the proposed solution and demo. The evaluation focused on four dimensions of evolving complex systems: dynamic, open, holistic, and cognitive systems. The results show that the proposed concept has significant potential for supporting co-evolution by enabling concurrent engineering, virtual collaboration, VP, and shorter time**-to-**

market. **Paper 2** is a significantly extended version of **Paper 6**.
Paper 3: ***Virtual Prototyping: Evaluating the Digital Twin Based Virtual Factory for New Product Introduction*** The paper responds to the need for particular evaluation of the DT-based VF concept in the VP cases addressed in **Paper 1** and **Paper 2**. Therefore, the paper presents an evaluation of the DT-based VF concept for VP, particularly in the context of NPI operations of WTG manufacturing. The concept is demonstrated in two different cases, including wind blade manufacturing and nacelle assembly, and evaluated based on four different types of prototyping activities. These are 1) mock-up builds, 2) design prototypes, 3) process prototypes, and 4) 0-series production. The results show that DT-based VT can support experts to reduce the time-to-market and mitigate the risks of unforeseen issues. The paper is a substantially extended version of **Paper 8**.
Paper 4: ***Conceptual Foundations and Extension of Digital Twin Based Virtual Factory to Virtual Enterprise*** The paper attempts to 1) frame and discuss the conceptual and theoretical foundations of the DT-based VF to handle co-evolution in the complex manufacturing domain, 2) introduce and discuss the extension of the DT-based VF to the virtual enterprise, 3) generalise and discuss the prescriptive knowledge presented in **Paper 1, Paper 2,** and **Paper 3**. General systems theory and complexity theories were elaborated to frame the foundational principles of systems, their parts, interrelations of the parts, and particular propositions on the evolving complexity of systems' social, natural, and artificial structure. The concepts of business cycles are used to understand the laws of industries' evolution and the link between industry dynamics and the internal domains of manufacturing enterprises. Moreover, the paper aims to provide a theoretical foundation for the design principles of the DT-based VF concept as well as its extension to the virtual enterprise. Therefore, the paper is attempting to contribute to the knowledge base with theory elaboration by fulfilling the duality criterion of case studies, as (1) situationally grounded (empirically disciplined) and (2) having a sense of generality with broader theoretical understanding through abstractions.
Paper 5: ***Designing Collaborative and Coordinated Virtual Reality Training Integrated with Virtual and Physical Factories*** This paper introduces the design and development of collaborative and coordinated (multi-user) VR training simulations integrated with the VF and physical factory via MES. The demonstration and evaluation of multi-user VR training integrated with virtual and physical factories showed that such

integration could support various challenges in terms of effectiveness and efficiency with greater precision, accuracy, and reliability of the VR training data. Therefore, the papers contribute to the knowledge base by revealing implications in the immersive VR research domain.

Figure 9 Overview of thesis structure and papers covered in thesis chapters, outlines the structure of the thesis, including the purpose of each chapter and the respective papers on which each chapter was built. Although the various arguments and discussions of each chapter are built on the published articles, the author tried to avoid repeating the content of the papers in this thesis, but instead attempts to present an overview of the research and close some missing gaps that are not directly discussed in the published works for the readers of this thesis.

Next, the EMPIRICAL FOUNDATION chapter mainly introduces the united literature review and gaps of each research phase. However, since the main concepts, technologies, and the fundamental knowledge regarding the conceptual and empirical foundation of VF were introduced in **Paper 1**, it is mainly built upon the discussion in **Paper 1**. Chapter 3 THEORETICAL FOUNDATION is built upon **Paper 4**, which introduces and frames the conceptual and theoretical foundations for the DT-based VF concept. However, we took the opportunity to extend the theoretical discussion with more foundational and philosophical discussion before summarising **Paper 4**. Although each research phase shown in Figure 7 Research phases (work packages) incorporated specific DSR activity and presented the respective methodology in a particular paper (**Paper 1**, **Paper 2**, **Paper 3**), the overall research is designed in an iterative cycle. Therefore, Chapter 4 RESEARCH DESIGN introduces and discusses the overall research design which guided the three years of PhD study, after addressing some ontological and epistemological matters. Chapter 5 RESULTS summarises the results based on three journal papers as the main outcomes of the three research phases. While **Paper 1** focuses more on the initial design of the artefacts and development methods of the VF demos, **Paper 2** concentrates more on the extension of the concept with DT and the multi-user VR capability and respective demonstration and evaluation. **Paper 3** directs the main attention to the particular implications of the DT-based VF concept into NPI operations for VP. Since Chapter 6 DISCUSSION frames the various discussions, limitations, and implications of the research, we took advantage of exploiting **Paper 5** for elaborating the implications of the DT-based VF concept in other research domains, particularly VR training. Chapter 7 CONCLUSION summarises and concludes the overall PhD study and this dissertation.

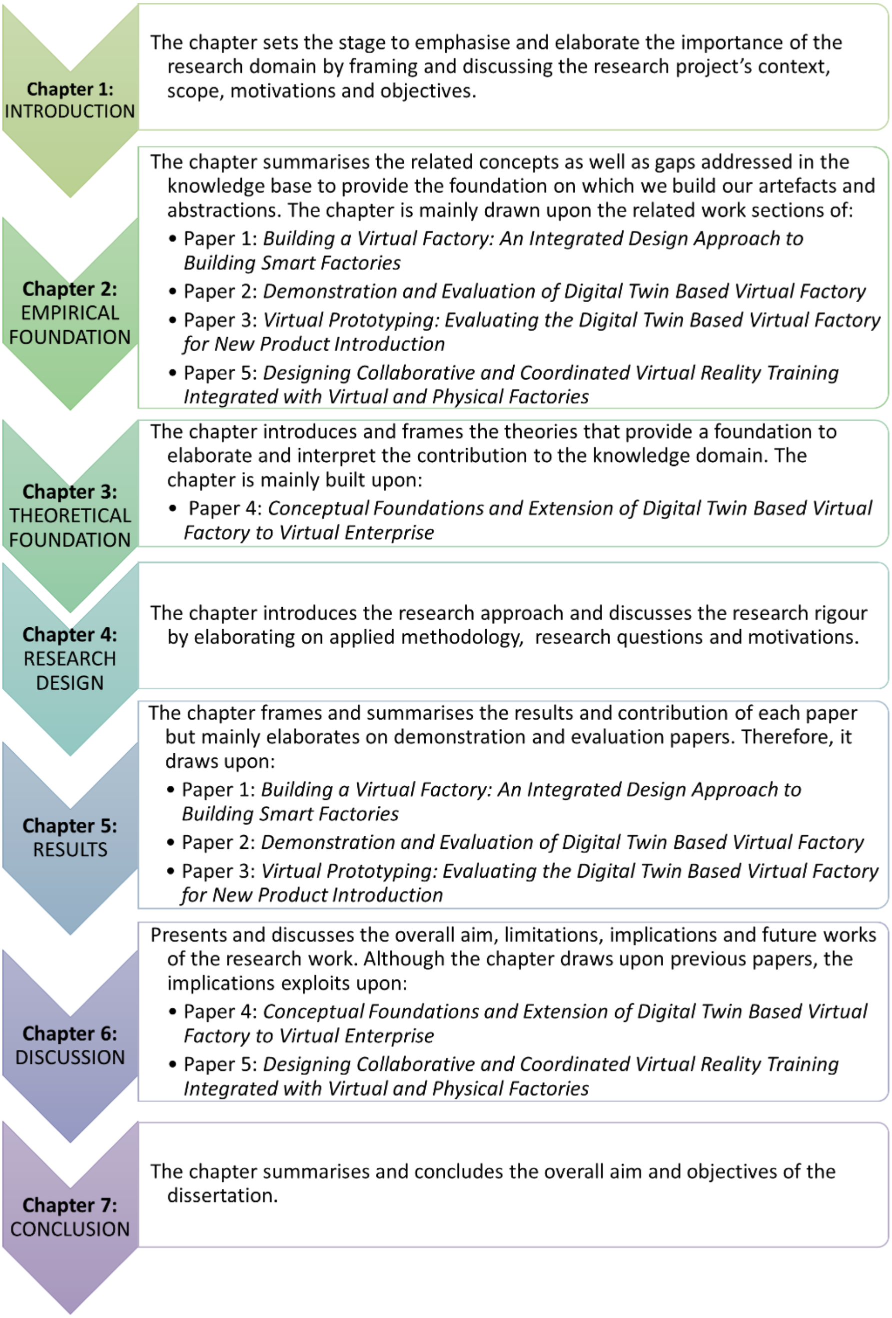

Figure 9 Overview of thesis structure and papers covered in thesis chapters

CHAPTER 2. EMPIRICAL FOUNDATION

The VF research project between industrial and academic stakeholders was formulated in the scope of studying the means for achieving capabilities incorporated by smart factories. Therefore, there is a need to present and discuss the empirical background of the subject research, including various related technological concepts. In this chapter, some of these empirical concepts, as well as their respective history, gaps and future research trends, will be introduced to provide a basis for a common understanding of how they are employed in our research and what empirical gaps were addressed in the knowledge base. Therefore, this chapter provides a more structured and established foundation for the identified problems, opportunities, and motivations in respectively Section 1.3, Section 1.4, and Section 1.5 from the knowledge base. Thus, this chapter mainly draws upon the literature review and related work sections of **Paper 1**, **Paper 2**, and **Paper 3**. Moreover, some gaps in the knowledge base that were identified to be addressed by the VF research work are also introduced.

2.1. SMART FACTORY

Due to the leap in information technologies that has emerged during the last two decades, conventional production concepts and manufacturing industries face profound changes. Together with the evolution in the competitive dynamics of the markets, the organisational and technical architectures of production systems are affected by the computer-integrated enterprise (CIE), computer-integrated manufacturing (CIM), and factory automation (Hozdić, 2015). Factories are becoming more flexible than ever to respond to ever-changing modern market dynamics. Therefore, on the threshold of Industry 4.0, modern smart manufacturing concepts should be integrated with both horizontal (integration of data flow between suppliers, partners, and customers) and vertical (integration within the organisational frames from development to the final product) production entities to meet the industrial and non-industrial partners' needs (Hozdić, 2015). Such integration between physical, digital, and virtual entities of production operations, which is also called CPPS, is the foundation for the smart factories to achieve rapid response to market changes (Monostori et al., 2016).

Although the term "smart factory" is used extensively by industry experts and scholars, a commonly accepted and consistent definition is absent (Schou et al., 2021). Yet the concept of a smart factory is envisioned from recent advances in information and communication technologies (Westkaemper et al., 2005). Thus, it was influentially defined as a manufacturing plant that enables *"dynamic organisation, utilising human-responsive context-aware production lines, maintaining connected smart machines, data warehouses, and integrated sensing technologies"* (Radziwon et al., 2014; Yildiz & Møller, 2021). A similar definition of the smart factory was formed as a "*self-organised multi-agent system assisted with big data-based feedback and coordination*" by (Wang, Wan, Zhang, et al., 2016). They also demonstrated a distributed intelligent negotiation method for achieving smart factories (Wang, Wan, Li, et al., 2016).

Moreover, extensive research is dedicated to the review of smart manufacturing technologies, including their systems, concepts as well as roadmaps of various countries for the digitalisation of those countries (Kang et al., 2016). A recent review by (Napoleone et al., 2020) was conducted on CPSs as the essential building blocks of future smart factories from the perspective of operations management to distinguish the technological and operations management characteristics of such systems. Both studies addressed the lack of strategic approaches and concrete implementation guidelines for the utilisation of the technologies and methodologies in various lifecycles such as design, planning, operations and maintenance (Kang et al., 2016; Napoleone et al., 2020). Moreover, particular attention to 1) the need for knowledge on *"how new technologies should be combined together and managed to successfully face the current and future scenarios"* and 2) *"an investigation on the effects of both technological and operations management characteristics on business competitiveness"* was suggested by (Napoleone et al., 2020). These gaps addressed in the knowledge base were among the main motivations of the VF research presented in this thesis.

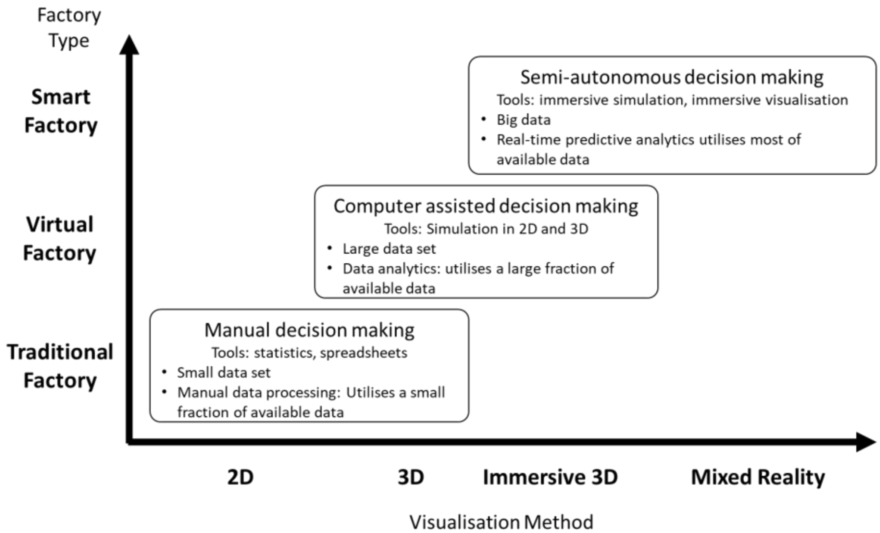

Figure 10 Factory types and data visualisation methods [adapted from (Turner et al., 2016)]

Moreover, some initiatives considered that the practical development and implementation of the VF concept is the manifestation of the fourth industrial revolution to persevere in smart factories (Turner et al., 2016). Accordingly, the association between kinds of factories and data visualisation methods were illustrated as in Figure 10 Factory types and data visualisation methods [adapted from (Turner et al., 2016)]. Therefore, we acknowledge the significance of the VF concept utilising the DT, VR, and 3D DES technological concepts as well as its demonstration in industrial cases for practical implementation of smart factories of the future. However, although the VF concept was introduced two decades ago, a commonly accepted concept definition and artefacts are absent. The following section will present a short review of the studies on the VF concept.

2.2. VIRTUAL FACTORY

Some of the earliest indications of the VF go back to the early 1990s. A study by (Masahiko Onosato & Iwata, 1993) proposed the "Virtual Manufacturing" concept that incorporates product and factory models as an essential aspect of the VF. Afterwards, VF appears in various ways, including virtual organisations, emulation facilities, and integrated simulations (Jain et al., 2001). However, a more prominent and early definition of the VF concept "*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"* that embodies factory and product models was introduced by (Jain et al., 2001). Later on, a quite similar virtual manufacturing concept was introduced as an integrated virtual environment that utilised simulation and VR technologies for the effective and economic introduction of products (Souza et al., 2006). Another noteworthy study on the virtual holonic factory concept was conducted by (Bal & Hashemipour, 2009) for achieving robust and dynamic manufacturing scheduling using VR technology.

Here we should mention the term "holon" briefly for more clarification. Herbert Simon's theory on the evolutionary speed of complex systems (Simon, 1962, 1996) led to the introduction of the term "holon" by Arthur Koestler (Edwards, 2003). In his book called "*The Ghost in the Machine*", he analysed the hierarchies and intermediate forms of complex systems and proposed the word *holon* in order to explain the hybrid nature of sub-wholes and parts in real-life systems (Koestler, 1968). His works therefore led to the development of the "*theory of holon*" as well as associated studies including multi-agent systems (Fischer, 1999) and holonic manufacturing systems (Bal & Hashemipour, 2009; Valckenaers et al., 1998). Therefore, although it seems a distinct term, "holonic factory", which represents factories and their respective sub-systems as an integrated virtual model, could be considered as similar to the VF concept.

In more recent studies, (Jain et al., 2016) introduced VF as a multi-resolution model of actual manufacturing systems. The respective demonstration for a faster deployment approach for VF was also presented by (Jain et al., 2017). Moreover, various VF tools as a platform for collaborative design and analysis of manufacturing operations were also introduced by (Yang et al., 2015). A broader perspective of VF as a virtual environment that enables collaborative business process monitoring was conducted by (Shamsuzzoha et al., 2017). They focused on the extended role of VF to achieve various business opportunities in the whole business context.

It is worth mentioning that not all the studies were dedicated only to the capabilities and roles of the VF tools and technologies. Considerable research activities focused on the data models and ontologies to capitalise on the potentials of CPSs as well as the interoperability of digital tools (Agyapong-Kodua et al., 2013; Kádár et al., 2013; Lee & Banerjee, 2011; Negri et al., 2017). Moreover, the Italian Flagship Project named “Factories of the Future” (La fabbrica del futuro 2012–2018) resulted in a significant contribution to the VF domain (Tolio et al., 2019). Various scholarly works under this extensive project provided a sound basis for the knowledge base for the VF research presented in this thesis.

The VF concept developed and introduced in **Paper 1** adapted various aspects of concepts previously introduced by (Choi et al., 2015; Jain et al., 2001; Tolio et al., 2013). Particular clarification and discussion of the similarities and differences were presented in the corresponding paper (Yildiz & Møller, 2021). Since the DSR artefacts evolve and become mature through numerous design and evaluation cycles (Sonnenberg et al., 2012), the VF artefacts were slightly changed and extended in subsequent papers and took the form as seen in Figure 11 Digital Twin-based Virtual Factory concept (Yildiz et al., 2019, 2020b; Yildiz, Møller, & Bilberg, 2021a).

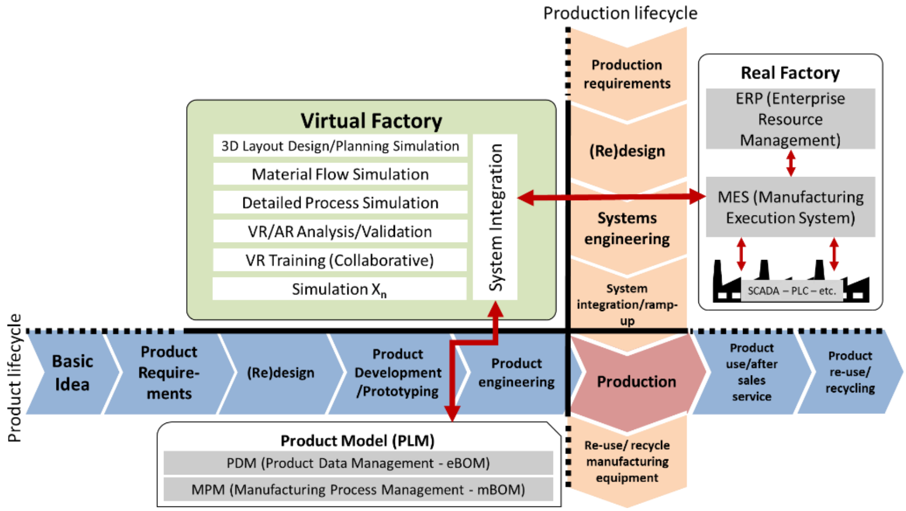

Figure 11 Digital Twin-based Virtual Factory concept (Yildiz, Møller, & Bilberg, 2021c)

The DT-based VF concept has been developed based on various technological concepts due to 1) the challenges and requirements of the application domain, 2) gaps and existing developments in the knowledge base, and 3) recent advances in such technologies. Therefore, the following sections will briefly discuss such technological concepts, namely, M&S, DT, and VR. Integrating such technological concepts does not only exploit the value of the VF concept, but such integration also enables extended valuable cases for both scholarly works and industrial implications. Thus, the next section will address various related works in the knowledge base on M&S as well as addressing some gaps that can be addressed in the context of VF research.

2.3. MODELLING AND SIMULATION

Recent advances in M&S in terms of data integration, data generation, data analytics, model-based design and embedded VR capabilities provide a sound basis for considering M&S as a founding technological concept to develop the VF concept (Alcácer & Cruz-Machado, 2019; Jain et al., 2017). Moreover, achieving M&S capabilities within the manufacturing operations was also considered as among the significant steps for accomplishing smart factories (Weyer et al., 2016). Two recent comprehensive reviews investigated the M&S technologies in terms of the evolution of the technologies, recent developments and knowledge gaps in the application domain (Mourtzis, 2020; Mourtzis et al., 2014). Both reviews addressed the significant data integration capabilities of M&S technologies across the manufacturing value chain. However, essential gaps for VF research were revealed as 1) the need when using VR and CIM technologies for collaboration and communication, 2) utilising VR as an integrated (embedded) function of VF, and 3) a lack of advanced planning functions of MES, also called *"decision myopia"*. The integration with VR-enabled VF simulations and MES and evaluation of the solution in industrial cases for collaboration and communication was addressed in **Paper 1** with the aim of closing such gaps.

In this regard, the integration of DES and MES consolidates the potential for handling decision myopia. Moreover, some review studies dedicated to VR-integrated 3D DES showed the significant advantages of 3D/VR-enabled M&S tools for 1) analysis, validation, verification, experimentation, and 2) the development of VF, which is inherent in the realisation of the smart factory (Akpan & Shanker, 2019; Turner et al., 2016). Furthermore, some studies considered the VF as a prerequisite for dealing with the co-evolution paradigm (Tolio et al., 2013).

Some of the essential studies mentioned above provided the empirical foundation for utilising M&S technologies for the empirical design and development of the VF concept introduced in **Paper 1**. Moreover, such scholarly works in the knowledge domain supported the study approach assumed by VF research to pave the way to building smart factories. In this regard, utilising the VR technology and near-real time data from the manufacturing operations is considered highly valuable for more accurate and precise factory models by enabling DTs in VF simulations (Yildiz & Møller, 2021). Therefore, the next two sections will summarise the history and present state of related DT and VR studies respectively.

2.4. DIGITAL TWINS

The DT concept was first introduced by Grieves in 2003 (Grieves, 2014) during an industry presentation. Later on, the concept was revisited and redefined as *"an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin"* in NASA's integrated technology roadmap (Glaessgen & Stargel, 2012). Since then, the DT concept has been given significant attention by scholars and industry experts. Nevertheless, there is a lack of common understanding and definition of the DT concept. Some scholars endorse the simulation aspect of the DT concept (Maurer, 2017; Weyer et al., 2016), while some focus on virtual, physical and connection aspects (Grieves, 2014; Qi & Tao, 2018). Indeed, such extensive focus on the DT concept led to various associated notions like the digital twin shopfloor (DTS) (Tao & Zhang, 2017) and experimental digital twins (Schluse & Rossmann, 2016).

NASA's definition of DT, which concentrated on real-time mirroring and probabilistic simulations of the physical counterpart, was limited with bidirectional data integration. Therefore, (Qi et al., 2018) underlined that DTs should be more dynamic simulations of physical systems instead of just mirroring such systems, and considered the interaction between physical and virtual spaces the inevitable direction. Achieving such dynamism and bidirectional data integration can enable digital counterparts to guide their physical counterparts to respond to the changes in their respective environments (Tao et al., 2017).

In addition, large-scale implications of DTs in complex and flexible systems can enable the development of smart manufacturing systems by the interoperability and collaboration services of DTs. Therefore, given the trend towards developing smarter systems-of-systems, DTs are acknowledged as being among the core elements of complex CPPSs for analysis, design, end operations management (Park et al., 2020; Zhang et al., 2020). As a result of the huge potential and increasing attention to DTs, there has been a significant increase in the number of scholarly works as well as literature reviews on the subject studies in recent years (Cimino et al., 2019; Hribernik et al., 2021; Lattanzi et al., 2021; Leng et al., 2021; Lim et al., 2020; Liu et al., 2021). Due to the extensive review studies on the DT concept, we draw the DT extension of the VF concept on various existing reviews.

One of the consequential reviews on DT classified the physical and digital counterparts from the data integration level (Kritzinger et al., 2018). Accordingly, they distinguish the digital model, digital shadow, and DT, as seen in Figure 12 a) digital model (DM), b) digital shadow (DS) c) digital twin (DT) (Kritzinger et al., 2018), and such segregation and bidirectional real-time data integration are generally accepted in later studies (Lattanzi et al., 2021). (Kritzinger et al., 2018) concluded that the majority of the studies (55%) were only concept development, and only a small part (18%) of the studies give attention to bidirectional data integration or twin control aspect of the concept. What is more significant is that similar results were presented in later reviews (Cimino et al., 2019; Lattanzi et al., 2021; Lim et al., 2020; Liu et al., 2021) when addressing the importance of 1) bidirectional data integration, 2) utilising VR in DT simulations, and 3) case-specific industry implementation. Thus, the extension of the VF concept with bidirectional data integration with MES in **Paper 2** aimed to address such needs.

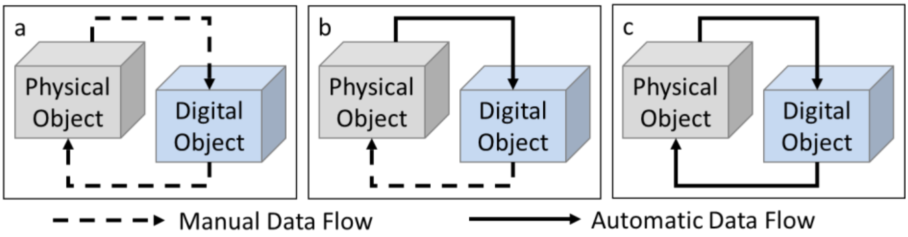

Figure 12 a) digital model (DM), b) digital shadow (DS) c) digital twin (DT) (Kritzinger et al., 2018)

Some studies (Lattanzi et al., 2021; Rosen et al., 2015; Tao et al., 2019; Vachálek et al., 2017) were particularly dedicated to industrial applications of DT technologies and showed that prognostic health management, product design, and production covers most of the development and implementation areas for DTs in the industry. Some of the potential value-promising cases for DTs in production systems are determined as planning, evaluating, and optimising the production by self-learning and self-organising. Interaction and collaboration of DT simulations in production is considered valuable for the consistency of process validations during the production systems engineering phases (Rosen et al., 2015; Vachálek et al., 2017). Moreover, achieving twin control with bidirectional data integration was extensively investigated by the Twin-Control project under Factories of the Future (FoF) within the European Framework Programme for better controlling manufacturing systems (Mikel et al., 2018).

Consequently, DTs are considered the core of the future prospect of the next generation simulation technologies for monitoring, optimising, and rapid adaptation of complex production operations (ANYLOGIC, 2018; Weyer et al., 2016). Moreover, the potential for improving the fidelity for handling complexities with DT simulations was also highlighted (Ding et al., 2019). More recent studies on the DT concept stressed the significance of context-awareness (cognitive DT) by integration, interaction, cooperation, and collaboration of AI-enabled DTs (intelligent DT) (Hribernik et al., 2021; Maschler et al., 2021).

Considering the increasing complexity of the product, process and system models in the manufacturing domain, the analysis and interaction of such models stand as a significant challenge. Simply, given the demand for dynamism, complexity and interaction, computer screens are not good enough to deal with such models in the product, process, and system domains. Thus, immersive VR technology stands out as a superior user interface, providing advanced analysis, verification, and interaction capabilities for complex digital manufacturing models. In this regard, the next section will present a summary of works on VR technology.

2.5. VIRTUAL REALITY

"The Ultimate Display" was envisioned as *"a room within which the computer can control the existence of matter"* in 1965 by (Sutherland, 1965). Yet, it took almost three decades to see significant studies on VR technology in scholarly and industrial enterprises (Adam, 1993). Starting from the second half of the 1990s, knowledge on VR technology was exploited among both the academic and industrial communities by utilising the technology for various purposes. Some of the use cases in which VR technology was adopted can be listed as training and learning (Abidi et al., 2019; Cote et al., 2008), concept design, development, and evaluation (PWC, 2016), visualising abstract data (Dam et al., 2000), and virtual building prototyping (Mobach, 2008).

VR technology has been recognised as a viable solution in the manufacturing domain to handle complexity by enabling immersive user interfaces since relatively early on in its maturity (Wilhelm et al., 2005). A more recent industry survey underlined the strategic value of using VR technology for the industry (Berg & Vance, 2017). Utilising immersive and interactive VR in manufacturing operations, including product and process design, optimisation, and ergonomics, was considered an efficient solution for higher precision (Peruzzini et al., 2020). As mentioned earlier, a recent survey shows that VR-enabled simulations are recognised as a common modelling methodology due to their higher performance in model development, verification, validation, analysis, and experimentation (Akpan & Shanker, 2019).

Therefore, immersive VR technology is utilised during all phases of the VF research. This was also relatively easy because of the embedded VR functions of recent 3D DES tools. Such advances also make it easy to develop and use VR capabilities for industry experts. Moreover, interaction and collaboration (multi-user VR) capabilities were enabled in the DT-based VF simulations.

2.6. KNOWLEDGE GAPS AND RESEARCH OBJECTIVES

The core driving motivations for VF research were 1) the consideration of VF as a prerequisite to handling co-evolution (Tolio et al., 2013), which was defined as the main challenge by the application domain, and 2) the claim that the development of VF is the realisation of the smart factory (Turner et al., 2016). Moreover, various research gaps and motivations were identified from the knowledge base that formed the research problems and questions of VF research presented in Problem Identification. Some of the essential gaps in the knowledge base, addressed in the dissemination activities of this research, are listed as follows:

- Need for knowledge on *"how new technologies should be combined together and managed to successfully face the current and future scenarios"* (Napoleone et al., 2020).
- Need for *"an investigation on the effects of both technological and operations management characteristics on business competitiveness"* (Napoleone et al., 2020).
- A need for application guidelines for the actual utilisation of technologies and methodologies for each life cycle step of products and factories for smart manufacturing (Kang et al., 2016).
- A gap in the use of VR and computer-aided manufacturing systems for collaboration and communication (Mourtzis et al., 2014).
- The lack of advanced planning functions of MES, also called *"decision myopia"* (Mourtzis, 2020).
- Need for case-specific industry implementation (Cimino et al., 2019).
- Need for utilising VR in DT simulations (Lim et al., 2020; Liu et al., 2021).
- Significant advantages of 3D/VR-enabled M&S tools for analysis, validation, verification, and experimentation (Akpan & Shanker, 2019).
- The importance of bidirectional data integration (Lattanzi et al., 2021).

The abovementioned gaps required reconsideration of the existing VF concepts in the knowledge base in light of the recent developments in the DT, VR, M&S technologies. Moreover, the need for more practical guidelines to help the actual utilisation of technologies as well as methodologies for concurrent design, modelling, analysis, and simulation of product and factory models drives the objectives of the research as follows:

1) Design and develop a VF concept solution based on a real-life manufacturing case that can utilise state-of-the-art technologies including digital twins and integrates product, process, and production system modes.
2) Discover the guidelines for the actual utilisation of technologies and methodologies for simultaneous design, analysis, and M&S of product and factory models.

3) Discover the enablers and barriers for designing, developing, and implementing the VF for industrial purposes.
4) Discover and evaluate the industrial value of VF.

The first and the second research objectives were mainly addressed in the first and second phases of the research, while the third and fourth objectives were addressed in all phases in order to close the abovementioned gaps. Before discussing the research design and methodology used to achieve such objectives, there is a need to discuss various concepts in order to articulate the theoretical foundations of the DT-based VF concept in the context of the co-evolution paradigm.

2.7. CHAPTER SUMMARY

The scholarly works mentioned above demonstrate the standalone advantages of M&S, DT and VR for design, development, verification, and validation of engineering complex manufacturing operations as well as learning/training. However, there are still considerable gaps and needs, particularly for (process, product, system) model integration, bidirectional data integration, collaborative, and interactive VR for manufacturing engineering. VF research was not specifically dedicated to discovering knowledge in a particular technology domain but, instead, as a more generic solution that integrates such technologies and models (data) across the product, process, system domains of manufacturing to handle co-evolution. Therefore, the novelty of the multi-user VR-enabled DT-based VF concept lies in the integration of the abovementioned state-of-the-art technologies and their demonstration in actual industrial cases. Moreover, we believe that such a generic solution and its evaluation in industrial cases will provide valuable knowledge for scholars investigating specific issues in each technological concept mentioned above.

The knowledge base does not determine a smart factory definition agreed by all scholars, but the properties and functions attributed to smart factories focus on the integrated use of various technological concepts. Designing, developing, and evaluating such a concept in a real-life manufacturing case is challenging. Therefore, scholars investigate smart manufacturing either at a conceptual level or through narrower specific aspects. VF research aims to synthesise a relatively broad spectrum of technological concepts, including M&S, DT, collaborative, and interactive VR, since a system is not just the collection of its parts but *"the product of the interaction of its parts"*(Ackoff, 2005), and *"in such systems, the whole is more than the sum of the parts"* (Simon, 1962). Thus, investigating such complex problems, which require interdisciplinary and transdisciplinary work, calls for a study founded on several theories and concepts that explains and explores the problem. Therefore, the theoretical foundations of VF research will be articulated further in the next chapter.

CHAPTER 3. THEORETICAL FOUNDATION

Although we are approaching industrial challenges correlated with numerous empirical methods and tools, the intended artificial solution (the designed artefact) as a treatment demands more discussion for a viable conceptual and theoretical justification. The VF research was conducted mainly on empirical means that relied on various engineering methods, tools, and data. However, the objectives of the study and the intended outcomes were not (meta-level) artefacts particular to the application context. The conceptual model of DT-based VF is considered a generic (meta-meta-level) solution for complex manufacturing enterprises to handle co-evolution for adapting to constantly changing dynamics. Therefore, a high-level research approach like DSR was embraced instead of a meta-level research approach like Model-based System Engineering. Thus, the research calls for interdisciplinary and transdisciplinary study. Accordingly, we need a high-level understanding of some of the main concepts, paradigms and theories associated with the research subject, its tools, and objectives.

Some theoretical discussion dedicated to manufacturing enterprises' external and internal nature such as general systems theory and complexity, concepts of business genetics, and competence-based strategic management concepts (also called competence theory) were addressed in **Paper 1** and **Paper 2**. But more extensive discussion of the theoretical foundations of DT-based VF and its extension to a virtual enterprise are introduced in **Paper 4**. However, the author took the opportunity to address some philosophical and foundational discussion on understanding and changing the present, followed by a brief introduction of the conceptual discussion articulated in **Paper 4**.

3.1. FUNDAMENTALS OF MODELLING

At the early stages of VF research, a novel definition for DT-based VF is proposed 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*" (Yildiz & Møller, 2021). The reason for introducing this definition that attributes such advanced capabilities and properties to the VF concept was derived not just from the advances in the technologies utilised in the DT-based VF concept, but also from the overall purpose of achieving smart manufacturing systems by utilising DT-based VF solutions. The prior purpose of having a DT-based VF solution is to enable manufacturing organisations to achieve more precise and accurate "as-is" models of their existing/present social, natural, and artificial systems. Modelling such systems is typically not a challenge for engineering. Formalising and analysing approaches by simplifying the complexities of system entities as well as their relations and behaviours are quite convenient methods. Designing and developing discrete models like material flow diagrams, process flow diagrams, and 2D and 3D layouts associated with manufacturing can be considered some examples of analysis approaches. However, the purpose of modelling the architectures and behaviours of manufacturing enterprises is not to understand the present or the past but to modify, transform or invent more efficient or effective “to-be” models that can be implemented in reality. A supporting indication of such purpose is shown in **Paper 1**, where *(re)designing factories (layout, line, process flow)* was ranked as the first value-promising case by the industry experts. Moreover, it was demonstrated in the industrial case studies in **Paper 1** and **Paper 2** that having a VR user interacting with DT-based VF models is considered highly valuable not only for training or learning but also for predicting the impact of VR user performance (new/manipulated process) on the actual (DT-based) manufacturing processes on the shopfloor. When we take into consideration the increasing complexity and shortening lifecycles of product, process and associated system models, simplifications for more efficient modelling activities become an obstacle for designing reliable “to-be” models.

In short (and simply), *“a model is a representation of a structure in a given system”* (Lesh et al., 2013, p. 17). There are various kinds of models like mental, geometric, process, mathematical or physical models. Models can also be “*descriptive*”, representing changes by functions of time, and “*dynamic*”, designating equations of change determined by interaction rules (Hestenes, 2006). Therefore, models are conceptual systems that can reside in the mind and are expressed via interacting representational media by using written symbols, spoken language, pictures or diagrams, physical materials, computer algorithms, etc. Thus, modelling can be used for describing, explaining, controlling, or manipulating systems in the world (Lesh et al., 2003). When reflecting a model into representational media by forming a concrete object, there is an abstract reflection of a physical or mental system which is also constructed in a human cognition perpetually. Although human thought and the science of the mind are essential in this matter, we will spare the reader extended interpretations of cognitive science. However, we can state that the development of cognitive science and the evolution of modelling research have a profound contribution and common ground for modelling theory and, thus, interdisciplinary research. Thus,

> “*Models are conceptual systems (consisting of elements, relations, operations, and rules governing interactions) that are expressed using external notation systems, and that are used to construct, describe, or explain the behaviors of other system(s) – perhaps so that the other system can be manipulated or predicted intelligently*” (Lesh et al., 2003).

Discussion of “what is a system?” will be addressed in Section 3.3, but there is first a need to articulate the relationship between the physical world and conceptual models. The objective of modelling in our research context is to develop abstract reflections of the physical world – such as physical factories and processes/actions – which represent the physical reality as it is. However, it should not be perceived that conceptual models (such as a VF model developed in a simulation tool) are identical representations of physical reality. Since the subject models are human constructions and their rules are what engineers/scientists have decided they should be, they are merely limited abstract representations. Although such models are constructed by means of iterative adjustment to assimilate into real systems for higher accuracy and precision, the distinction between the physical world, mental world and conceptual world will remain crucial to articulate on the subject, as illustrated in Figure 13 three worlds. Such improvement – in accuracy – and distinction in conceptual models of the physical world can be observed in the scientific models, such as improving the three-dimensional space model to Einstein's four-dimensional (space–time) model, yet as a limited model instead of a representation of the real world (Lesh et al., 2003). Mental models are individual constructions that can be enhanced to conceptual models (Hestenes, 2006). Thus, conceptual models enable stimulating the corresponding mental models in various individual minds. Since mental models are central to cognition and, therefore, subject to cognitive science, the author of the thesis will avoid discussion of cognitive semantics due to a lack of expertise, and remain within the scope of the intended discussion.

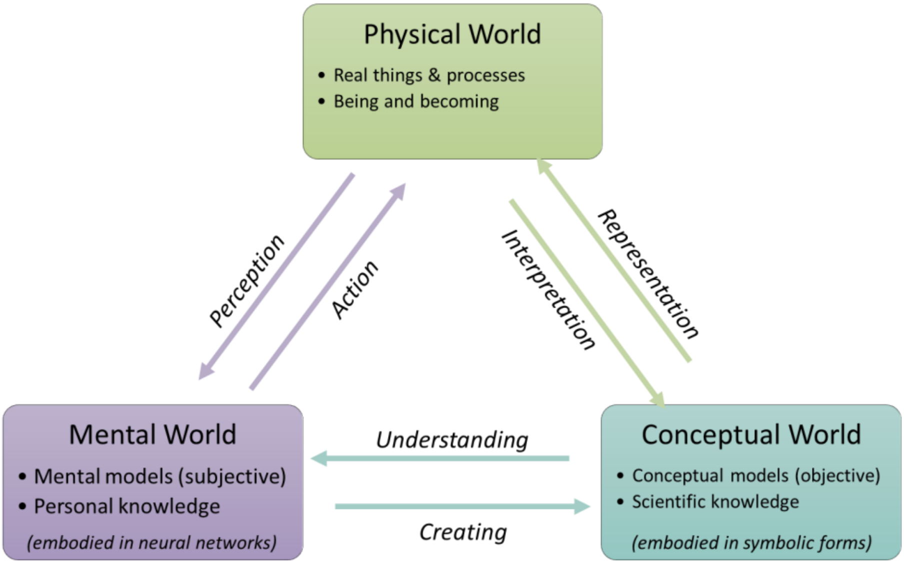

Figure 13 three worlds [borrowed from (Hestenes, 2006)*]*

Using models for engineering studies (e.g. model-based systems engineering) is considered convenient and effective for validating and verifying concepts. Therefore, a model's level of precision and accuracy with its corresponding real system needs to be in an "acceptable range" for the required/intended purpose (Sargent, 2013). Accordingly, a simulation, which can be defined as an execution of a model input/output behaviour in a dynamic way to imitate the real-world process or system, should also be fast and accurate (Vangheluwe et al., 2002). Although the distinction between a model and the physical reality has been addressed before, the accuracy of a conceptual model relative to its corresponding real system can be high or low depending on the purpose of the work. But high accuracy does not necessarily mean higher utility and effectiveness for all circumstances. If we take a map of a certain physical geographical area, for example, accuracy can be described as the closeness of the measurements – such as distances – on the map to the reality, which is simply the scale of the map. Consequently, increasing the scale of a map will make the model more accurate. So, to what extent can or should a model (a map) be accurate? An old story, but one that continues to be relevant for drawing discussions, "On Exactitude in Science" (Borges & Miranda, 1658) could be a convenient allegory for us to elaborate on the accuracy of M&S activities.

> "*What a useful thing a pocket-map is!*" I remarked. "*That's another thing we've learned from your Nation*," said Mein Herr, "*map-making. But we've carried it much further than you. What do you consider the largest map that would be really useful?*" "*About six inches to the mile*." "*Only six inches!*" exclaimed Mein Herr, "*We very soon got to six yards to the mile. Then we tried a hundred yards to the mile. And then came the grandest idea of all! We actually made a map of the country, on the scale of a mile to the mile!*" "*Have you used it much?*" I enquired. "*It has never been spread out, yet*," said Mein Herr: "*the farmers objected: they said it would cover the whole country, and shut out the sunlight! So we now use the country itself, as its own map, and I assure you it does nearly as well*." (Carroll, 1894, p. XI, 169)

Such an allegory is considered adequately descriptive for the objective of utilising VF models and not confusing means with ends. State-of-the-art technologies like DT and VR are not necessarily employed exclusively for greater accuracy but for utility as well. Real-time data synchronisation between physical systems, for instance, is considered highly useful during modelling and remodelling in frequently changing situations such as NPI processes. The increasing accuracy and reliability of the models enabled by real-time data synchronisation (DT) are considered more valuable for VR learning and training simulations instead. It is considered informative for the VF research, as well as the reader, to refer to (Baudrillard, 1994) for instigating a philosophical discussion on how immersive simulations can replace the reality in society (via social media) with the charm of abstraction. Thus, it can be anticipated that resources invested in greater accuracy and precision of models are means to achieve the primary objective of creating added (use) value in industries.

Thus, "as-is" models in the context of VF research can be summarised to understand/interpret the world/reality as it is. This instigates the discussion on the purpose of understanding the world.

3.2. THE PURPOSE OF UNDERSTANDING THE WORLD

It is no longer a nascent debate on how instruments as a medium like a telescope or quantum observer, which is used to interpret reality, can alter the knowledge of the reality/truth. For instance, a telescope changes a planet's (visual) size by refracting the light, or a more contemporary instance could be particle-wave duality in quantum mechanics. A cognition, therefore, relies on the truth of its environment to create an "as-is" model as an abstract reflection of the perceived environment. Thus, Hegel (Hegel, 1807a) recognised cognition as a faculty of a definite kind and scope that obtains a boundary between cognition and *the Absolute* (reality). Therefore, cognition can mediate as an instrument that certainly does not allow the Absolute to be what it is for itself, but alters and reshapes it without a precise definition of its limits and nature (Hegel, 1807a).

Although it could be argued that the instruments decouple the truth from its context, they provide the closest version of the truth itself. Such instruments enable the interpretations of reality in terms of 1) "as-is" models. And the truths can be changed/altered to 2) "to-be" models via an apparatus. The latter can be defined as the intention of the DSR, which was the guidance of the subject research. Similarly, the purpose of designing and developing more precise and accurate "as-is" models of complex manufacturing enterprises is to modify, transform or invent more efficient or effective "to-be" models.

This conveys the impression that the association between "as-is" and "to-be" models of reality echoes in the longstanding yet contemporary debate on understanding and changing the world (the present). Karl Marx listed the demand for world change in his *Theses on Feuerbach,* as often quoted: *"The philosophers have only interpreted the world (die Welt), in various ways; the point, however, is to change it."* (Marx, 1845). An imminent counterargument came from Martin Heidegger; *"A change of the world presupposes a change of the conception of the world, which can only be established by an adequate interpretation of the world"* (Heidegger, 1969). But the intention of the subject research is not to interpret/understand the World (*die Welt*); rather, it is the Environment (*um Welt*) which can be interpreted and changed.

However, since every result in scientific study raises new questions (n+1), academic knowledge production appears to fall into *ad infinitum*. Thus, the question of what is an "adequate interpretation" of the world arises. Hegel distinguished between bad infinities like never ending numbers in mathematics, and good infinities like the self-contained Mobius strip (Hegel, 2010). Another depiction could be (good) infinitely renewable resources of nature and (bad) infinite growth and consumer desires, which could degrade and destroy the natural resources (Frodeman, 2013). Likewise, Karl Marx demonstrated the bad infinite in the use and exchange value of goods, and the latter appears to be infinite, leading to periodic economic crises. Robert Frodeman, on the other hand, questions the shrinking disciplinary boundaries together with the limited utilisation of infinitely (n+1) increasing academic knowledge beyond the boundaries of the academic world (Frodeman, 2013). He also argues that the collision of (public and academic) epistemic worlds increasingly calls for interdisciplinary and transdisciplinary knowledge production. Therefore, the current study intends to concentrate on interdisciplinary subjects (in a general sense; social science, natural science, design science), while aiming for transdisciplinary knowledge production (co-production) between non-academic and academic actors.

By addressing such notions, we aim neither to embark on recondite discussion of the epistemic justification of phenomenal knowledge nor to set up a mistrust of science by creating a fear of falling into errors (Yildiz, Møller, & Bilberg, 2021a), instead stressing the standpoint of the author of this thesis that a fear of falling into inaccuracy while interpreting the reality might reveal itself as a fear of the truth. Therefore, we spare the readers from a long epistemological discussion of phenomenal knowledge. However, it can be concluded that the essence of our dialectical effort to understand the complex natural, social, and artificial systems affects both its knowledge and its present reality, which is precisely what is called experience.

The abovementioned discussion of models and the purpose of modelling are limited in terms of the nature and laws of systems. Therefore, the flow of the dialogue calls for a more extended articulation of system theory and the nature of complexity. The next section will attempt to fill such a need.

3.3. SYSTEMS THEORY AND COMPLEXITY

One of the origins of the problems and challenges for the dynamic interaction of organisation and wholeness in various fields of science is considered the increasing disciplinarity of modern science and knowledge production. Therefore, such challenges lead to the emergence of a theory, not of a particular kind, but of universal principles, models, and laws pertaining to systems in general or their subclasses, as well as the relations between their components (Bertalanffy, 1968). Since the early 1950s, the interest in and recognition of the association between system theory and diverse subjects such as economics, psychology, and biology have been gradually increasing. In parallel to developments in system theory, advances in information theory and cybernetics benefitted from the constructs, notions, and principles of system theory (Bertalanffy, 1956). System theory articulates and formulates the differences between the behaviours of processes and parts in isolation and the behaviours of organisations and the order unifying the parts and processes (Guberman, 2004). A system is defined by (Ackoff, 1994) 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*

> *an independent effect on the whole, and (3) no subgroup of which can have an independent effect on the whole.”.*

Therefore, the essential properties and the performance of a system are determined not by the independent behaviours of its parts (sub-systems) but by the interactions. Correspondingly, a system is not just the collection of its parts or sub-systems, but *“the product of the interaction of its parts”* (Ackoff, 2005), 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”* (Simon, 1962). In due course, scholars identified various types of systems, including organismic, mechanical, and social systems, and an enterprise was interpreted by rendering the distinctions in the context of each type (Ackoff, 1994). Since manufacturing enterprises and particularly factories incorporate similar types of systems in concurrently evolving environments, the dynamic nature of the systems illustrates the complex systems of actively interacting problems.

The complexity of a system can be assessed in various ways (Simon, 1976), yet a straightforward description of a complex system could be “*a system made up of a large number of parts that interact in a nonsimple way”* (Simon, 1962). The terms “complex” and “complicated” are often used synonymously to define a system or a situation, generally due to difficulty understanding the nature and interactions between the components of a system. A combustion engine or a car may seem too complicated or complex to many, while an automotive engineer may consider the same fairly simple. However, ecosystems like individual organisms, entire species or an entire rainforest that accommodate various emergent properties and behaviours are easily considered highly complex (Mitchell & Newman, 2001). The distinction is made as follows: a complicated system like a jumbo jet could be predicted through analysis, while a complex system like a rainforest is inherently unpredictable (Kahlen et al., 2017, pp. 25–48). Thus *“a jumbo jet is complicated, but a mayonnaise is complex”* (Cilliers, 2002, p. 15).

Organisational theory and practice promote simplifications for ordered circumstances on the grounds of a fundamental assumption that states that *“a certain level of predictability and order exists in the world”* (Snowden & Boone, 2007). Such simplifications can be revealed in analysing approaches, such as taking complex systems into parts and processes in isolation. However, since the complexity and the frequency of changes in systems and situations are increasing faster than ever before, the predictability of complex organisational systems is decreasing substantially. Therefore, conventional leadership, management, and simplification approaches increasingly fail (Sanchez, 1997; Snowden & Boone, 2007). Therefore, complementary to the analysis approach, there is a need for a synthesis approach that examines systems and their parts as a whole in order to deal with complex challenges (Ackoff, 1994, 2005). In other words, *“the truth is the whole”* (Hegel, 1807b).

In this context, the DT-based VF concept is also considered a viable solution to deal with co-evolution by facilitating a holistic representation of highly complex manufacturing organisations and their respective operations. Moreover, the multi-resolution modelling capabilities of VF extend the conventional simulation of factories and enable analysis at discrete levels of detail (Jain et al., 2017). Moreover, recent developments in M&S tools and cutting-edge capabilities enable more advanced digital integration across production lifecycles (Mourtzis, 2020). DT and VR capabilities support novel analysis and interaction methods with complex system and process models (Turner et al., 2016; Yildiz, Møller, & Bilberg, 2021c). The advanced diagnostic, predictive and prescriptive analysis potentials of simulation tools enhance the management and engineering competencies of the DT-based VF concept to analyse and synthesise complex systems. Thus, the DT-based VF concept can enhance the experimental mode of management required by complex organisational domains (Snowden & Boone, 2007).

General system theory and complexity theory contribute a sound basis for extending our understanding and interpretation of the nature of complex organisations and how DT-based VF can be utilised for the holistic representation of complex organisations including their sub-systems with multi-resolution capability. However, complex manufacturing organisations are open systems that are embedded in their environments, like markets, nations, and supply chains. Therefore, such organisations are strongly intertwined with the lifecycles of the industries. In this regard, the next section will investigate some basic concepts and principles of evolution in industrial lifecycles, as well as the relationship between manufacturing enterprise operations and the external domain of enterprises.

3.4. EVOLVING INDUSTRIAL CYCLES

Different industries like automotive, wind energy, mining and aerospace have their specific dynamics that impact the lifecycles of each industry. However, it is possible to determine some common forces and principles that can impact industrial lifecycles permanently. Since enterprises are embedded in industries with supply chains, such dynamics and changes are among the fundamental forces that govern the matter of survival for enterprises. In order to reveal such forces and laws of industrial lifecycles, Charles Fine applied the principles of evolutionary biology to industrial lifecycles in his work titled “Clockspeed: winning industry control in the age of temporary advantage” (Fine, 1998). By implementing the clock speed (the internal speed of living organisms’ metabolism) technique into various industries, Fine determines the relative speeds of evolution in industries (Fine, 1996). His work also frames relatively universal principles about the nature of industry evolution. Some of the principles revealed in the work are as follows:

- There is no permanent domination for companies. All domination is temporary.
- The faster the rhythm of evolution, the shorter the reign of domination.

- The ultimate core advantage for the enterprise is the ability to adapt to evolving industrial environments.
- Certain forces and their intensity determine the rhythm of change in the industries (Fine, 2000).

Some of the essential forces that regulate the rhythm of evolution in industries are identified as 1) technology and innovation, 2) level of competition, 3) regulations, and 4) demography (Lepercq, 2008). The essential element of Fine's concept is the identification of three angles of the particular rhythm of the industrial evolution: product, process, and organisation (system). Fine examines the nature and relationship between industries as the external domain in which organisations are embedded. The concepts of evolving industrial lifecycles investigate the organisations in the scope of the manufacturing supply-chain (Fine et al., 2002). Therefore, the evolution of manufacturing systems to respond to the changing industrial ecosystems is illustrated by a double DNA helix representing the integration and disintegration cycles (Fine, 2000). Thus, as a response to co-evolution in the manufacturing domain (Leitner, 2015; Tolio et al., 2010), (Fine, 2000) addresses the 3-dimensional concurrent engineering. Accordingly, (Tolio et al., 2013) concentrate on the factories and acknowledge VF as a prerequisite to deal with co-evolution due to its capability of the integrated use of diverse engineering methodologies. The concepts of evolving industrial cycles articulate the association of the co-evolution of complex manufacturing organisations with the industries as external domains by considering the supply-chain systems as essential interfaces. Therefore, the concepts of evolving industrial cycles provide a sound basis for the argument that handling co-evolution can support manufacturing enterprises during their evolution to adapt their respective industry and, thus, their survival.

Nevertheless, the abovementioned theories and concepts do not directly address "how" to examine a complex organisation that can evolve according to dynamic conditions and circumstances. The next section will discuss the Competence-Based Strategic Management concepts to address this gap.

3.5. COMPETENCE-BASED STRATEGIC MANAGEMENT

The concepts of Competence-Based Strategic Management (also called Competence Theory) harmonise the concepts and laws of system, complexity, and strategy theories to consolidate a more inclusive, systemic, and dynamic characterisation of organisations (Sanchez, 1997, 2012; Sanchez et al., 1996). Competence theory identifies organisations as complex systems embedded in the evolving circumstances of industries as well as their competitive and strategic goal-seeking actions as outcomes of the interactions of the interdependent entities of a complex organisation (Sanchez & Heene, 1997). Therefore, organisations are open systems and constantly build and leverage competencies to adapt and compete in strategic environments. Sanchez describes the strategic management of organisations *"as a* *process of designing organisations as adaptive systems"* by redesigning resources, capabilities, and coordination (Sanchez, 1997).

Furthermore, competence theory determines relatively feasible and consistent organisation design principles to sustain competencies (Sanchez, 2004). For instance, competence theory puts an emphasis on the analysis and synthesis processes of the product and production design activities required for the architectural transition of a manufacturing organisation and recommends a principle of architectural isomorphism (Sanchez, 2012). The *"principle of architectural isomorphism"* suggests that *"Maintaining effective strategic alignment of an organisation with its environment requires achieving isomorphism across a firm's product, process, and organisation architectures"* (Sanchez, 2012). Thus, the process rendezvous of the product and production lifecycles within DT-based VF simulations (Yildiz, Møller, & Bilberg, 2021c) can support the aim of architectural isomorphism across manufacturing organisations.

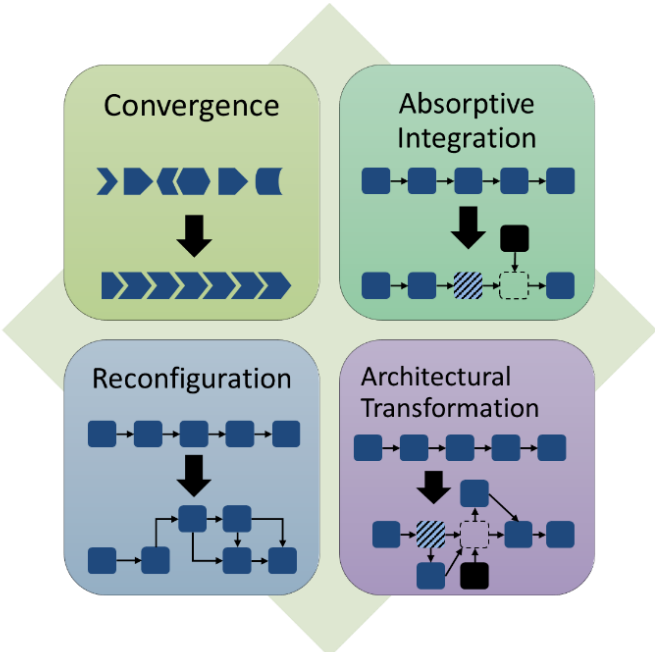

Figure 14 Types of changes in an enterprise's architecture (Sanchez, 2012)

Moreover, Sanchez formulates the four types of strategic environments and four types of changes that can be carried out in the tangible and intangible assets of a manufacturing enterprise (Sanchez, 2012). Figure 14 Types of changes in an enterprise's architecture (Sanchez, 2012) illustrates such changes, including *"convergence, reconfiguration, absorptive integration, and architectural transformation"*. More inclusive interpretations of how a DT-based VF solution can support each change are presented in **Paper 4**. Another essential element of competence theory for the study of DT-based VF is that it grounds and frames four dimensions/cornerstones to accomplish competence-based strategic management. These dimensions, namely, dynamic, cognitive, holistic, and open, provide a sound basis for a consistent and inclusive vocabulary to form a conceptual framework to interpret how the co-evolution needs to be explored (Sanchez, 1997). The DT-based VF concept, including its utility and effectiveness, is investigated in the context of the four dimensions of competence theory in **Paper 4**.

The present study suggests that the DT-based VF concept can provide a solution to design, develop, simulate, analyse, and optimise the four types of changes in product, process, and organisation models to stimulate management strategy and forms of reconcilability and flexibility by achieving four cornerstones (Yildiz, Møller, & Bilberg, 2021a, 2021c; Yildiz, Møller, Bilberg, et al., 2021; Yildiz & Møller, 2021). Although the majority of VF studies focus on various aspects of engineering methods and technological capabilities, the experimental capabilities in different resolutions of integrated simulations promise significant value for operations management. (Snowden & Boone, 2007) stress the same, as follows:

> *"Playing a metaphorical game increases managers' willingness to experiment, allows them to resolve issues or problems more easily and creatively, and broadens the range of options in their decision-making processes. The goal of such games is to get as many perspectives as possible to promote unfettered analysis."* (Snowden & Boone, 2007)

Therefore, the essential premise in the study is that the proposed DT-based VF concept solution can achieve isomorphism across the process, product, system architectures of manufacturing enterprises to cultivate effective strategic alignment (evolution & competition) with the respective environments.

Competence theory is conventionally articulated at a relatively high level of abstractions. Therefore, it is applicable to all kinds of organisational operations and processes, including production systems. "Nonetheless, to the best of our knowledge, there has not been any work that attempts to depict the abstractions of competence theory in a production system context" (Yildiz et al., 2020a). Thus, VF research utilises the high-level concepts and principles of competence theory to form a conceptual foundation and to achieve a sense of generality in terms of a broader theoretical understanding by means of theoretical abstractions. Moreover, the new knowledge discovered during the empirical studies of VR research also provides valuable data to support the various theoretical arguments and assumptions of the competence theory. Therefore, the theoretical contribution of the research can be positioned as theory elaboration through a reconciliation of the particular (situationally grounded) with the general (Yildiz, Møller, & Bilberg, 2021a).

3.6. THEORETICAL FRAMEWORK

The abovementioned theories and concepts, including their associations, are illustrated in Figure 15 Theoretical framework (Yildiz, Møller, & Bilberg, 2021a). Systems theory and complexity theory are briefly investigated and utilised to ground our efforts to describe the nature of the co-evolution paradigm in complex manufacturing systems. System theory maintains various principles and concepts about the nature of systems, including the dynamics and relationships of subsystems and parts in general. Since complexity theory is presented and discussed in the systems theory context, it can also be expressed as complex systems theory. Complex systems theory determines various propositions on the nature of the evolving complexity of natural, social, and artificial systems. Such propositions are employed to interpret how a DT-based VF solution can be utilised for the analysis and synthesis of complex systems.

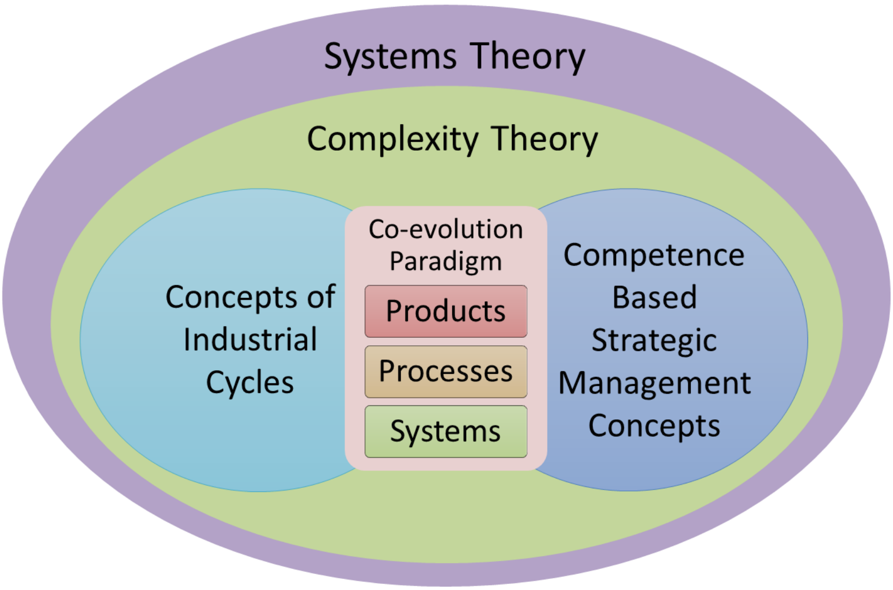

Figure 15 Theoretical framework (Yildiz, Møller, & Bilberg, 2021a)

Numerous scholarly works focusing on the digitalisation of manufacturing operations are prefaced by the challenges and problems generated by evolution in industries. However, there is limited discussion of the nature of the evolving dynamics in the industries and their impact on the internal domains of the manufacturing enterprises. The discussions about interpreting the principles of industry evolution and their impact on manufacturing enterprises' internal dynamics are provided to articulate the nature of co-evolution in the context of manufacturing organisations. The concepts of industrial cycles and competence-based strategic management are utilised to articulate how the co-evolution problem is explored in the context of both the internal and external domains of manufacturing enterprises. The principles and concepts of industrial cycles and competence-based strategic management highlight the co-evolution of three domains of manufacturing organisations in the external and internal perspectives.

VF research makes use of the conceptual and theoretical arguments and guidelines provided by competence theory on how a DT-based VF solution can support competence leverage and development within the complex manufacturing context. VF research, on the other hand, informs the competence theory by employing its concepts and propositions for the utilisation of a DT-based VF solution in the particular manufacturing contexts together with empirical evaluations in various cases.

3.7. CHAPTER SUMMARY

The theoretical discussion in this chapter is built upon **Paper 4**, with an extended discussion on modelling theory in the evolving conditions. In order to articulate the nature of complex manufacturing organisations, some principles of systems theory were introduced and discussed. The nature and dynamics of systems and the relation of their interdependent parts were extended with the fundamentals of complexity theory. Such concepts and discussion support the interpretation of the internal dynamics and evolution of complex systems. The concepts of industrial cycles inform the reader on the nature of the relationship between evolving industrial environments and manufacturing enterprises. Following the theories and concepts that explain the nature of the co-evolution problem, competence-based strategic management concepts which incorporate relatively more inclusive and practical guidelines on how the problem of adapting to evolving complex environments should be addressed. Four dimensions of the competence-based management concept provide pragmatic guidelines on how the co-evolution problem should be explored. The DT-based VF concept is investigated in the context of each cornerstone in **Paper 4**.

The previous three chapters introduced the application context of the research project, existing knowledge and gaps in the knowledge base and conceptual foundations to articulate how to explore the problem respectively. Thus, the next chapter will introduce and frame the overall research design and methods to address the abovementioned problems, gaps, opportunities and motivations.

CHAPTER 4. RESEARCH DESIGN

This chapter aims to present and discuss the overall research framework designed to respond to the problems mentioned above, opportunities, and motivations. The overall research design materialised throughout the three years of this PhD research. Each scholarly publication on which this thesis was built addressed particular methodological issues regarding the respective activities performed to produce the knowledge presented. Therefore, this chapter enables us to present the holistic research design, including the conformity of various systematic activities of each research phase, as well as to articulate extensive discussion of some methodical challenges.

4.1. EPISTEMOLOGICAL RESEARCH POSITION

A force of knowledge, in other words, technological innovation, could be determined among the major forces that shaped modern society throughout history. Two things proceed from this knowledge, which are 1) creating the knowledge and 2) applying the knowledge (Betz, 1998, p. 3). In Figure 16 Technology and science dualism [adapted from (Baskerville et al., 2018)], these two activities are depicted as synergistic interactions of the evolutionary interplay between the exercises of science and technology.

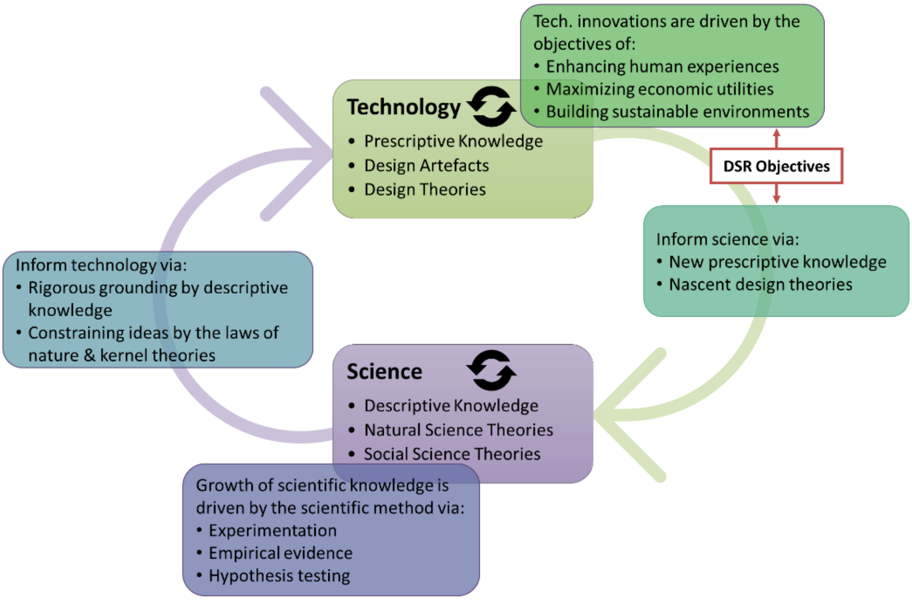

Figure 16 Technology and science dualism [adapted from (Baskerville et al., 2018)*]*

Through the application of scientific methods, including experimentation, observation, and empirical evidence collection, we are enabled to discover descriptive knowledge about natural phenomena. By facilitating that descriptive knowledge, in other words, by discovering the truth about natural phenomena, we have a better understanding of nature. Thus, we were able to manipulate that very nature by purposefully designed artefacts (Baskerville et al., 2018). When such artefacts take physical forms like tools, machines, etc., we call the by-product of this manipulation a new technology. The emerging use of new technologies has empowered new scientific methods and discoveries. Consequential scientific reflection on inventing telescopes and water pumps, for example, gave the initial theories of optics, thermodynamics, and astronomy (Mokyr, 2011). The intention here of addressing the discussion on science–technology dualism is not to embark on a prolonged interpretation, but merely to stress that the prescriptive knowledge presented and discussed in this dissertation aims to contribute to the scientific knowledge domain in the forms of the models, methods, instantiations, and theory elaboration that are constrained by the kernel theories in the scientific domain.

Therefore, the research study presented in this thesis aims to create knowledge on the design, development, and utilisation of VFs, which accommodates both practical relevance and the theoretical contribution. Since its early definitions, the VF concept has been depicted as an artificial system representing the corresponding physical systems, including their sub-systems (Jain et al., 2001). Therefore, we are researching the design of an IS that integrates diverse systems, technologies, models, and data structures across a manufacturing organisation. As a result, various challenges are emerging in terms of the research design. One of these emerging difficulties is that the subject IS we are investigating is not just a technological system but also a phenomenon that emerges when social, natural, and artificial systems (IS) interact. Thus, the IS theory to understand the phenomenon links the social world, natural world, and the artificial world that is constructed by an individual (Gregor, 2006). Another challenge is the constantly evolving complexity of the subject natural, social, and corresponding artificial systems. Therefore, the study is not just concerned with how things are but also with how contingent things might be. Accordingly, the body of knowledge that this study aims to create capitalises on natural science, social science, and "the science of the artificial" (Simon, 1996), which is also called "design science" (Hevner et al., 2004).

4.2. THE SCIENCES OF THE ARTIFICIAL OR DESIGN SCIENCE

It is relatively easy to comprehend that natural science is concerned with understanding natural phenomena while social science studies the vast array of topics under social phenomena. However, it is not very easy to interpret that the science of the artificial studies artificial phenomena. This is partially because of the distrust of the term "artificial" due to its pejorative connotations. Herbert Simon's (Simon, 1996) study titled "The Sciences of the Artificial" distinguishes natural science and the science of the artificial. It is commonly accepted that his study lays the foundations of the DSR approach. The term “artificial” is used “as meaning man-made[14] as opposed to natural” (Simon, 1996). Although it does not seem challenging to comprehend what is “natural”, like a forest or an – untouched – stone, and what is “artificial” like an axe or plough, it is not a trivial matter to distinguish a plough, the concept of a plough, the design of a plough, a method for building a plough, a method for using a plough, the action of ploughing and the ploughed field. These terms are examples that are called artefacts, which are not fully separate from nature (Simon, 1996). While such artefacts are bounded by the laws of nature, they also embody the knowledge to satisfy human goals and purposes.

In other words, compared with explanatory research approaches that aim to explain the past or present, design science focuses on reconstructing and improving the present. It would be less complicated to articulate the difference between design science knowledge and natural science knowledge with an analogy. When we consider a stone, for example, natural science is interested in the very nature of the stone itself. It studies the nature of the stone to create descriptive knowledge in terms of the stone’s properties, physics, chemistry, etc. based on empirical evidence from experimentation and observation. The refractive index of a stone – even though it is tacit knowledge – can be an example of descriptive knowledge about a stone that capitalises on natural science. Design science, however, concerns the design of artefacts – both physical and abstract forms – in order to satisfy human desires and needs by improving the ways humans, for example, travel (stone wheel), cut (stone axe, stone blades), hunt (stone arrowheads), farm (stone hoe), eat (grinding stone, e.g., for wheat) by consuming the descriptive knowledge about the stone. Therefore, the design sciences *“are concerned not with the necessary but with the contingent – not with how things are but with how they might be – in short, with design”* (Simon, 1996, p. xii). Since both the natural laws and human desires are embodied in such artefacts, design science encompasses the means for relating these two elements (Simon, 1996). Accordingly, an artefact can take the forms of models (design of a wheel), methods (guidelines to shape a stone blade or to use it in a more effective way), or a theory (explanation of aspects of stones, interrelation properties and classification of stones to be fit for purpose). Therefore, artefacts are what they are to achieve certain sets of functional requirements; as the requirements change, so too do the artefacts.

4.3. RESEARCH CONTEXT

Although Simon and some others positioned his work on the science of the artificial as a “theory for design and action” (Gregor, 2006), some others have recognised

[14] The word "man" is used as an androgynous noun, encompassing both sexes equally in its scope.

design science as a research activity (Baskerville et al., 2018; Hevner et al., 2004; Peffers et al., 2007). By any means, knowledge generated during the design science activities can take the forms of constructs, models, methods, and theory for performing the know-how to create artefacts that can accomplish certain sets of functional requirements. Thus, DSR creates missing knowledge in terms of artefacts that represent ideas, products, actions, and technical capabilities by performing design, analysis, abstraction, and reflection (Peffers et al., 2012). The objective of this research is to support manufacturing organisations in solving the problems emerging from co-evolution that are addressed in the INTRODUCTION Chapter, by designing and developing artefacts that can utilise state-of-the-art knowledge and capabilities and by demonstrating and evaluating the designed artefacts in actual industrial cases. Therefore, DSR is more suitable for our research approach to deal with the gap between theory and practice compared with the traditional experimental and explanatory research approaches (van Aken et al., 2016).

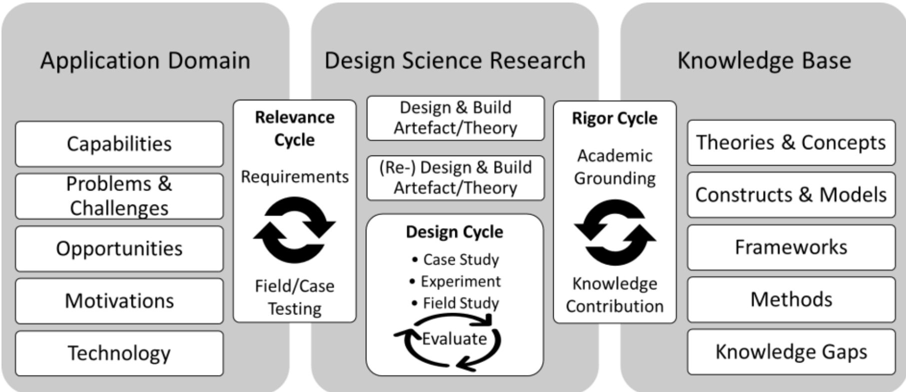

Figure 17 Design Science Research approach [adapted from (A. R. Hevner et al., 2004) *and* (A. R. Hevner, 2007)

Figure 17 Design Science Research approach [adapted from (A. R. Hevner et al., 2004) and (A. R. Hevner, 2007) illustrates the DSR framework that depicts the three inherited research cycles and activity domains. The relevance cycle bridges the application domain of the research project (Vestas's manufacturing plants) with DSR activities. The rigour cycle bridges the design science activities with the knowledge domain of scientific foundations in terms of theories, existing concepts, models and constructs, and methods, as well as the gaps addressed to be investigated. The design cycle as the central activity of DSR represents the iterative processes of artefact construction, evaluation, and subsequent refinement of the design.

The application domain represents the organisational systems, including social, natural, and technical systems, that contribute to the research activity by identifying the requirements of a solution (artefact) in terms of determining the problems, challenges, opportunities, and motivations in an actual application environment. Therefore, the application context also provides the acceptance criteria for the evaluation of the designed solutions. That being said, however, the problem identification, as well as the objectives of a solution, should also comply with the kernel theories, concepts, and methods from the knowledge base. The knowledge base informs the DSR activity by means of 1) state-of-the-art knowledge (experience and expertise) and 2) existing artefacts and processes (meta-artefacts) (A. R. Hevner, 2007).

Moreover, it is necessary to address the fact that, even though the requirements for the artefact design are determined by the particular problems of the application context with contextual idiosyncrasies, the artefacts should be designed as a generic solution that complies with the universal theories through abstractions (Ketokivi & Choi, 2014). The output of the DSR returns to the application domain through field studies, case studies, action studies, simulations, or similar for the evaluation of the design to measure the improvements in the application context. The evaluation of a design in an application context within the DSR approach has attracted particular attention from some scholars and will be discussed in later sections (Prat et al., 2015; Sonnenberg et al., 2012). Extensions to theories, methods, and novel (meta-) artefacts, as well as the overall experience and knowledge gained during the execution of the research study, can be determined as contributions to the knowledge base. The mode of contribution to the knowledge in terms of the empirical (novel artefact construction) and theoretical (theory generation, theory testing, theory elaboration) also calls for particular attention and will be discussed further (Baskerville et al., 2018; Ketokivi & Choi, 2014).

The questions in Table 3 Design Science Research checklist [adapted from (A. Hevner & Chatterjee, 2010)] provide a specific checklist of questions used to guide and assess the progress of the research work for each phase. It is adapted from (A. Hevner & Chatterjee, 2010) to ensure that the research process addresses the key aspects of DSR.

Table 3 Design Science Research checklist [adapted from (A. Hevner & Chatterjee, 2010)]

Question	***Answers***
1. What are the design requirements of the application context (problems, opportunities, motivation)? What are the research questions?	
2. What are the existing artefacts that can help fulfill the design requirements?	
3. What design process will be used to build the artefacts?	
4. How are the designed artefacts and design processes grounded by the knowledge base? What theories (if any) support the designed artefact and/or design process?	

5. *How are the artefacts introduced to the application context? What metrics were used to demonstrate the artefacts' utility?*	
6. *How is the evaluation of the design performed? What design improvements were identified during the design cycles?*	
7. *What is the contribution to the knowledge base and in what form (new theory, method, concept, etc.)?*	
8. *Were the research questions answered adequately? What are the future research needs?*	

Moreover, Figure 18 DSR contextualisation illustrates a simplified contextualisation of the DSR approach to the subject of this thesis and maps the questions in Table 3 Design Science Research checklist [adapted from (A. Hevner & Chatterjee, 2010)] to the appropriate research cycle to help to demonstrate the relationship between such questions.

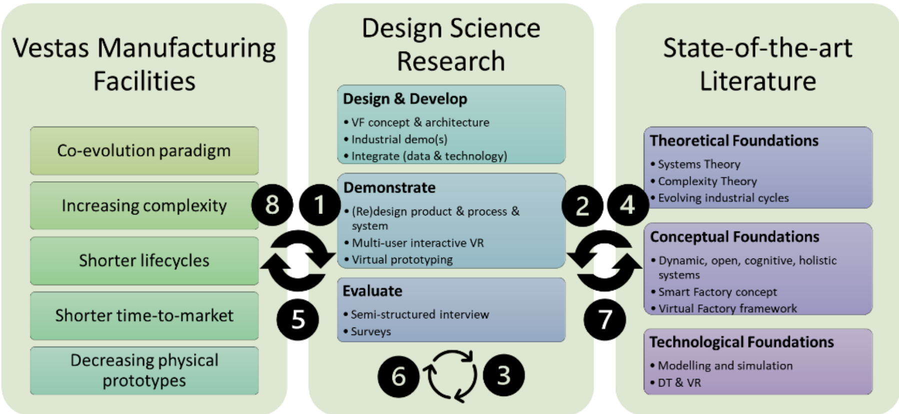

Figure 18 DSR contextualisation

Although the application environment comprises people, capabilities, IT infrastructure, architectures, etc., in the interest of simplicity, Figure 18 DSR contextualisation illustrates just the main challenges and motivations. The knowledge base (state-of-the-art literature) is depicted as some kernel theories, concepts, and technological foundations, which will be elaborated extensively in the following chapters. Moreover, particular requirements of the application domain for empirical relevance and specific academic grounding in the interest of scientific rigour need to be established for each design and evaluation activity, meaning the research phase. Therefore, the research cycles shown in Figure 17 Design Science Research approach [adapted from (A. R. Hevner et al., 2004) and (A. R. Hevner, 2007) are revisited during each research phase shown in Figure 7 Research phases (work packages). Consequently, aside from the research project objectives initially formulated in collaboration with the industry and academic stakeholders, each phase incorporates particular research objectives, problems and questions derived from the overall project objectives. Therefore, more comprehensive discussion on the research methodology is presented in the next section to articulate how the research objectives and problems should be addressed.

4.4. DESIGN SCIENCE RESEARCH

Since DSR is a relatively new approach in the field of IS, it is challenging to verify commonly acknowledged and long-established methods in the literature. Yet, there are numerous studies conducted by reputable scientists and dedicated to establishing research methods, frameworks, and guidelines for DSR activity in IS (Drechsler & Hevner, 2016; Dresch et al., 2018; A. Hevner & Chatterjee, 2010; Holmström et al., 2009; Johannesson & Perjons, 2014; Peffers et al., 2007). The research presented in this thesis was conducted on the trails of these frameworks and guidelines. The Design Science Research Methodology (DSRM) process model, which covers six main research activities (Peffers et al., 2007), was adopted and followed. Figure 19 DSRM process framework [adapted from (Johannesson & Perjons, 2014)]illustrates the process model framework adapted.

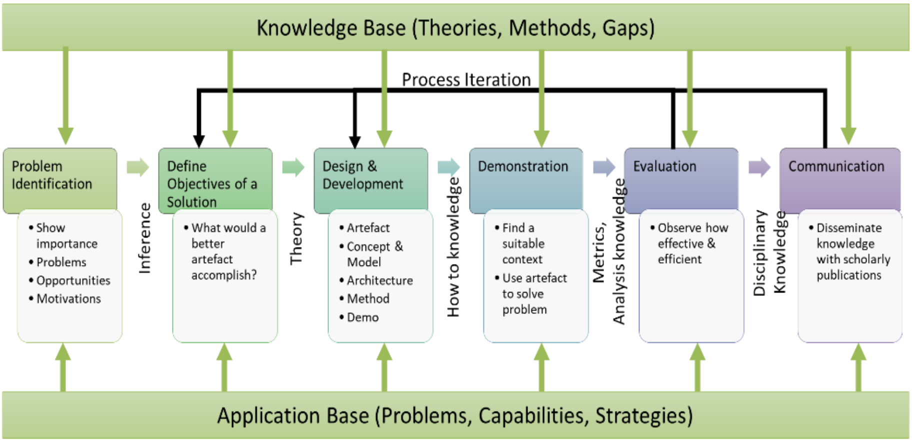

Figure 19 DSRM process framework [adapted from (Johannesson & Perjons, 2014)]

Each of the six DSRM activities will be discussed in later sections. However, we need to restate that each activity of the methodology was revisited for each phase. Each activity of DSRM gets some inputs from the knowledge base, application base and previous research activity. Accordingly, each activity may contain various sub-activities. The problem identification process, for example, can consume some inputs from the application domain as a result of a survey conducted with the industry experts. At the same time, the knowledge base may inform the research activity with appropriate methods, guidelines, rules, and instruments for such a survey. Moreover, the knowledge base may inform the problem identification activity with domain-specific gaps and research questions as a result of the systematic literature review activity. Furthermore, the outputs of the problem identification activity maintain the inputs for the next research activity with the requirements of the explicated problem.

Correspondingly, the Design and Development activity of DSRM accommodates various design activities like abstractions of concepts and construction of models and methods. Such studies can be conducted by exploiting existing artefacts and kernel theories from the knowledge base while employing application context-specific domain knowledge, skills, and expertise. Moreover, artefact design and development activity may absorb the knowledge created during – if any – previous evaluation and communication activities.

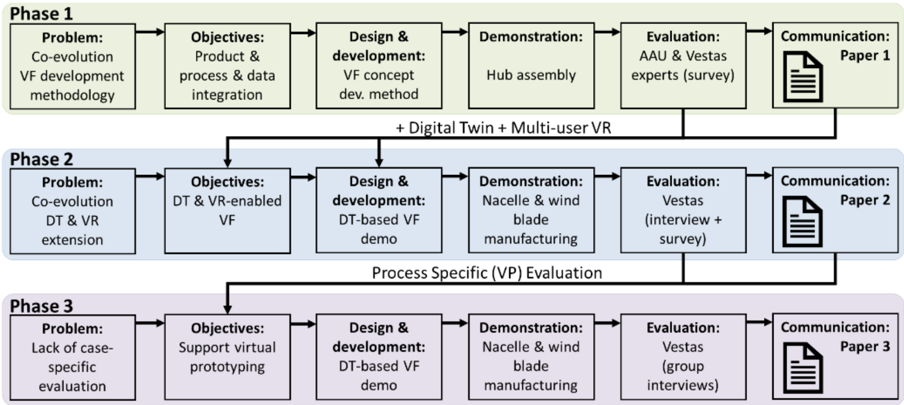

Figure 20 DSRM process iterations

Figure 20 DSRM process iterations depicts the abstraction of the DSRM implementation to each research phase as well as the relationship between the processes of each phase during the research project. Although initially three journal publications – one for each phase – were planned, extensive discussion was stimulated incidental to the research implications, and reflections on kernel theories gave rise to additional dissemination dedicated to theoretical issues. The paper also introduces the concept of the virtual enterprise, which is an extension of the VF concept to the enterprise level. Therefore, it attempts to generalise and discuss the knowledge discovered during the previous research phases, aiming to provide generic guidelines for managerial purposes.

Figure 21 DSRM contextualisation [adapted from (Yildiz & Møller, 2021)] illustrates the implementation of the proposed DSRM process model for IS (Peffers et al., 2007) into the specific context of Phase 1 with a higher resolution relative to Figure 20 DSRM process iterations. Undoubtedly, it is still an oversimplified illustration of the long-term research activity, and a more comprehensive process model of DSRM methodology followed. Therefore, as a result of the knowledge discovered and experience gained during the research activity, we increased our understanding and interpretation of the research topic. More particular problems and questions emerged throughout the research study. Each of the DSRM activities and their implications in our research study will be discussed further on.

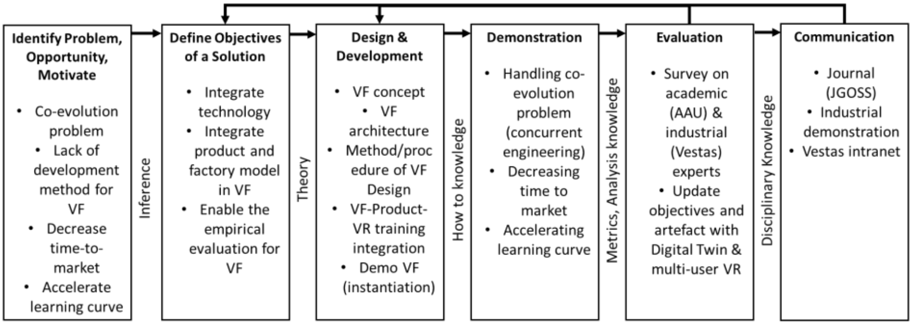

Figure 21 DSRM contextualisation [adapted from (Yildiz & Møller, 2021)]

4.4.1. PROBLEM IDENTIFICATION

Since DSR concerns both the design of innovative artefacts and the implementation of the designed artefacts in the application context to ensure the desired improvement in the environment, DSR is an ideal approach to contribute to both the research and practice in the digital innovation field (Hevner et al., 2019). Therefore, problem identification is critical to formulate and describe an explicit problem that determines the gap between the present and desirable state in the application domain. However, it has to be noted that the problem should not be specific to one particular stakeholder. Although the symptoms can be gathered from one particular case, the existing knowledge in the literature and the gaps need to provide adequate pieces of evidence to explain why the problem is of general interest.

To illustrate this activity by depicting an analogy, when a physician is questioning a patient, she[15] collects the data specific to that patient, her age, gender, blood type, medical history, how the patient perceives her own situation, etc. Thus, the physician performs her inquiry based on certain methods provided by the healthcare knowledge domain, such as patient inquiry forms or inspecting vocal resonance with a stethoscope. Moreover, there is no doubt that physicians exploit extensive knowledge from the literature in diagnosing a disease that is also addressed in the knowledge base. Therefore, problem identification and the methods used to justify the problem are significant elements to show the importance of the research study.

[15] The words "she", "her", and "hers" are used as androgynous pronouns, including women and men equally in their scope.

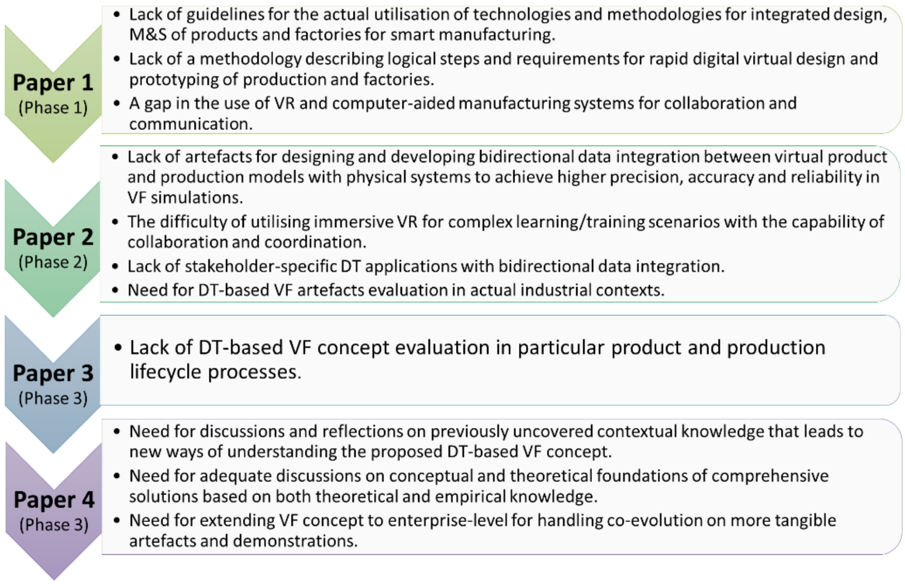

Figure 22 Identified problems and gaps

Accordingly, the problem identification of each phase is performed based on empirical knowledge and requirements from the industry stakeholder and gaps addressed in the knowledge domain. Aside from the problems, particular opportunities, and motivations specific to Vestas, as well as the general interest of the manufacturing industry, were identified in each paper except **Paper 4**. **Paper 4** is derived from the need for a more comprehensive and inclusive discussion of the overall study to frame the conceptual foundations as well as potential future extensions of the proposed artefacts. Figure 22 Identified problems and gaps summarises the problems and gaps for each paper and phase formed by both the application and knowledge domains. Table 4 The outline of research phases, research questions and research methods shows the breakdown of the previously introduced main research questions with respect to each paper and research method. The research questions are derived from both the empirical challenges and the gaps addressed in the literature. Therefore, it is ensured that the problems identified during the research are responding to the empirical challenges and interest in the application domain while addressing the general knowledge gaps and concepts.

Table 4 The outline of research phases, research questions and research methods

Research Phase 1 (Paper 1): Building the VF: Concept design, integration, & discover value cases
Research Question 1: How can a VF concept that integrates the product, process, system data, as well as state-of-the-art technologies, be designed and

developed for an industrial case?	
Research Question 1.1: How can VF be designed and developed rapidly for a real-life manufacturing case?	**Research Method:** Exploratory research approach (simultaneous design, development, and evaluation of artefacts) and retrospective analysis (design and implementation).
Research Question 1.2: How can a virtual product model be linked with production processes?	**Research Method:** Case Study (WTG Hub Assembly Line).
Research Question 1.3: What are the possible use-cases that promise high value in the manufacturing industry for using VF?	**Research Method:** Survey with industry experts and scholars. Unstructured interviews.
Research Phase 2 (Paper 2): Extending the VF: Synchronised (Digital Twin) & collaborative VR (multi-user VR)	
Research Question 2: Can DT-based VF support manufacturing organisations to handle the co-evolution of product, process, and system models by enabling concurrent engineering and a shorter time**-to-**market?	
Research Question 2.1: Can the DT-based VF concept achieve the four cornerstones of competence theory: a dynamic, open, cognitive, and holistic system?	**Research Method:** Semi-structured industrial interviews.
Research Question 2.2: Can DT-based VF enable concurrent engineering of products, processes, and production systems?	**Research Method:** Case Study (WTG Nacelle Assembly Line & WTG Blade Manufacturing).
Research Question 2.3: Can DT-based VF support manufacturing organisations in shortening product and production lifecycles?	**Research Method:** Semi-structured industrial interviews.
Research Question 2.4: Are DT-based VF artefacts useful, effective, simple, and consistent enough to implement VF solutions in actual manufacturing scenarios?	**Research Method:** Industrial survey.

Research Phase 3 (Paper 3): Case evaluation: Virtual prototyping	
Research Question 3: How can DT-based VF solutions support the new product introduction process by enabling virtual prototyping?	
Research Question 3.1: Can DT-based VF enable virtual prototyping during the new product introduction processes?	**Research Method:** Multiple case study.
Research Question 3.2: How can DT-based VF support new product introduction in the context of virtual prototyping?	**Research Method:** Semi-structured group interviews.
Research Question 3.3: What is the value of virtual prototyping using DT-based VF tools?	**Research Method:** Semi-structured group interviews.
Research Phase 3 (Paper 4): Conceptual foundations and extension of digital twin-based Virtual Factory to virtual enterprise	
Research Question 4: What are the conceptual and theoretical foundations of the DT-based VF concept that can support the extension of the concept to enterprise level for handling co-evolution?	
Research Question 4.1: What are the conceptual foundations of DT-based VF to support the co-evolution of organisational systems?	**Research Method:** Deductive and descriptive analysis.
Research Objective 4.2: How can DT-based VF be extended to enterprise-level operations to handle co-evolution?	**Research Method:** Inductive and exploratory analysis.
Research Objective 4.2: How could previously discovered knowledge about the DT-based VF concept be generalised to provide managerial guidelines for utilising the concept?	**Research Method:** Retrospective and prescriptive analysis.

As seen in Table 4 The outline of research phases, research questions and research methods, each phase of the research addresses the main research question, which is deduced from the main objective of this thesis. Moreover, in each research phase, each research paper addressed detailed and more specific sub-questions that determined the research methods. Retrospective analysis, case studies, semi-structured (individual and group) interviews, and surveys (among scholars and industry experts) were among the methods employed to address the research questions. Although problems and the research questions address some core issues in both the application and knowledge domain, they do not directly translate into the objectives of an artefact. However, the output of the problem identification contributes to the inputs for the next DSRM activity, which determines the objectives that a solution needs to accomplish.

4.4.2. OBJECTIVES OF THE SOLUTION

One of the main questions that need to be answered in the second activity of DSRM is "*What would a better artefact accomplish?*" (Peffers et al., 2007). However, before that question, "what type of artefact is needed to solve the defined problem and to answer the defined question?" should first be asked, since the question determines the kind of response, as it imposes the methods. A "how" question, for instance, generally calls for a method, process/procedure definition/guideline, or similar, as can be seen in Research Question 1 and its sub-questions (Table 4 The outline of research phases, research questions and research methods). Moreover, in a highly broad and complex solution domain like VF, some aspects, capabilities, and/or technologies may emerge as more critical than others. For example, accomplishing DT and multi-user VR capabilities with VF artefacts in Phase 2 is undoubtedly more prominent and critical for our research, since the extensive literature on such capabilities calls for further studies on such state-of-the-art technologies. Therefore, the objectives of the solution in the second phase of the research focused more on automated bidirectional data integration between VF and physical shopfloors, as well as collaborative and coordinated VR training capabilities. However, more mature simulation capabilities like kinematic motion or linear stress simulation were not included in the development work due to their limited contribution to the novelty of the concept and demo. Nevertheless, possibilities to extend the VF demo with such long-established simulation capabilities are also addressed during the demonstration, evaluation, and dissemination activities. This is critical to appreciate the difference between the conceptual model and its contextual application (demo) during such activities.

VF research is engaging with real-life problems in manufacturing operations to create instrumental knowledge to be used for designing and implementing systems, actions, and processes within multiple phases. Thus, it was expected that the artefacts would evolve through various design and evaluation cycles during the DSR (Sonnenberg et al., 2012). Therefore, the objectives for each phase and artefact are also adjusted according to the problems, questions and opportunities defined for both the specific phase and the overall research. Moreover, the high-level requirements and characteristics of artefacts should be both applicable and verifiable in the particular context while responding to the generic issues, because the problems defined in the first step of DSRM are not specific to the context but generic problems. The objectives of designing and developing the VF based on 3D DES and VR capabilities in Phase 1, for example, were imperative to perform enhancements for Phase 2 with less effort and time. In addition, various revisions in terms of empirical problems, objectives, and design were expected at the initial stage due to the incremental growth of experience and knowledge during the research.

4.4.3. DESIGN AND DEVELOPMENT

The third activity of the DSRM comprises the creation of the artefact by means of design and development. Conceptually, any designed object on which research knowledge is capitalised can be a DSR artefact (Peffers et al., 2007). Primarily, the objective of an artefact is to be used for solving a practical problem. Therefore, the creation of the actual artefact incorporates determining its key functionalities. Aside from the objectives/requirements of the solution, inputs for the design and development of the artefacts could be knowledge derived from the kernel theories, existing artefacts, empirical requirements like technologies, resources, capabilities, and other contextual idiosyncrasies.

Segregating the construction, function, and environment of an artefact can be more convenient to analyse an artefact's design and development activity (Johannesson, 2015). The construction of the artefacts concerns the components of the artefact as well as how the inner components of an artefact are related and working together. In order to elaborate on the consistency of an artefact, its construction needs to be introduced and demonstrated adequately. Such need for models, methods, or instantiations was fulfilled at various levels during the research. Phase 1 of the VF research, for instance, focused more on the construction of the VF concept, VF architecture, and VF design and development methods. Phase 2, however, concentrated more on DT and multi-user VR aspects of the models and instantiations, while Phase 3 focused on functions and instantiation of the artefacts into specific environments. However, DT-based VF and design and development activity in general demands interdisciplinary and transdisciplinary knowledge creation. Therefore, some of the VF research's design and development activities are subdivided into more discrete activities.

The functionality of an artefact concerns the effects of using such artefacts for the benefit of users. Since the DT-based VF concept incorporates a broad spectrum of tools, technologies, and capabilities that can be adopted in different manufacturing contexts, the VF research focuses on specific and fundamental functions that can address common problems and objectives. For example, integrating various advanced tools, models, data, and methods with VF artefacts was more essential to deal with general challenges, including handling co-evolution, complexity, virtual collaboration, and shorter lifecycles. Moreover, various functions like optimisation, cloud computing, AI or machine learning were not the focal point of dealing with the problems addressed. Although the possibility of extending the models with the abovementioned functions was discussed and disseminated, the essence of developing the DT-based VF concept requires that the solution can maintain its position as a stable intermediary system to accelerate the evolution of highly complex systems like Smart Factories. Thus, functions addressing the generic requirements and problems should be compatible with the construction of the artefact as well as the environment.

The environment or application context defines the external surroundings in which the artefact will work. Although each application context has its own peculiarities, the artefact should be consistent with common circumstances or be adaptable to a particular context with presumable variations. Therefore, the peculiarities of the environment in which the artefact is designed and developed and its resemblances to the diverse context in the same application domain need to be clarified. The development of the DT-based VF concept and demo for a global WTG manufacturing organisation, for example, provides some advantages in terms of integrated, all-inclusive PLM and MES solutions that most small and medium enterprises (SMEs) do not possess. Furthermore, as mentioned earlier, the application environment incorporates various manufacturing facilities, models, data, as well as expertise to demonstrate the artefacts. On the other hand, everything is not so totally straightforward in the research environment. Such comprehensive and unwieldy tools and platforms are inconvenient for rapid and agile artefact development as well as a hindrance for multi-vendor network connectivity with their custom firewalls and complicated procedures.

4.4.4. DEMONSTRATIONS

The demonstration activity of DSRM aims to answer how the designed and developed artefacts are used to achieve the defined objectives in an actual context. The demonstration method of an artefact can take various forms, such as a case study, experimentation, proof of simulation depending on the research approach, scope, and application context. The gravity of the rigorous demonstration activity relies on both the justification of the chosen case in terms of the correspondence level to the problem and the justification of the methods used for demonstration. It is not ambiguous that the two are closely associated. The justification for choosing the WTG nacelle assembly and WTG blade manufacturing cases for the DT-based VF demonstration, for instance, imposes various limitations on the methods for such demonstration. Although such challenges will be discussed in later sections, we can refer to the complex nature of the application context that accommodates social, natural, and artificial systems and restrained us from conducting experimental or semi-experimental studies.

The objective of a demonstration does not have to be a full proof for solving the problem, but solving one or more instances of defined problems can provide sufficient data to enable an adequate interpretation for generalising the discovered knowledge. That is why each phase of the research addressed various aspects of the co-evolution paradigm. Moreover, demonstration activity capitalises on the knowledge that defines how to use the designed artefacts in an effective way in a specific application context. This type of knowledge enables valuable interpretation and discussion of deviations when transferring the generic artefacts to different contexts. For this reason, the dissemination of rich data about the demonstration activity can be very useful for experienced professionals. Therefore, the rich visual data regarding the DT-based VF demonstration was disseminated publicly during the research(Yildiz, 2020a, 2020b). Some of the DT-based VF demonstration data, however, was subject to the financial/intellectual interest of the industry stakeholder and therefore covered by the provisions given to the industry partner by the research collaboration agreement. Yet, the demonstration of a highly comprehensive concept alone does not guarantee sufficient data for a proof-of-concept to solve the problem in all its aspects. Therefore, further evaluation activity is required.

4.4.5. EVALUATION

The evaluation activity of DSRM focuses on measuring *"how well the artefact supports a solution to the problem"* (Peffers et al., 2007). Such evaluations aim to compare the objectives of a solution defined during the second activity with the results of the demonstration of the artefact by means of various relevant empirical evidence as well as logical arguments. Hence, the evaluation methods can take numerous forms derived from the nature of the problem domain, as well as the designed and developed artefacts. Some evaluation studies, for example, can be conducted with more quantifiable measures, while others require more qualitative research approaches like conversational, narrative, and intertwined knowledge construction to instigate reflections for new ways of understanding the designed artefacts. Therefore, mixed methods including case studies, surveys, retrospective analysis, unstructured and structured interviews with groups and individuals were performed during the evaluation of the DT-based VF artefacts.

Evaluation activity in DSR attracted particular attention from scholars since its importance for research rigour and relevance is paramount (Johannesson & Perjons, 2014, pp. 137–150; March & Smith, 1995; Prat et al., 2015; Sonnenberg et al., 2012; van Aken et al., 2016). Since the objectives of the designed solutions are to solve practical problems with pragmatic methods, the justification of the design during the evaluation activity is not interested in the truth. Still, it covers the question of pragmatic validity (*How strong is the evidence that the design will produce the desired results?* (van Aken et al., 2016)) and practical relevance (*In what way does the design make a valuable contribution to addressing a significant field problem or exploiting a promising opportunity?* (van Aken et al., 2016)). Scholars have proposed various evaluation strategies and methods for DSR evaluation activities. The evaluation criteria of DSR artefacts include, but are not limited to, their utility, completeness, internal consistency, external consistency, elegance, the broad purpose and scope, effectiveness, simplicity, novelty, the fruitfulness of further research, and interestingness (March & Smith, 1995; Simon, 1996; Sonnenberg et al., 2012). Depending on the type of artefact, whether it is a construct, method, model, or instantiation that is being evaluated, and the phase/time of the research, some criteria can reflect how extending the designed artefacts can address the problems and achieve the objectives. The evaluation activity of Phase 1, therefore, does not propose a conclusive evaluation outcome, but rather attempts to demystify future research directions in terms of enhancements of artefacts and industrial implications. Evaluation activity also incorporates the decision making on the iteration to activity 2 (objectives of the solution) or 3 (design and development) before communication. In this respect, the feasibility of the iterations in each research phase is revisited during the evaluation activity.

Since the outcome of the DSR activity capitalises on prescriptive knowledge, and some (Iivari, 2007) have argued that the prescriptive knowledge incorporates no truth value in itself, a more comprehensive evaluation approach for conducting DSRM was proposed by Sonnenberg et al. (Sonnenberg et al., 2012). Although the evaluation activity of DSRM typically focuses on *"to what extent the designed solution addresses the problems"*, the phenomena (artefacts) that have been investigated usually do not exist at the initial stage of the scientific investigation (Gregor, 2009). Consequently, the prescriptive knowledge that is demonstrated in an artefact's utility alters the validity of early DSR phases. Therefore, it is significant to understand the expected impact of an artefact on the world ex-ante – a world with a real problem before an artefact has been applied to it – by rigorously reasoning, justifying, evaluating, and documenting the design by means of relevant theories (Gregor & Jones, 2007; Sonnenberg et al., 2012).

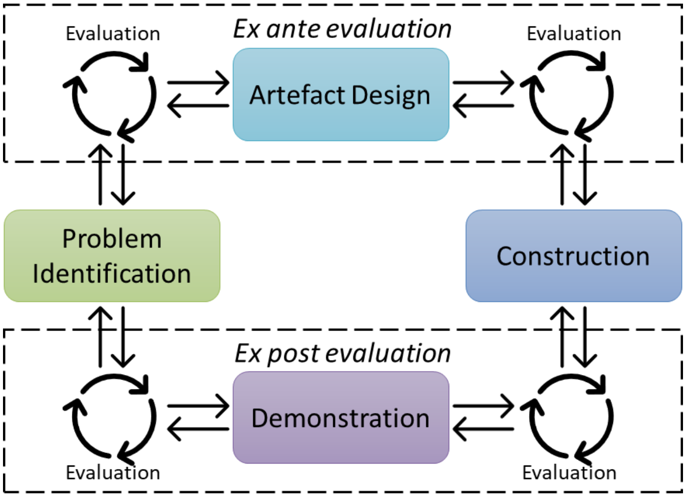

Figure 23 DSR evaluation activities [borrowed from (Sonnenberg et al., 2012)*]*

Consequently, a more comprehensive *"design-evaluate-construct-evaluate pattern"*, as seen in Figure 23 DSR evaluation activities [borrowed from (Sonnenberg et al., 2012)], was proposed, which incorporates both the validation of the artefact design (ex-ante evaluations) and the validation of artefact instances (ex-post evaluations). Such an approach for the evaluation processes of DSR is essential for validating the design of an artefact in terms of the internal consistency of the design objectives, principles, form, and function before demonstrating and proving the artefact design in an actual context. Thus, it enables the dissemination of rigorously evaluated design by informing the knowledge domain and receiving scholarly feedback for the required revisions. The iteration of evaluation activities shown in Figure 23 DSR evaluation activities [borrowed from (Sonnenberg et al., 2012)] was spread throughout the three years of the VF research study and manifested itself during the various communication activities.

Paper 1, for instance, addresses the construction of the generic VF concept by describing the internal structures of the artefacts, their components, relationships, as well as argumentation about the decisions made during the design process. **Paper 2**, however, focuses mainly on the functions of the artefacts – describing how to build such functions and how such functions can fulfil the objectives – and the effects of the artefacts – discussing the direct, indirect, intended, unintended effects. **Paper 3** concerns the usability of the solution in terms of particular processes and operations, as well as how the artefacts can be improved. Lastly, **Paper 4** articulates the design theories for the DT-based VF concept's internal and external entities by framing various kernel theories and concepts to ground the design decisions.

4.4.6. COMMUNICATION

Communication, as the sixth and the last activity of DSRM (Peffers et al., 2007) covers disseminating the knowledge discovered during the research activity to the relevant audiences, including researchers and practising experts. Scope dissemination covers the problem identification, its importance, the artefact, its novelty, utility, effectiveness, the rigour of its design, as well as potential implications in scholarly research publications. Communication in peer-reviewed scholarly journals is critical to ensure the contribution to the knowledge base, as well as obtaining critical inspection resting on disciplinary knowledge. Moreover, scholarly reviews are valuable to form future research and development directions regarding the further objectives of the artefacts, design, and development improvement, etc.

4.5. METHODOLOGICAL DISCUSSION

Although DSRM is essentially suitable for discovering the effects of intervention in highly complex organisational systems like DT-based VF, there are, however, various matters that need further discussion. In spite of the six DSR activities being introduced sequentially, there is no hard requirement that the activities should be followed from one to six. Conducting DSR activities in a nominal sequence from activity one to six is designed based on a problem-centred approach. Indeed, various DSR initiation approaches like design and development-centred, objective-centred, context-/demonstration-centred were introduced by Peffers et al. (Peffers et al., 2007).

In this respect, Phase 1 of the VF research was conducted based on a problem-centred DSR approach. Various challenges related to the co-evolution as well as opportunities derived from the emerging IT developments and real-time data were among the factors that initiated the VF research. However, phase 2 of the research started with activity 2 (define objectives of a solution) since it was triggered by the need to enhance the existing artefacts with DT and multi-user VR capabilities. Phase 3 of the research followed a context-initiated approach that starts with activity four, and the research rigour was applied to the processes retroactively.

4.5.1. DSR AND EXPLANATORY RESEARCH PARADIGMS

The objective of explanatory research, expressed in an elementary way, is to explain or describe the present or the past of a natural or social phenomenon by using scientific methods. The explanatory research paradigm, the outstanding example of which is physics, generally aims to discover knowledge about causation that is justified on the basis of explanatory and descriptive validity (van Aken et al., 2016). Accordingly, the research activity is conducted from a detached observer perspective. For instance, a commonly known experimental research logic shown in Table 5 Classic experimental research design (Pawson & Tilley, 1997, p. 5) exemplifies the simple framework of experimentation (Pawson & Tilley, 1997, p. 5). Such logic of experimentation inherits the basic design requirements ingrained in philosophical reasoning on the nature of explanation. In the explanatory research paradigm, therefore, the knowledge about the treatment (intervention) is uncovered from random samples that are similar to the whole population.

Table 5 Classic experimental research design (Pawson & Tilley, 1997, p. 5)

	Pre-test (T0)	**Treatment**	**Post-test (T1)**
Experimental Group	Q1	X	Q2
Control Group	Q1		Q3

The objective of DSR, however, concentrates on improving the present by designing and developing artefacts to satisfy human goals and purposes. Therefore, DSR aims to discover the prescriptive knowledge derived from justified interventions based on pragmatic validity and practical relevance. Thus, explanatory research seeks the truth about its subject phenomenon (what it is) while DSR seeks to improve its matters (what can be).

However, since VF research is associated with manufacturing engineering, IS, and operations management, the subject of DSR presented in this dissertation emerges when the natural, artificial, and social phenomena interact. Considering that the social phenomenon inherits the complex, open and dynamic characteristics, complete understanding of the sociotechnical and socioeconomic nature of such complex systems is highly challenging or even impossible. Furthermore, it is very difficult to isolate the contextual environment or the research groups for experimental or quasi-experimental research. Thus, this leads to some confusion about the internal validity of causal inferences (Lonati et al., 2018). Therefore, to minimise such confusions, the initial phase of the study required the investigation of the existing prescriptive and descriptive knowledge (kernel theories) to establish rigorous foundations for the artefact design (Walls et al., 1992). Moreover, to handle such complexity, DSR study requires the simultaneous formulation of the problem domain and the solution domain in multiple DSR iterations in which the problem and the solution (Gill & Hevner, 2013) cohere (Gill & Hevner, 2013). Such cohesive evolution of the problem (co-evolution) and the solution (DT-based VF artefacts) materialises itself throughout the three phases of VF research, each of which is a DSR iteration. This is the reason for **Paper 1** focusing on the existing artefacts and clearly identifying each aspect/feature borrowed from previously introduced artefacts like concepts, models, methods, etc. Moreover, **Paper 4** is particularly dedicated to framing the relevant kernel theories and concepts as well as their relationship to rigorously ground the design decisions predicated upon the appropriate social and natural constraints and capabilities.

Although it is not particularly the subject of this discussion, it would be worth mentioning that general system theory is proposed as an overarching scientific theory for the design of IS (Baskerville et al., 2018; Demetis & Lee, 2016; Matook & Brown, 2017). Although there are still significant debates on the subject (Mingers, 2017; Robey & Mikhaeil, 2016), we need to state that the author of this dissertation acknowledges the relevance of general system theory to interpret the complex nature of the problem space and thus its relevance to the DSR as it is articulated in the next chapter.

4.5.2. GENERALISING THE DESIGN AND THE KNOWLEDGE

Another fundamental issue regarding the DSR is the generalisation of the design and the knowledge. Both the DSR and explanatory research intend to discover generic research outcomes instead of case-specific results (van Aken et al., 2016). Such generic outcomes can gain ground in particular contexts by providing insights on the essence of deviations from the average towards the particular. Explanatory research generally aims to produce the general outcomes by general (average) relations. In clinical research, for instance, the effectiveness of a medicine (intervention) comes from well-defined random samples as they provide the average outcomes. Then, physicians contextualise the generic results to particular patients (van Aken et al., 2016). In DSR, however, the relevance and validity of the designed solution rely on the level of its desired pragmatic results and practical implications in a particular problem context. But the requirements derived from a particular problem context are often addressed as a generic problem. As articulated before in the analogy of a patient's specific symptoms, the clinician constructs a diagnosis that is generally a known disease. Therefore, the artefacts in DSR such as constructs, models and methods are often generic designs that target the generic problem. Instantiations, however, demonstrate the applicability of such constructs, models and methods to an actual working system, which enables empirical evaluation of the artefact's practical relevance to its determined functions (Baskerville et al., 2018). Thus, in DSR, although the generic design is developed based on the requirements from a particular context, it can be transferred to different contexts within a certain application domain, while maintaining its essential functions and capabilities.

Therefore, testing the DT-based VF concept in different manufacturing contexts like the blade, nacelle, and hub manufacturing enables the interpretation of deviations specific to each application context, while providing knowledge particular to each case. The impact of context-dependency generally relies on the level of social components, since they are less tangible than technical components. It is not always possible or necessary to disclose such context-specific deviations, but experienced professionals and designers may handle context-dependency based on given "user instructions" (van Aken et al., 2016). Although the outcomes of Phase 1 did not provide adequate evidence to have an extensive discussion on deviations, we believe Phase 2 and especially Phase 3 produced satisfactory data to prompt such discussion. **Paper 4**, produced as part of Phase 3, therefore, is dedicated to generalising the overall knowledge by providing discussion of the conceptual foundations as well as the extension of the concept to enterprise-level operations.

The knowledge contribution is contained in various levels of artefact abstractions framed on the degrees of maturity of the application (problem) domain by (Gregor & Hevner, 2013). Expecting an impactful innovation as a result of each DSR project is certainly not rational. Nonetheless, the demonstration of a novel IS artefact like DT-based VF can incorporate a contribution for subsequent design ideas and theories still to be established and articulated. Therefore, (Baskerville et al., 2018) argued that *"design of the IT artefact precedes the development of nascent design theories as a natural sequence of activities in a DSR project"* while stressing the importance of artefact building and evaluation activities as a priority. The reason for such prioritisation is justified with the ample time for understanding, articulating and formalising design principles as well as far-reaching implications for an artefact that was realised and evaluated in an actual context. A practical example of such an argument is the evolution and enhancement of the theoretical discussion and interpretation of the design principles of DT-based VF artefacts towards the end of the three years of VF research. **Paper 4**, which is the final and concluding outcome of the VF research, for example, presents a more holistic and sound conceptual and theoretical framework, as well as articulating the extension of artefacts to the enterprise level.

4.5.3. HUMAN IMPACT AND PRAGMATIC VALIDITY

Since operations management in manufacturing enterprises accommodates significant social elements, applying DSR to such systems causes some challenges which are not very common in engineering research. The DSR approach in dynamic and complex sociotechnical and socioeconomic systems can cause some internal validity confusion (Lonati et al., 2018). The reflections of such challenges can be observed in various empirical studies on VF that limit the broad spectrum of technologies, models and data and focus on more particular aspects, capabilities, or cases regarding the VF concept. Although narrowing the empirical scope may increase the reliability of the results, it also confines the application guidelines to comprehensive real-life scenarios.

Although the focus of VF research is mainly formed on a technical nature, there are also significant parameters that are contingent on human agency impacts like operators performing VR training or engineers designing, executing, and managing the process (organisational) changes. Therefore, predicting and evaluating a system's behaviour with full confidence becomes a significant challenge. Accordingly, evidence gathering for determining the pragmatic validity of the DT-based VF becomes more difficult. Although the mechanisms of social systems are relatively weak, it still enables the prediction of the expected impact of the artefact. Indeed, experiential learning relying on a series of case studies is considered a valuable study approach for problem, context, intervention, and outcome analysis (van Aken et al., 2016).

Active communication and coordination with industry experts are required to conduct a meticulous study on VF research during the various DSR activities, including problem identification, determining the objectives of a solution, design, and development, as well as a demonstration. The scope, objectives and means of collaboration and communication with people during DSR activities are governed in various ways to minimise the impact of social mechanisms. For example, some of the data collection activities to define challenges and problems with numerous experts who have the same background were conducted as separate individual interviews and the results were compared to minimise social and contextual idiosyncrasies. Moreover, evaluation of the demonstration by industry experts (focus group) during Phase 3 was performed with group interviews, each of which consisted of experts from diverse backgrounds. This resulted in fruitful dialogues by instigating various discussions between experts, and provided rich evidence for the final (disseminated) case evaluation.

Furthermore, in the explanatory research approach, broadening the explanation to achieve more extended practical relevance may result in a decrease in the explanatory validity (van Aken et al., 2016). In DSR, on the other hand, there is no such trade-off. Since the design of an artefact is performed for a generic solution, each instantiation can increase the practical relevance by providing more information on possible implications of a generic design in particular contexts.

4.6. CHAPTER SUMMARY

Although DSR is a relatively new research approach, it has shown the capacity for significant advances in domain-independent (interdisciplinary and transdisciplinary) new knowledge on inclusive solutions, processes, actions, and systems. Despite the challenges like generalisation and human impacts, it maintains adequate methods and guidelines which are significantly relevant for studies on comprehensive IS-based solutions in the highly complex operations management domain. The inclusive guidelines of DSR for various activities such as problem identification, definition of solution objectives, design and development processes, demonstration of the solution and evaluation provide sound approaches for the theoretical and empirical rigour of the research.

The next chapter will summarise the outcome of the VF research and provide the essential discussion on how each paper is positioned in the PhD study and contributes to the overall research problem.

CHAPTER 5. RESULTS

This chapter frames and summarises the findings of each of the three phases of the research based on the respective dissemination activities. Figure 24 Dissemination outlook illustrates the summary of dissemination during the research phases.

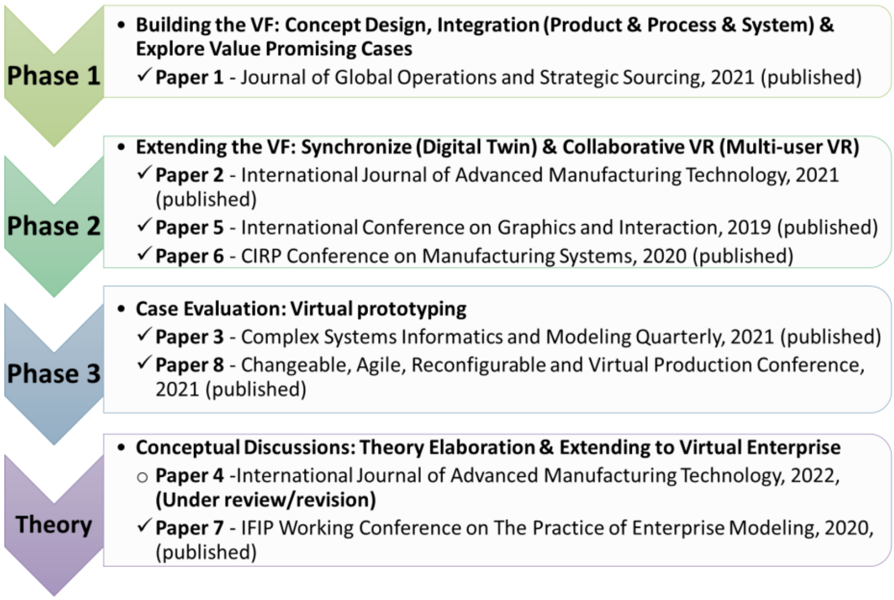

Figure 24 Dissemination outlook

Paper 1 introduces the results of the first research phase, which investigates and discusses the existing artefacts on VF and brings up to date the VF concept that integrates the product, process, and system models. It also clarifies the development of the first VF demo based on interactive VR-enabled 3D DES together with its demonstration in industrial cases to discover the future development and demonstration cases. One of the most value-promising industrial cases determined as VP is investigated in Phase 3 (**Paper 3**).

Paper 2, which is the extended version of **Paper 6**, demonstrates the VF concept, which is extended with DT and multi-user interactive VR capabilities in two industrial capabilities in the context of handling co-evolution. Semi-structured individual interviews with thirteen industry experts followed by a demonstration provide rich discussion and arguments to evaluate DT-based VF in specific respect to dynamic, open, holistic, cognitive, time-saving, concurrent engineering and collaborative VR perspectives.

Paper 3, which is extended from **Paper 8**, presents an evaluation of DT-based VF for VP in the context of NPI. Since the NPI operations call for interdisciplinary engineering expertise, the demonstration and evaluation activities of Phase 3 were performed with groups of industry experts who participate in the NPI operations and have diverse backgrounds. Twenty experts in four groups, each of which includes five experts, participated in the evaluation and provided well-grounded arguments and data to explore the interpretations and perspectives on utilising DT-based VF for VP during NPI operations.

Paper 4, which incorporates the conceptual interpretations and the extension of the DT-based VF concept to enterprise-level, was not part of the initial research plan, as seen in Figure 7 Research phases (work packages). Therefore, in addition to conceptual and theoretical foundations, it also contributes to the implications in the next (DISCUSSION) chapter together with **Paper 5**, which is focused on multi-user (collaborative and coordinated) VR learning/training technology.

Since the VR research presented in this thesis aims to deal with the co-evolution paradigm, we aim to develop a comprehensive solution that utilises various technologies and their demonstration in industrial cases. Therefore, the research does not particularly aim to create knowledge in specific technological concepts but rather a more common industrial challenge. Yet, as a comprehensive study, VF research produces valuable knowledge that could be effective and pragmatic for particular research activities concentrating on the technological concepts utilised in our research. Thus, Figure 25 Virtual Factory research framework illustrates the research work by illustrating the association of the empirical knowledge utilised from the knowledge base during each research phase, as well as the empirical output in the form of the artefacts introduced. Furthermore, the main research questions and corresponding journal papers are shown in each phase. Finally, the conceptual and theoretical contribution of the research activity is depicted in **Paper 4** as the theory elaboration and extension of the concept to a virtual enterprise.

Moreover, since the Smart Factories project is a part of MADE as a digital innovation hub in Denmark, the achievements of the VF research, as well as its significant potential industrial implications, were acknowledged by a nomination. Vestas, as the industrial stakeholder of the project, nominated VF research to The Otto Mønsted Foundation's MADE Award[16] and the project made it to the last four nominees. The following sections will present a glimpse of the results of each research phase based on the respective journal papers. Therefore, please refer to the papers attached in the APPENDED PAPERS for more accurate and comprehensive knowledge on the subject matter.

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[16] https://en.made.dk/news/five-sharp-for-a-nominee-building-a-virtual-factory-demonstrator/

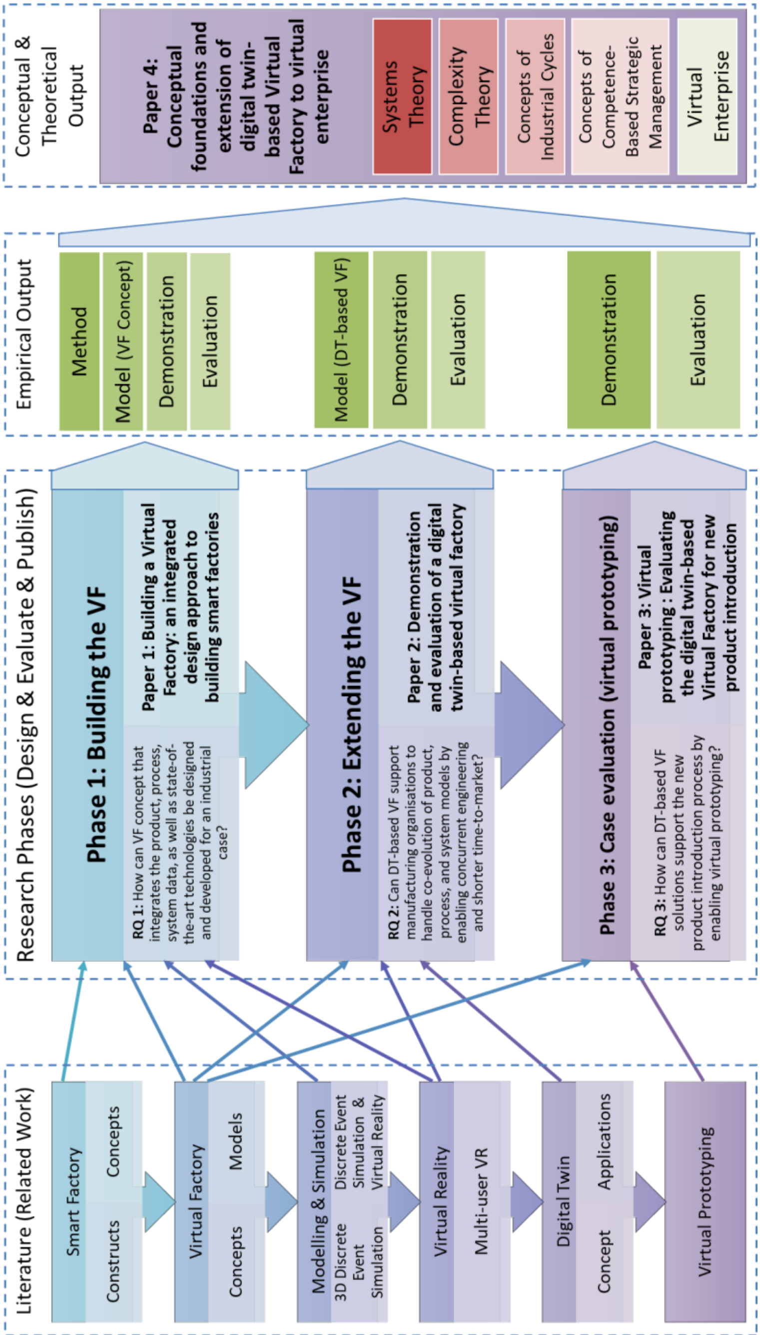

Figure 25 Virtual Factory research framework

5.1. PAPER 1: BUILDING A VIRTUAL FACTORY

Paper 1 is titled *"Building a virtual factory: an integrated design approach to building smart factories"* and published as part of a special issue *"Smart production and industry 4.0"* in the Journal of Global Operations and Strategic Sourcing (Yildiz & Møller, 2021). **Paper 1** introduces the initial VF concept, which utilises interactive VR simulation capabilities. The initially proposed VF concept incorporates novel properties and perspectives by distinct consideration of product, process and system models, as well as maintaining design and development methods for actual integration and utilisation of 3D DES and interactive VR. However, since there was no real-time bidirectional data integration between the VF simulations and shopfloor operations in the first phase, the developed and demonstrated demo was a digital shadow. Thus, the concept design introduced in **Paper 1** is revised and updated in **Paper 2** (Figure 11 Digital Twin-based Virtual Factory concept (Yildiz, Møller, & Bilberg, 2021c)).

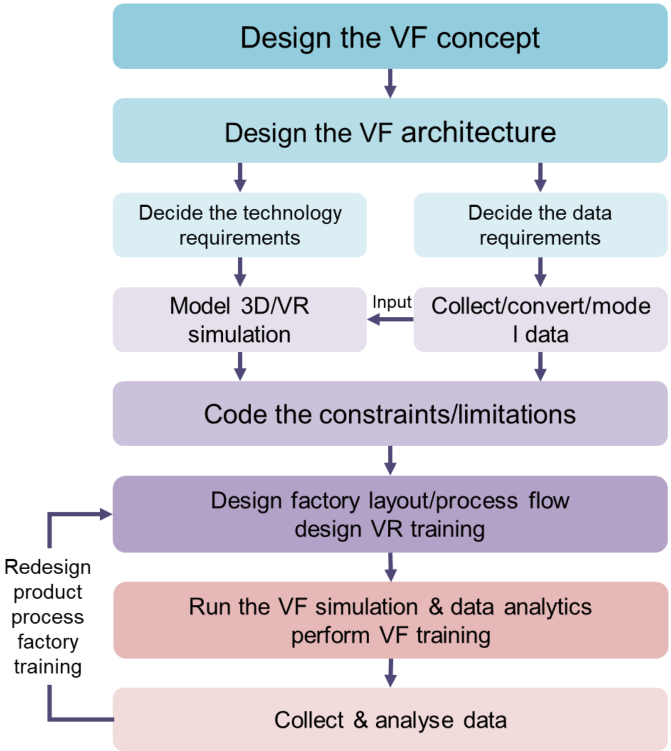

Figure 26 Design and development procedure for VF (Yildiz & Møller, 2021)

Moreover, **Paper 1** focuses on means for simultaneous design and development for VF as well as its demonstration in wind turbine manufacturing (hub assembly) cases. The design procedures of the VF concept, shown in Figure 26 Design and development procedure for VF (Yildiz & Møller, 2021), together with the demo development methods, were introduced and evaluated by industry experts and scholars. There is a need for a caveat to the reader on an amendment to the "General Methodology for VF Development" introduced in **Paper 1**. Since the demo VF in Phase 1 was limited to one simulation model developed in the FlexSim tool and lacked real-time bidirectional data synchronisation, there was a need for a revision to the VF development methodology according to subsequent DT and collaborative VR training/learning simulation enhancements of the solution. Therefore, Figure 27 General methodology for DT-based VF development illustrates the revised methodology for DT-based VF development based on the corresponding methodology introduced in **Paper 1**. The methodology was improved by adding particular data synchronisation and multi-user VR training/learning simulation.

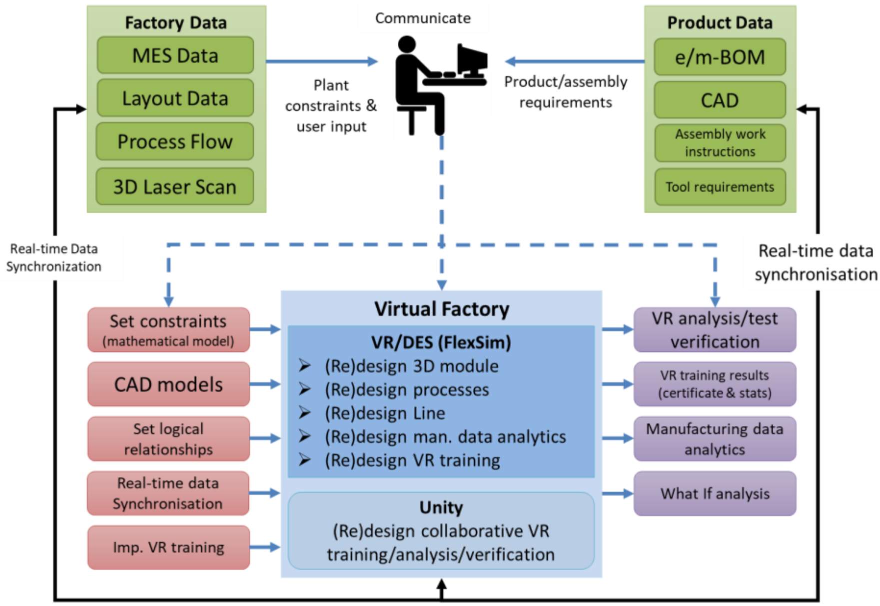

Figure 27 General methodology for DT-based VF development

The VF demonstration, shown in Figure 28 Virtual Factory hub assembly case (Yildiz & Møller, 2021), was performed both for industry experts and for scholars to explore both the industrial and the academic potential of the research idea. The demonstration results show that utilisation of the proposed solution can reduce the ramp-up times for designing new factories and reconfiguring existing manufacturing systems while supporting managerial-level decision-making. Moreover, the utilisation of interactive VR integrated with 3D DES, which is shown in Figure 29 Mixed production and crane control in VF-integrated VR training (Yildiz & Møller,

2021) is considered significantly valuable for collaboration and communication (knowledge management) by industry experts.

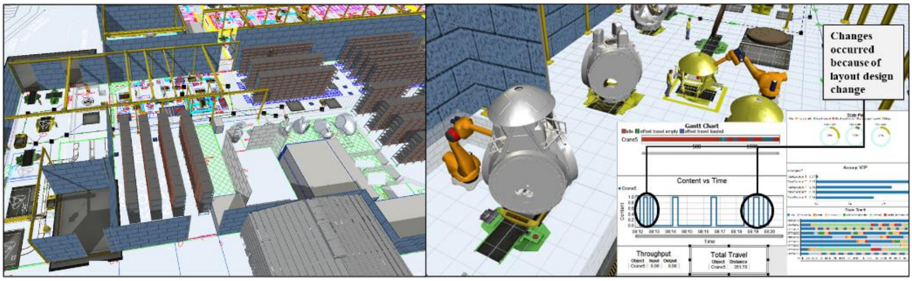

Figure 28 Virtual Factory hub assembly case (Yildiz & Møller, 2021)

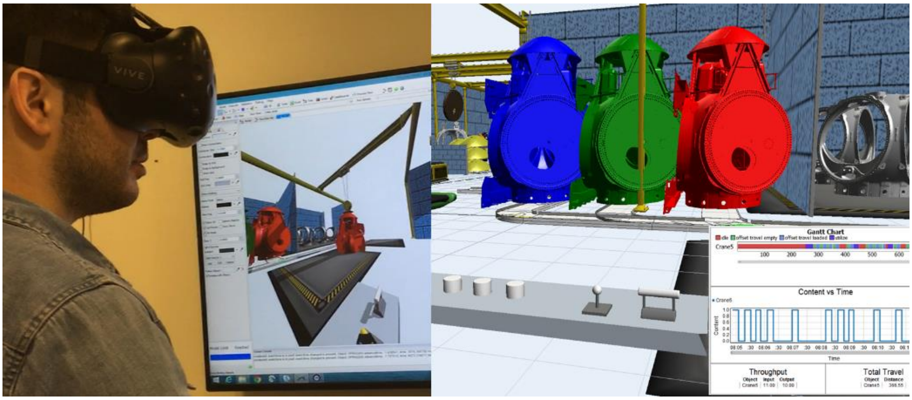

Figure 29 Mixed production and crane control in VF-integrated VR training (Yildiz & Møller, 2021)

In addition, the design and development methodology and logical steps for rapid, digital, and virtual development of VF incorporate the research knowledge into the knowledge base. It is critical to state that the author of this thesis is now working for the industry stakeholder of the VF research and benefitting from the methods and procedures introduced in **Paper 1**. Current professional practice in the industry shows that the 3D DES models that incorporate product, process and system models are evidently being used by professional simulation experts and bringing significant value for the (re)design and development of existing and new factories.

In short, **Paper 1** of the VF research contributes to the manufacturing engineering and information systems field by introducing a novel VF concept and a compelling design and development approach, as well as evaluation of the proposed solution in an actual manufacturing case. Knowledge discovered in the first phase of the VF research led to further developments/improvements of the concept and its respective demo and evaluation in phase 2. The fundamental outcomes of phase 2 are disseminated in **Paper 2** and summarised in the next section.

5.2. PAPER 2: DEMONSTRATION AND EVALUATION OF DT-BASED VF

Paper 2 is extensively enhanced from **Paper 6** and introduces the extension of the VF concept with the DT and multi-user VR capability. **Paper 6** is appended to this dissertation for the readers' reference. Moreover, **Paper 2** concentrates on disseminating the demonstration of the DT-based VF concept together with a comprehensive evaluation by industry experts within the context of handling co-evolution. The VF concept introduced in Phase 1 was extended with real-time bidirectional data integration with shopfloor operations via MES as well as multi-user (collaborative and coordinated) VR training/learning simulations, as shown in Figure 11 Digital Twin-based Virtual Factory concept (Yildiz, Møller, & Bilberg, 2021c). Thus, the models in the VF simulations were extended from digital shadows to DTs. The concept presented in Phase 2 was demonstrated in two distinct manufacturing cases: 1) a nacelle assembly line and 2) a wind blade manufacturing plant provided by Vestas. Higher-resolution multi-user VR simulation (Figure 30 Collaborative and coordinated VR training demonstration) was integrated with low-resolution VF simulations and actual production systems, as seen in Figure 31 Integration model for (1) multi-user VR simulation, (2) production line simulation, and (3) physical shopfloor via MES (Yildiz et al., 2020b). Please refer to the public media file at (Yildiz, 2020a, 2020b), for rich insights and extensive knowledge on the demonstration.

Figure 30 Collaborative and coordinated VR training demonstration

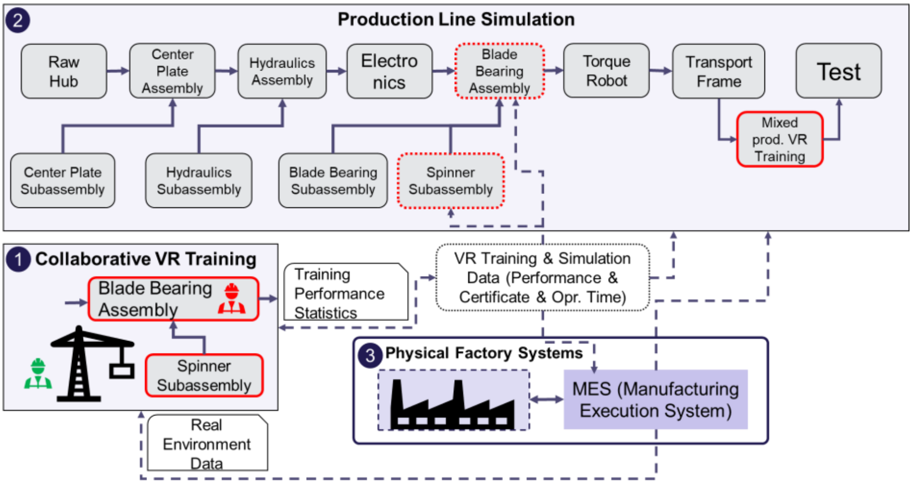

Figure 31 Integration model for (1) multi-user VR simulation, (2) production line simulation, and (3) physical shopfloor via MES (Yildiz et al., 2020b)

The evaluation of DT-based VF artefacts, including the concept, the revised architecture of the concept (Figure 32 DT-based VF architecture), and revised architecture for multi-user VR (Figure 36 Data synchronisation architecture of DT-based VF extended with multi-user VR) are presented as seen in Figure 33 DT-based VF artefacts evaluation by industry experts and further discussed in **Paper 2**.

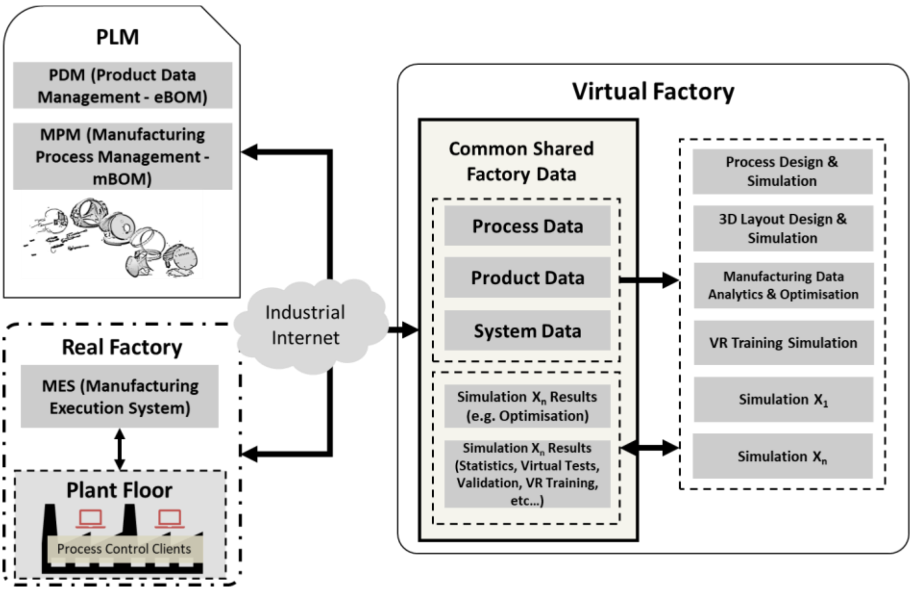

Figure 32 DT-based VF architecture (Yildiz, Møller, & Bilberg, 2021b)

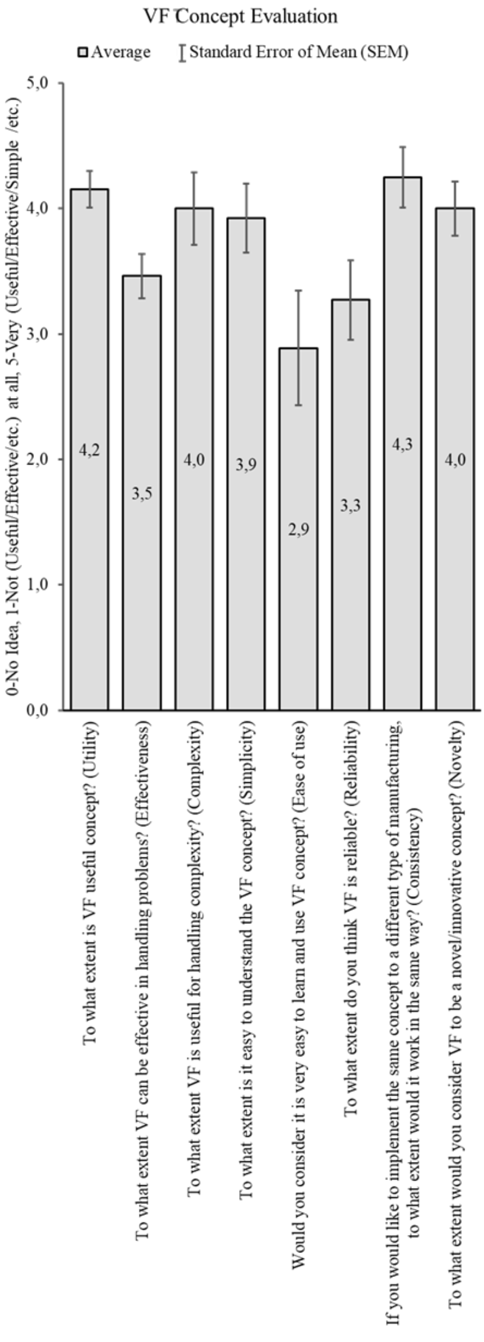

Figure 33 DT-based VF artefacts evaluation by industry experts (Yildiz, Møller, & Bilberg, 2021b)

Semi-structured individual conversational interviews were performed with 13 experts with diverse specialities. Evaluation of the solution was performed mainly in the four dimensions of competence-based strategic management concepts, namely, dynamic, open, holistic, cognitive. The summary of the evaluation is shown in Table 6 Summary of DT-based VF evaluation (Yildiz, Møller, & Bilberg, 2021c). Furthermore, discussion on concurrent engineering, time-saving during the NPI, VP and collaborative VR was also introduced.

Paper 2 attempts to answer the main **Research Question 2**: Can DT-based VF support manufacturing organisations to handle co-evolution of product, process, and system models by enabling concurrent engineering and a shorter time-to-market?, and the corresponding four sub-questions seen in Table 4 The outline of research phases, research questions and research methods. Thus, **Paper 2** introduces the demonstration and evaluation of DT-based VF artefacts, which are matured after various design iterations, within the range of the problems and challenges addressed by the application domain. Such challenges particularly arise from the handling of the co-evolution of product, process and system models, the complexity and shorter lifecycles. Therefore, the four cornerstones of competence-based strategic management, namely dynamic, open, cognitive, and holistic, shaped the essential evaluation dimensions.

The overall results show that VR-enabled DT-based VF promises significant potential for concurrent engineering by enabling virtual collaboration and simultaneously reforming and regenerating product, process, and system models. The solution is also considered useful and effective for complexity handling and decreasing the time-to-market with advanced analysis and verification and design capabilities for manufacturing engineering during NPI. Furthermore, DT- based VF is recognised as a useful solution for decreasing the number of physical prototypes during the NPI operations by enabling VP.

The experts stated that a high level of confidence in DT-based VF is needed for decreasing the physical prototypes. But the accuracy and precision in VF simulations are dependent on the data from legacy engineering platforms. Although numerous value-promising industrial cases for the DT-based VF concept were provided by the experts, VP was recognised as a highly promising case for the concept. Therefore, Phase 3 of the VF research was dedicated to the demonstration and evaluation of the solution in the VP case.

Thus, DT-based VF is recognised as a promising solution for manufacturing organisations in adapting to evolving complex conditions by enabling a process rendezvous for production and product lifecycles.

Table 6 Summary of DT-based VF evaluation (Yildiz, Møller, & Bilberg, 2021c)

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

5.3. PAPER 3: VIRTUAL PROTOTYPING CASE STUDY

Paper 3, which is extended from **Paper 8**, presents the demonstration and evaluation of the DT-based VF concept in VP cases of NPI operations by industry experts. During Phase 1 and Phase 2 of the study, some data was provided by the industry experts about the potential for utilising the DT-based VF during the NPI processes. However, there was a lack of in-depth discussion on how to utilise the solution for the various phases of the prototyping during the introduction of new products to the market. Thus, Phase 3 of the research was conducted by narrowing down the scope of the demonstration and evaluation of the proposed solution to the VP during the NPI operations. The empirical knowledge discovered during the case evaluation was disseminated in **Paper 3**.

Paper 3 addresses the main **Research Question 3:** How can DT-based VF solutions support the new product introduction process by enabling virtual prototyping? Therefore, the research presented in **Paper 3** follows the trails of an explanatory study to "discover knowledge on 1) how the DT-based VF can be utilised in VP operations of WTG manufacturing, and 2) what benefits can be gained from such industrial implementation" (Yildiz, Møller, Bilberg, et al., 2021).

The evaluation and the discussion, grouped into the four main activities of the NPI operations, and the summary of the results are shown in Table 7 Summary of evaluation (Yildiz, Møller, & Bilberg, 2021b). A significant decrease in the number of physical prototype-builds by utilising the DT-based VF solutions is not considered as realistic in the short term. However, the solution provides a significant capacity to handle serious time-consuming and costly quality problems during the NPI. Mainly the capability to simulate factory operations in the very early stages was considered crucial for risk mitigation, as well as design for manufacturability. "Since the bidirectional real-time data integration is inherent in the DT-based VF concept, questions are raised on how to utilise the historical data of a digital twin technology for a fast-changing model. For example, the historical data of a DT could simply be irrelevant in a totally new production setup. Therefore, DT-based VF is considered more valuable for later phases of NPI operations due to the larger volume of data and more mature models. Moreover, this may support the view that easy-to-use DES tools without advanced integration (with MES and PLM) and the DT capability could still be more valuable for early concept/idea simulations by enabling rapid iterations of lightweight model development and simulations." (Yildiz, Møller, Bilberg, et al., 2021).

Thus, the VP case evaluation shows that the DT-based VF can provide significant industrial value in multiple phases of NPI operations by reducing the time required for prototyping and achieving a better quality of the products and manufacturing processes.

Table 7 Summary of evaluation (Yildiz, Møller, & Bilberg, 2021b)

PROTOTYPING ACTIVITY	***SUMMARY OF EVALUATION***
MOCK-UP BUILDS	• Most of the experts agree that the DT-based VF concept cannot fully eliminate physical mock-up builds due to mandatory physical tests for legal certification. • A minimum of 4 mock-up builds for the wind turbine blade is inevitable. • 3D simulation is beneficial for higher confidence in the models. • Time and error reduction during the mock-up build can be promising value cases for DT-based VF. • Extending the simulation tools with detailed material behaviours and resin injection is considered highly valuable for blade manufacturing.
DESIGN PROTOTYPES	• The majority of experts consider the DT-based VF concept more beneficial for design prototypes than mock-up builds since it is less focused on specific/critical material behaviours. • The majority of the failures, corrections, and improvements faced during the late blade introduction processes were design-related. • Some stated that eliminating the physical design prototype in the near or medium future is optimistic. • Utilising DT-based VF during the design prototype processes is considered useful for decreasing the time-to-market.
PROCESS PROTOTYPES	• DT-based VF is considered highly useful for process prototypes to simulate production execution. • Most experts considered the results of physical prototype activities highly useful for 0-series and serial production optimisation. • Some underlined the significance of integrating the high- and low-resolution simulations to achieve a holistic view within the single platform.
0-SERIES PRODUCTION	• The 0-series production is considered the most effective use case for DT-based VF since the design and processes are more mature in this phase. • DT-based VF promises high value by enabling the right sequence, the right staffing, the right factory layout, and having a shorter time-to-market. • Some stated that VF could accelerate the learning curve and achieve actual takt time by reducing 25% of the time of 0-series, which may take three to six months at present. • Discovering the limiting factors and bottlenecks such as a lack of crane capacity is considered very valuable.

5.4. CHAPTER SUMMARY

This chapter provides a very brief frame of the results discovered during each phase of the VF research and builds on journal papers published during the respective phase. **Paper 1** focuses on the initial design and development of the concept and demo while trying to explore the implications of the solution in the application domain as well as future requirements for advances. Subsequently, **Paper 2** incorporated the improvements of the solution with DT and multi-user VR capabilities and the industrial evaluation of the solution for handling co-evolution problems. Finally, **Paper 3** narrowed down the evaluation scope and presented the particular case evaluation of the solution. Each phase of the study was conducted successfully with minimum deviations from the original objectives determined at the beginning of the study.

However, the knowledge discovered during each phase that formed the results was not just cultivated during the evaluation activities of each phase. In DSR, profoundly compelling knowledge for both scholars and experts can be inherently embedded in the design, development, demonstration, and evaluation activities. Therefore, the published articles during each research phase did not just focus on the results of the evaluation of the solution in the industrial cases but also on theoretical and empirical arguments underlying the decisions made during the design and development of the artefacts and the demo. Yet, each research activity had its own scope, limitations and assumptions that needed to be discussed. Therefore, the next chapter will be dedicated to articulating such issues.

CHAPTER 6. DISCUSSION

Each scientific study generates knowledge by attempting to answer important scholarly questions. Every result and answer, therefore, provokes new questions to be answered further. Thus, there is always something to discuss in dwelling on the results of scholarly activity. Consequently, this chapter discusses 1) the limitations of the research study, 2) potential implications including the extensions of the concept and utilisation of particular technologies, and 3) future works stemming from the limitations, implications and knowledge discovered during the study.

6.1. LIMITATIONS

As it was interpreted in the Methodological Discussion section, conducting research following the trails of DSR in a complex manufacturing organisation that inherits sociotechnical, socioeconomic, and artificial systems faces some limitations. Such limitations could be listed as 1) conducting experimental or quasi-experimental research, 2) generalisation of the context-specific knowledge, and 3) human impact were, among other such challenges. Since more comprehensive discussion was presented under the Methodological Discussion section, we will not dive into the same discussion here.

Considering that the VF research concentrated on a generic solution to support manufacturing organisations for handling co-evolution, the developed demo VF was limited to advanced analytic prescriptive and optimisation algorithms. Although various scenarios for shopfloor simulation models, including multi-scenario simulations, were performed during the demonstrations, the objective was not the evaluation of the particular capabilities of a simulation tool but the utility of the concept solution. Similarly, the demonstrations were limited to the probabilistic analytic capabilities. Thus, the particular capabilities of the simulation tools and technologies were out of the research scope.

Moreover, the DT-based VF concept was limited to the manufacturing facilities due to the limited scope defined by the academic and industry stakeholders. Some critical elements of the product domain, such as product design and development processes in PLM, were out of the scope. Correspondingly, data accumulation from the shopfloor was achieved by MES integration, and the methods, technologies, and quality of the data in the MES solutions were not included in the study. Although the significance of the quality and reliability of the production data was addressed in the study, the objective was to discover and explore the solutions to create value from the existing data. Therefore, specific issues associated with IoT or IIoT were not examined in the study.

6.2. IMPLICATIONS

Designing and developing the DT-based VF of a manufacturing plant is a process that is highly dependent on contextual idiosyncrasies such as company-specific requirements, resources, IT infrastructure, capabilities, data availability, and company culture. Therefore, the successful design, development and implementation of a VF depend not only on the available and useful concept, methods, and architecture, but also on the manufacturing enterprise's goals, tangible, and intangible assets. Thus, the implementation of the DT-based VF concept into different manufacturing organisations requires consideration of contextual factors.

Even though the initial problems, motivations, opportunities and design requirements were accumulated from the particular application domain, the DT-based VF concept is constructed upon the existing knowledge in the literature and designed as a generic solution to handle co-evolution. As a result, it can be implemented by utilising various M&S tools, DT and VR capabilities as obliged by the contextual requirements. Thus, some similarities and distinctions between wind blade manufacturing and other industries were briefly discussed in the published papers. Moreover, **Paper 1** identified various value-promising use cases provided by industry experts. Some of the highest-ranked cases were (re)designing factories (1-layout, 2-line, 3-process flow) and virtual prototyping. Moreover, various implications for the solution concept were identified and discussed in the appended **Paper 2** and **Paper 3**.

The author of this thesis, as a full-time worker at Vestas at present, would like to inform the readers that the VF concept as an integrated simulation model of factories is active in the development and use of rapid and agile design approaches to model various layout concepts of upcoming production facilities. DT capabilities were not considered in the early development and implementation of the solution due to a lack of time and proper data. However, extensive work for the full integration with PLM, ERP and MES platforms and various simulations is ongoing for future utilisation of DT capabilities.

Some practical VF developments at the production line level were conducted for mixed production concepts at the industry stakeholder of the project, and promising results were observed. However, more efficient and effective data integration capabilities, as well as agile development methods, were required for rapid developments. Since the transformation of product, process and systems needs to be fast enough to respond to the changes, prolonged simulation design and development projects for factory simulations are limited to supporting the decisions before their physical implementation.

Moreover, using VF simulations to evaluate various reconfigurable manufacturing systems (RMSs) at both factory and enterprise levels is under consideration. VF simulations integrated with ERP and MES systems can be used for evaluating RMSs design and development (Andersen, 2017) and for business case evaluations to support investment decisions (Kjeldgaard et al., 2021). Practical VF design and development work for RMS concept verifications is under consideration in the application domain due to the high complexity of the technical and business-level implications of RMSs. There are two approaches that are considered critical for utilising the VF approach to RMS evaluations: 1) design and simulation of the configurations of RMS in the factory, 2) business case (life-cost/benefit) evaluations for RMS investment. Therefore, there are two strands of DT-based VF implications, for higher-resolution operations (also addressed in **Paper 3**) and lower-resolution operations (also discussed in **Paper 4**). Both approaches are considered critical to handle the complexity of engineering and business decisions by scholars and industry experts. However, the latter requires an extension of the VF concept from factory level to broader business level. Similar needs were observed in various cases in the application domain, in which a significant number of decisions on production were triggered by the business requirements, which are not inherently part of the production plants. For example, various significant changes in production facilities, including the increase in the production capacity, building a new plant, or shifting to mixed production, are triggered due to changes in the supply chain or new sales orders. Therefore, an extension of the VF concept to enterprise level by the integration of supply chain simulations and project (sale)-specific business case simulations was taken into consideration. Such discussions and decisions were among the motivations and driving forces that shaped **Paper 4**, which is briefly discussed in the next section.

6.2.1. PAPER 4: EXTENSION TO VIRTUAL ENTERPRISE

Paper 4 was the consequence of the discussion and demand for a more comprehensive and inclusive understanding of the knowledge discovered during the empirical study conducted in the industrial context. The need to extend the DT-based VF concept from factory (manufacturing) level operations to the enterprise (business) level operations emerged as a result of extended interpretation of the conceptual and theoretical foundations of DT-based VF together with the means and goals.

As observed in the application domain and stressed in the previously published papers multiple times, the existing studies focus on either particular confined aspects of the digital transformation of manufacturing such as IoT, DT, VR, etc., or very generic and high-level concepts like smart factories, intelligent manufacturing, etc. However, digital transformation both towards smart manufacturing to handle co-evolution and to respond to the changes in the business environments closely related to business and market dynamics are closely linked (Tolio et al., 2010; Zhu et al., 2021). Moreover, the development of particular technological concepts like DTs for automating businesses by integrating supply chains is also critical but absent (Leng et al., 2021). Therefore, **Paper 4** attempts to 1) frame and interpret the conceptual and theoretical foundations of DT-based VF concepts, 2) extend the concept to enterprise-level as a virtual enterprise, and 3) generalise and interpret the prescriptive knowledge discovered during Phase 1, Phase 2, and Phase 3 of the VF research in order to close the gap between particular empirical studies and the conceptual study.

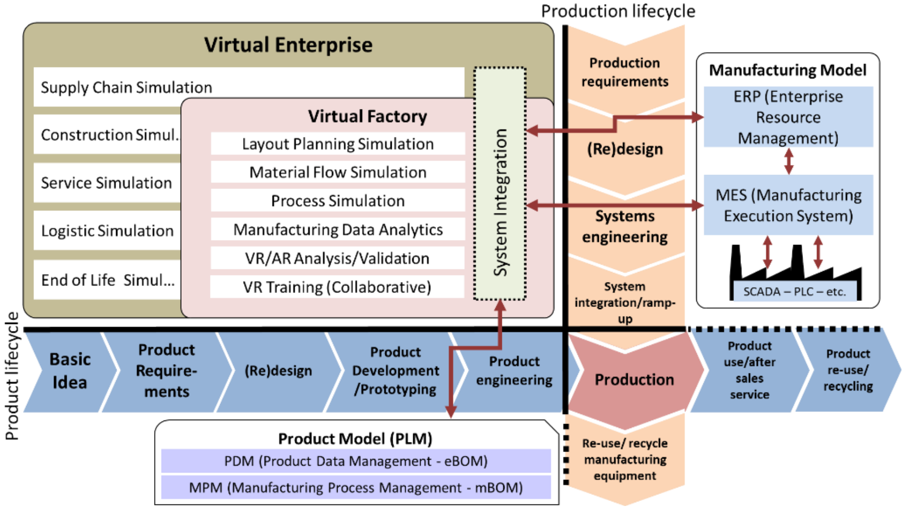

Figure 34 Virtual enterprise concept extended from DT-based VF (Yildiz, Møller, & Bilberg, 2021a)

The first part of **Paper 4** articulates the concepts and theories framed in Figure 15 Theoretical framework (Yildiz, Møller, & Bilberg, 2021a)in order to interpret how to explore the co-evolution paradigm within the complex manufacturing context. The paper elaborates on the systems and complexity theories to interpret the internal dynamics of complex manufacturing organisations. Moreover, concepts of business genetics and competence theory are examined to illustrate the principles of organisational evolution to respond to the evolving environments and to stay competitive. The association between the manufacturing domains and the rest of the enterprise's operations as contextualised in Figure 3 Manufacturing dynamics for wind turbine generator manufacturing [adapted from (Tolio et al., 2010)] calls for more extended representation of the enterprise operations for better handling of co-evolution. Therefore, the DT-based VF concept is extended to the virtual enterprise based on the framed concepts and empirical evidence discovered during the VF research in order to maintain managerial guidelines for utilising such a concept, as seen in Figure 34 Virtual enterprise concept extended from DT-based VF (Yildiz, Møller, & Bilberg, 2021a). The motivations for the extension of the concept, the four cornerstones of competence-based strategic management (a dynamic, open, cognitive, holistic system), and the four types of change (convergence, reconfiguration, abortive integration, architectural transformation) were investigated and discussed in the context of the VF solution.

In short, **Paper 4** attempts *"to fulfil the so-called duality criterion of case studies, which is (1) situationally grounded (empirically disciplined and comply with contextual idiosyncrasies), and (2) a sense of generality (broader theoretical understanding through abstractions)* (Ketokivi & Choi, 2014). *Therefore, this article's contribution can be positioned as theory elaboration by a reconciliation of the particular with the general"* (Yildiz, Møller, & Bilberg, 2021a).

Moreover, the extended implications of the VF concept to enterprise-level operations by developing business case (sales/project-specific outbound supply chain) simulations integrated with factory simulations are in progress while we draw up these lines. Figure 35 Project-specific outbound supply chain simulation demo illustrates some of the early developments to extend the DT-based VF concept within the WTG manufacturing industry. Richer media files can convey more information about the subject work. Thus, please refer to (Yildiz, 2022) for a publicly available video.

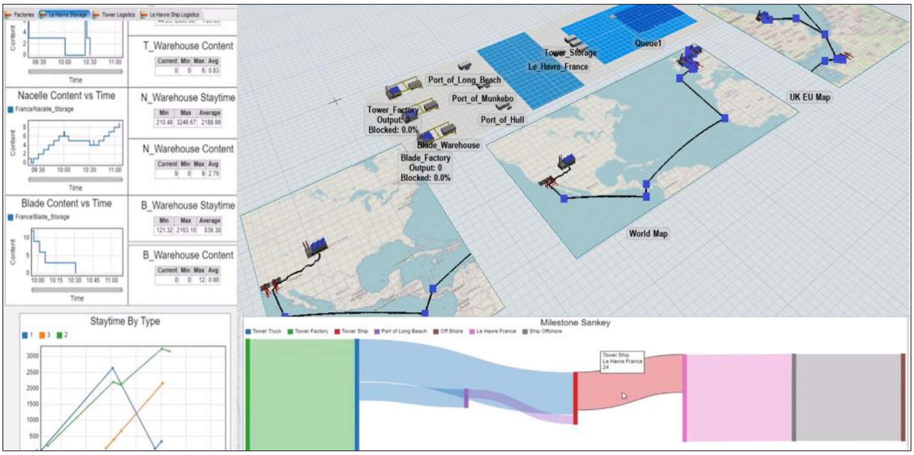

Figure 35 Project-specific outbound supply chain simulation demo

In addition to the implementation of the DT-based VF concept in the low-resolution operations of a manufacturing enterprise, the need for higher-resolution operations was addressed by the experts (**Paper 3**). Resin injection and VR training/learning simulations were among the examples given for such high-resolution simulation cases. **Paper 5** is concentrated on the VR integration of the VF research and summarised in the next section.

6.2.2. PAPER 5: MULTI-USER VR

Paper 5 focuses on the design, development, and integration of the multi-user VR simulation as part of the VF solution for the collaborative and coordinated VR training/learning scenarios. **Paper 5** stands as a suitable instance of how the DT-based VF solution as a generic concept can maintain significant value for particular technology domains. While multi-user VR technology can enable significant value for the DT-based VF solution, DT-based VF as an integrated simulation solution also increases the reliability, efficiency, and effectiveness of the complex VR simulations during the design, development, and utilisation phases. This is because developing multi-user VR simulations for complex manufacturing operations remains a challenge due to the low precision and accuracy of the data. Thus, **Paper 5** stands as a good example of how the VF concept can embody discrete implications for various relevant technologies.

Paper 5 aims to 1) design and develop multi-user VR simulation for collaborative and coordinated assembly training, 2) design and develop automated bidirectional data integration between VR training and other VF simulations, and 3) demonstrate the concept in a real-life wind turbine manufacturing case. The preliminary demonstration and evaluation by industry experts provide significant signs that the integration of multi-user VR simulation with a DT-based VF solution enables efficient and reliable training/learning simulations for industrial cases.

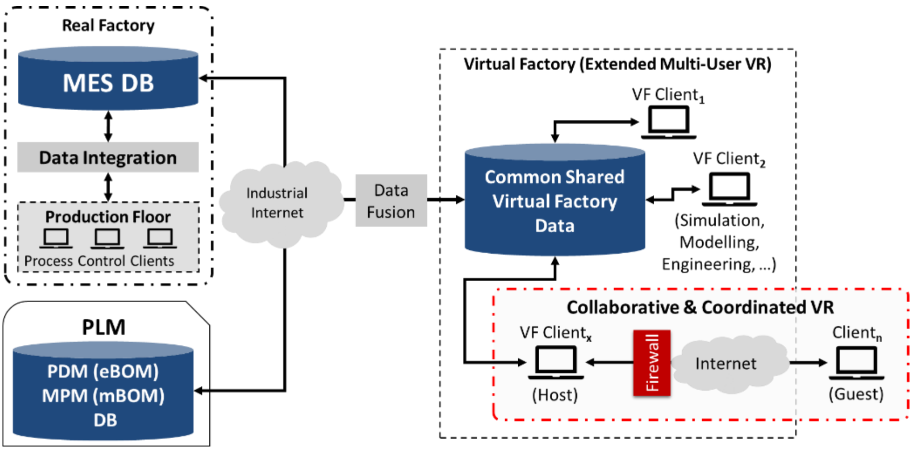

Figure 36 Data synchronisation architecture of DT-based VF extended with multi-user VR (Yildiz, Møller, & Bilberg, 2021c)

Figure 36 Data synchronisation architecture of DT-based VF extended with multi-user VR (Yildiz, Møller, & Bilberg, 2021c) illustrates the artefact designed and implemented during the collaborative VR study. More detailed discussion of the demonstration and evaluation of the collaborative VR is also presented in **Paper 2** and **Paper 3**. Since the VF research does not aim to study particular technological concepts and their potential in the industry, the research work does not dive into a more thorough evaluation and analysis for multi-user VR and other technological concepts such as M&S, DT, manufacturing data analytics, etc. However, future studies focusing on more particular technologies are considered and discussed in the next section.

6.3. FUTURE WORK

- *Develop, demonstrate, and evaluate the higher-resolution simulations:* The research presented in this thesis covers the proof-of-concept DT-based VF solution to handle co-evolution. Therefore, detailed simulation models dedicated to specific production processes were omitted from the scope of the study. However, the findings and expert arguments show that high-resolution simulations for critical production processes (e.g., the resin injection process in wind blade production) integrated with the VF simulations seem highly valuable during NPI operations. Future work should be dedicated to extending the development, demonstration, and evaluation of higher-resolution simulations in industrial cases.
- *Implement DT-based VF solution into the RMS cases:* Investigation of RMS solutions in collaboration between industrial (Vestas) and academic experts (Kjeldgaard et al., 2021). Particular discussion on utilising VF simulations to evaluate changeable manufacturing systems from the technical and business (return on investment) perspectives are considered both viable and critical by scholars and experts. Therefore, future studies will be dedicated to investigating the utilisation of DT-based VF solutions to simulate and evaluate various RMS concepts in the industry.
- *Demonstrate and evaluate the extended VF concept to enterprise level:* Due to significant changes in both the product, processes, and market dynamics in the wind energy industry (addressed in **Paper 3**), new and critical challenges are emerging to be dealt with. Therefore, extending DT-based VF to outbound supply chain operations, including transport, pre-assembly (on-site assembly of wind turbines), and installation, are viable and promising for the industry. **Paper 4** introduces the extension of the DT-based VF concept to the enterprise level but lacks the demonstration and evaluation of such extension in industrial cases. Thus, particular studies are needed to investigate the utility, feasibility, and effectiveness of such concepts in industrial cases. Accordingly, particular investigations to develop and demonstrate 1) project (sales/delivery) specific business case simulations, 2) site-specific pre-assembly simulations, and 3) outbound logistics/transport simulations integrated with DT-based VF simulations are being planned.

CHAPTER 7. CONCLUSION

The objective of this thesis was to establish comprehensive and methodical foundations for the empirical, conceptual, and philosophical discussions supporting the previously discovered and disseminated knowledge on DT-based VF that employs a collaborative VR capability that can integrate product, process, and system models to support manufacturing enterprises for dealing with coordinated evolution during the adaptation to evolving market dynamics, as well as the demonstration and evaluation of the solution in industrial cases. Therefore, the thesis contributes to the theoretical and empirical knowledge domains by 1) elaborating on theories that supporting previously introduced novel concepts and design methods, and 2), discussing and interpreting the design, development, and demonstration of the solution in empirical cases. Therefore, the methods, frameworks, and guidelines of DSR were followed to ensure 1) the rigour of the research by designing novel artefacts based on existing artefacts and theories in the knowledge base, as well as 2) the relevance by practically developing and demonstrating the solution in the application domain. Therefore, new knowledge discovered during the research is embedded not only in the designed artefacts and their evaluation in industrial cases, but also in the design, development, and demonstration processes of such artefacts during each phase of the research. Thus, the research contribution of this thesis is summarised as follows:

- *Novel DT-based VF concept including design and development models based on real-life manufacturing case*: This thesis and the papers on which the thesis was framed and formed introduce the DT-based VF concept, including its design requirements for the application context, as well as existing artefacts and research gaps for a novel solution to handle the co-evolution problem. The fundamental difference between the introduced concept and the existing artefacts in the knowledge base is a distinguished representation of the product, system, and process domains of a manufacturing enterprise. Such distinction indicates the transparency between different models in a manufacturing organisation while putting emphasis on the assignation of product and production lifecycle processes.
- *Knowledge on the practical implications and industrial value of DT-based VF*: This thesis is the outcome of a research project formed in collaboration with an industrial stakeholder to solve practical problems with pragmatic methods. Thus, the results in knowledge are mostly articulated on empirical data and findings. Therefore, this research contributes to the knowledge base with practically relevant findings and potentially assists the industrial challenges stemming from the coordinated evolution of the product, process, and system domains.
- *Guidelines for the actual utilisation of technologies and methodologies for simultaneous design, analysis, modelling and simulation of manufacturing*

operations: Existing research on VFs is either empirically confined to particular technologies or limited to highly theoretical and conceptual artefacts. Therefore, the empirical knowledge on the practical implications of the conceptual solution introduced in this thesis attempts to close the gap between theories supporting the design, management, and evolution of complex manufacturing systems and the actual implementation and integration of state-of-the-art technologies in the application domain. Thus, the research provides valuable knowledge for the operations management, systems engineering, information systems, and manufacturing engineering fields by providing conceptual and empirical guidelines for the actual utilisation of the technologies, methods, and concepts in various industrial cases based on specific, grounded, and precise pieces of evidence composed from expert evaluations.

- *Knowledge regarding enablers and barriers for designing, developing, and utilising DT-based VF for industrial purposes*: This thesis not only introduced a novel concept, but also various enablers and barriers for the practical design, development, and utilisation of the solution in the application context were addressed. Such knowledge is highly valuable and essential for the digital transformation of industrial production to develop virtual and smarter factories of the future.
- *Knowledge on conceptual and theoretical foundations for DT-based VF*: In addition to prescriptive knowledge grounded on empirical evaluations, this thesis articulates the conceptual foundations of the introduced solution, elaborating on theoretical knowledge. Thus, it provides a broader and sound basis for the social, natural, and artificial aspects of the DT-based VF concept.

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APPENDED PAPERS

Paper 1. Building a Virtual Factory: An Integrated Design Approach to Building Smart Factories

Yildiz, E., & Møller, C. (2021). Building a Virtual Factory: An Integrated Design Approach to Building Smart Factories. *Journal of Global Operations and Strategic Sourcing, S.I. on Smart Production and Industry 4.0*. https://doi.org/https://doi.org/10.1108/JGOSS-11-2019-0061

Building a virtual factory: an integrated design approach to building smart factories

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Abstract

Purpose – The complexity of manufacturing systems, on-going production and existing constraints on the shop floor remain among the main challenges for the analysis, design and development of the models in product, process and factory domains. The potential of different virtual factory (VF) tools and approaches to support simultaneous engineering for the design, and development of these domains has been addressed in the literature. To fulfil this potential, there is a need for an approach which integrates the product, process and production systems for designing and developing VF and its validation in real-life cases. This paper aims to present an integrated design approach for VF design and development, as well as a demonstration implemented in a wind turbine manufacturing plant.

Design/methodology/approach – As the research calls for instrumental knowledge to discover the effects of intervention on the operations of an enterprise, design science research methodology is considered to be a well-suited methodology for exploring practical usefulness of a generic design to close the theory–practice gap. The study was planned as an exploratory research activity which encompassed the simultaneous design and development of artefacts and retrospective analysis of the design and implementation processes. The extended VF concept, architecture, a demonstration and procedures followed during the research work are presented and evaluated.

Findings – The artefacts (models and methods) and the VF demonstrator, which was evaluated by industry experts and scholars based on the role of the VF in improving the performance in the evaluation and reconfiguration of new or existing factories, reduce the ramp-up and design times, supporting management decisions. Preliminary results are presented and discussed.

Research limitations/implications – The concept VF model, its architecture and general methodology as an integrated design and development approach, can be adopted and used for VF design and development both for discrete and continuous manufacturing plants. The development and demonstration were limited, however, because real-time synchronisation, 3D laser scanning data and a commonly shared data model, to enable the integration of different VF tools, were not achievable.

This paper forms part of a special section "Smart production and industry 4.0", guest edited by Astrid Heideman Lassen and Charles Møller.

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Originality/value – The paper presents a novel VF concept and architecture, which integrates product, process and production systems. Moreover, design and development methods of the concept and its demonstration for a wind turbine manufacturing plant are presented. The paper, therefore, contributes to the information systems and manufacturing engineering field by identifying a novel concept and approach to the effective design and development of a VF and its function in the analysis, design and development of manufacturing systems.

Keywords Discrete event simulation, Manufacturing system, Smart factory, Factory design, Factory planning, Virtual factory

Paper type Research paper

1. Introduction

An increase in competitiveness within the industry, as well as the shifting of decision-making power from companies to customers, are forcing companies to reduce their product, process and factory life cycles (Azevedo and Almeida, 2011). The new materials, technological developments and services, together with pressure due to cost-saving, require more frequent transformations in manufacturing systems than ever before. Rising demand for customised products is leading to an increase in the product complexity and production processes in manufacturing, which requires more complicated and interdisciplinary decisions, resulting in a long-term impact on organisations (Souza *et al.*, 2006). Therefore, to be able to adapt to changing demands, technology and regulations in real time, such advances mentioned earlier have led to requirements such as modularity, flexibility, scalability, agility and knowledge-based decisions, which are generally encompassed by the definition of the Smart Factory (Radziwon *et al.*, 2014). As a result, synchronisation and simultaneous engineering of the design and modelling of products, processes and factories remain a critical challenge in handling the concurrent evolution of products, processes and production systems, (also known as the co-evolution paradigm (Tolio *et al.*, 2010)).

The co-evolution problem requires the active and integrated use of different methodologies, tools and technologies. Consequently, interoperability between digital factory tools becomes paramount to support processes along the whole factory lifecycle (Tolio *et al.*, 2013). A virtual representation of manufacturing systems using the data from real factories can offer solutions for product development and support for product introduction processes, from design-to-manufacturing and simulation-based data analytics, can provide decision support for smart production systems (Lin and Fu, 2001). Accordingly, the virtual factory (VF) is an integrated, high-fidelity simulation model of a manufacturing factory, which offers an advanced decision support capability, and can support the evaluation and reconfiguration of new or existing manufacturing systems (Jain *et al.*, 2001).

Some leading manufacturing companies, including Ford Motor Company and Volvo Group Global, are implementing the VF concept (Jain *et al.*, 2017). Major software vendors are boosting the development of all comprehensive manufacturing system solutions integrating product, process and production system life cycles (Tolio *et al.*, 2013). Extensive research has addressed the challenges in VF, i.e. interoperability, data modelling, data analytics and integration. This research aims to explore concepts, models, and methods integrating various state-of-the-art technologies including 3D discrete event simulation (DES), virtual reality (VR), data analytics and real-life data from the products, processes and production systems, while demonstrating a VF in a real-life manufacturing case.

The reader should keep in mind that the work presented in this article only covers the first part of a three part research project, including:

(1) concept design and demo development;
(2) bi-directional data integration and multi-user VR training; and
(3) case study for virtual prototyping.

The following section presents the theoretical background and state-of-the-art technological concepts, problems and gaps which are identified and summarised in the problem identification section. The objectives of the research and artefacts are framed in the objectives section, followed by the presentation and discussion of the methodology. The VF concept and its design methods are introduced in the concept design and methods section, and the development of the VF demo for the case study are discussed in the model development section. The demonstration section presents the VF demonstration for the case study scenario, followed by the evaluation and discussion section before the conclusion and future works section.

2. State-of-the-art

2.1 Theoretical background

In this section, building a VF by integrating complex manufacturing systems is investigated, based on the theories and concepts (*concepts of business genetics* and *theory for complex systems evolution*) which were propounded by two reputable theorists (Charles H. Fine and Herbert A. Simon) and their proven techniques are applied to support their claims.

Charles Fine's concepts of business genetics are used to interpret external forces and the evolving nature of industrial dynamics and their effects on internal domains of companies, in terms of product, process and organisational systems (Fine, 1998). The concepts of business genetics enhances our understanding of the problems explained in the previous section, their reasons and the effects on enterprises. Charles Fine's concepts conclude that the ultimate core advantage for companies is the capability of evolving to fit ever-changing business environments. He also proposed three-dimensional, concurrent engineering in such domains to handle evolution (Fine, 2000; Lepercq, 2008). Evolution models for products, processes and production/organisation systems (the so-called *co-evolution paradigm)* were also examined in recent studies (Tolio *et al.*, 2010; Leitner, 2015), and some stated that VF, which allows us to integrate digital models in three domains, is the prerequisite for coping with the co-evolution problem (Tolio *et al.*, 2013). However, the level of complexity in the integrating systems, technologies and data structures in real-life scenarios makes the design and development of VF a challenging task for the industry. Thus, the question of how to design and build such complex systems emerges.

In this regard, Herbert Simon's theory for complex systems, which interprets the relationship between the internal dynamics and structure of complex systems, is used to enlarge our understanding about the social, natural and artificial systems in which we work. The theory lays the foundation to our claim that building VF as an intermediary, stable, complex system can accelerate the evolution of more complex systems, such as smart factories. Herbert Simon (1976) listed some of the aspects required to evaluate the level of complexity of a system and stated that the complexity of the problem domain of the theory, in terms of *symbols* and *parameters,* can also be useful in evaluating the complexity of a system. Instead of taking the formal definition of a *complex system* he preferred:

> a system made up of a large number of parts that interact in a non-simple way. In such systems, the whole is more than the sum of the parts, not in an ultimate, metaphysical sense, but in the important pragmatic sense 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 (Simon, 1962).

Another critical aspect of complex systems is the hierarchy. As a matter of fact, the hierarchy emerges in such social and biological systems through an evolutionary process. Herbert Simon's "*parable of the two watchmakers*" concludes that "*Complex systems will evolve from simple systems much more rapidly if there are stable intermediate forms than if there are not*" (Simon, 1962, 1996). Actually, the theory about the speed of evolution originated back to H. Jacobson's implementation of information theory to estimate the time needed for biological evolution (Jacobson, 1955) and, consequently, the lesson for biological evolution is apparent and direct. In contrast to biological systems, however, the complex form of an IS does not emerge from simple forms by entirely random processes but, instead, as a result of consciously made decisions. If we consider smart factories and smart manufacturing as the desired product of evolution, our aim is to design and develop a stable, intermediary demo and discover its empirical impacts. In the context of operations management, discovering various cases which promise relatively higher businesses impacts by demonstrating VF in real-life, can pave the way for faster adaptation and evolution of smarter factories.

2.2 Smart factory

The smart factory concept, which is envisioned from the advancements in computing technologies and tools (Westkaemper *et al.*, 2005), has been influentially defined by Radziwon *et al.* (2014) as a manufacturing plant which can provide dynamic organisation, using human-responsive context-aware production lines, maintaining connected smart machines, data warehouses and integrated sensing technologies. One of the first "*Technology Initiative Smart Factories*" was founded in 2005, in Germany, to develop and test future factory technologies with the aim of accelerating design, planning and setup for rapid adaptation to changes in products and operations (Zuehlke, 2010). Similar initiatives, such as the Smart Production Laboratory of Aalborg University (Madsen and Møller, 2017), were carried out to realise the smart factory vision. Wang *et al.* (2016) defined the smart factory as a "*self-organised multi-agent system assisted with big data-based feedback and coordination*", and they simulated distributed intelligent negotiation mechanisms to demonstrate a smart factory model (Wang *et al.*, 2016). An extensive literature covers the analysis of smart manufacturing technologies, concepts, systems and roadmaps of leading countries in the digitalisation of the industry, as reviewed by Kang *et al.* (2016). Kang *et al.* (2016) also addressed the need for strategic approaches and application guidelines for the actual utilisation of the technology and methodology in each life cycle step, including planning, design, manufacturing, operation and maintenance. This need is also one of the main motivations behind the work presented in this article.

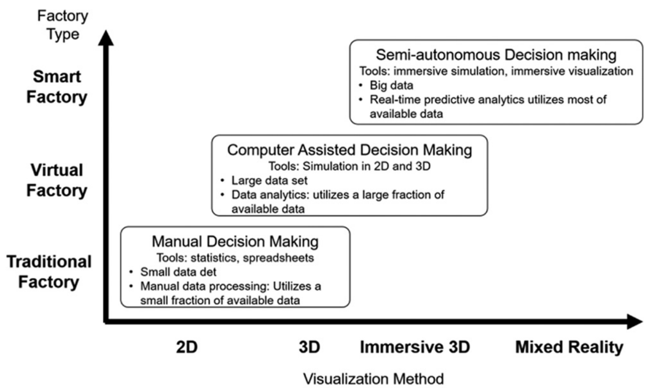
It was also stated by Turner *et al.* (2016) that, for some initiatives, the Smart Factory is the practical implementation of the VF concept and, possibly, the manifestation of the Industry 4.0 initiative being pursued. Turner *et al.* (2016) also illustrated the relationship between factory type and data visualisation methods (Figure 1) and showed the relationship between the smart factory and VF. The authors of this paper acknowledge the significance of VFs in building smart factories. However, there is no commonly accepted concept and definition of the VF. The following part of the literature review will present some of the works on VF.

2.3 Virtual factory

VF is defined in different ways in the manufacturing research and application domain, including integrated simulation, virtual organisation and emulation facility (Jain *et al.*, 2001). Onosato and Iwata (1993) introduced the virtual manufacturing concept by integrating product and factory models as a critical aspect of the VF. However, Jain *et al.* (2001) do not distinguish product and factory models and they 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.*" Souza *et al.* (2006) presented an approach for using virtual manufacturing as an integrated environment, comprising software tools and technologies such as VR and simulation to simulate each product introduction process effectively and economically. Bal and Hashemipour (2009) introduced a virtual *holonic factory* concept to control flow-line manufacturing to achieve robustness and dynamic scheduling, using VR technology in a medium-sized, die-cast manufacturing case study. Jain *et al.* (2016) presented VF as a multi-resolution model of real manufacturing, and Jain *et al.* (2017) demonstrated an approach to decrease the deployment efforts of VF models, based on manufacturing configuration data. Yang *et al.* (2015) presented VR based on three different VF tools as collaborative manufacturing system design and analysis platforms.

As Grieves introduced the digital twin (DT) concept in 2003 and it was defined by NASA (Glaessgen *et al.*, 2012; Grieves, 2014), DT implementations in the manufacturing domain have been given more attention by scholars. Nevertheless, it is difficult to see a common understanding of the DT concept. Some scholars argue that the DT concept should focus on simulations (Weyer *et al.*, 2016; Maurer, 2017), while others support the idea that it should focus on physical, virtual and connection dimensions (Grieves, 2014; Qi and Tao, 2018). Consequently, new notions related to the DT concept were proposed. Tao and Zhang (2017), for example, introduced the DT Shop-Floor (DTS) paradigm and illustrated the implementation methods for physical shop-floor, virtual shop-floor, shop-floor service system and shop-floor DT data. Shamsuzzoha *et al.* (2017) presented a VF as an environment for collaborative business process monitoring, in order to integrate manufacturing companies to achieve some business opportunities and show the extended role of VF in a whole business environment. Moreover, VF is also considered as an adaptive enterprise modelling and simulation (M&S) platform, to design and develop new competencies (Yildiz *et al.*, 2020a).

Alongside the focus on the different roles and capabilities of VF tools, attention has been paid to proper data models by using the ontologies to fully exploit the potentials of cyber–physical systems and interoperability between the VF digital tools (Lee and Banerjee, 2011; Kádár *et al.*, 2013; Negri *et al.*, 2017). In this regard, a semantic VF data model has been designed and presented by Terkaj and Urgo (2014) as a common data model for the



Source: Turner *et al.* (2016)

Figure 1.
Factory types and data visualisation methods

representation of factory objects related to production systems, resources, processes and products. Agyapong-Kodua *et al.* (2013) also reviewed the semantic modelling technologies by considering the requirements and evaluating the methodologies, tools and languages used. They concluded by identifying the gap between fast virtual design and the prototyping of virtual factories.

In this respect, some studies of emerging technologies such as 3D DES and VR, which are considered as core technologies for designing and developing VF, are reviewed and presented in the next section.

2.4 Discrete event simulation and virtual reality

M&S in manufacturing was recognised as being one of the significant steps in achieving smart factories by Weyer *et al.* (2016). Mourtzis *et al.* (2014) investigated the evolution and recent developments of simulation technology in the industry, as well as describing the gaps and future trends in the field. They addressed the gap in the use of VR and computer-aided manufacturing systems for collaboration and communication. Their work utilised VR interaction and training as an integrated function of VF. They also stressed the lack of advanced planning capabilities of manufacturing execution system (MES), calling this *decision myopia*. Therefore, integrating DES with MES can enable decision myopia and this needs to be dealt with. A recent review study by Mourtzis (2020) also stressed the significant capabilities of simulation tools for integrating the data across the manufacturing value chain. Akpan and Shanker (2019) analysed 162 studies on the impacts of 3D DES and VR versus 2D display, based on user performance in DES tasks. Contrary to the belief that 2D simulation is more useful for development, the review results showed that 3D/VR offers better overall performance in model development. Moreover, 3D/VR enables verification, validation, experimentation, and analysis of the results in a shorter time, but increases the model development time. Their study also indicated that 3D visualisation and VR in DES are rapidly becoming a common modelling methodology. Negahban and Smith (2014) presented a comprehensive review of DES publications in manufacturing, and they stated that future research needs to focus on the integration of simulation of the upper levels of enterprise systems to increase stakeholder engagement. Furthermore, Akpan and Shanker's (2019) review stated that 93% of simulation developers and decision-makers agreed that 3 D/VR visualisation is more effective than 2D in communicating with management and decision-makers. Turner *et al.* (2016) reviewed the extensive literature and presented the state-of-the-art in the area of combined VR and DES, in the case for smart factory adoption, while examining related active research topics, i.e. real-time integration and system design considerations. They also stated that it is a realistic goal for the development of VF, inherent in the delivery of the smart factory, to utilise big data processing from manufacturing, combined with VR DES, and to present it in near-real time in an interactive mixed reality environment. Moreover, real-time data integration between VR-enabled VF simulations are considered to be better models with higher precision, accuracy and reliability (Yildiz *et al.*, 2019).

The above-mentioned studies are essential developments that are paving the way to building smart factories. These studies also support the approach assumed in this article. The extensive research focuses on the concerns about VF, inherited by the smart factory paradigm and its role in the simultaneous engineering of product, process and factory models. In relation to this, Tolio *et al.* (2013) stated that VF is a prerequisite to coping with the co-evolution problem. The needs identified in the knowledge domain can be summarised as:

- A need for application guidelines for the actual utilisation of technologies and methodologies for each life cycle step of products and factories for smart manufacturing (Kang *et al.*, 2016).
- A need for a methodology supporting the described logical steps and requirements for rapid digital virtual design and prototyping of factories (Agyapong-Kodua *et al.*, 2013).
- A gap in the use of VR and computer-aided manufacturing systems for collaboration and communication (Mourtzis *et al.*, 2014).

While these gaps stem from practical needs for implementation methodologies and enabling functionalities, digitalisation and data-driven innovation increasingly entails multimodal management approaches (Winter, 2019). Consequently, co-existence and the link between different conceptual models is becoming a growing need in enterprises and calls for a more integrated design and development approach for IS systems. This growing need is emerging in the application context and shows a coherence with Herbert Simon's theory for the evolution of complex systems (Simon, 1962).

The theoretical frame and empirical challenges mentioned above motivated us to build our demo VF based on three technological concepts:

(1) M&S;

(2) VR; and

(3) integrated training to maximise the capabilities of our demo.

M&S can be considered as a foundation for design and development because of its capabilities for data integration, data analytics, data generation and model-based design, as well as integrated VR capabilities (Jain *et al.*, 2017; Alcácer and Cruz-Machado, 2019). Recent developments in VR technology undoubtedly enabled immersive experiences beyond reality, which enables advanced user interaction with highly complex and dynamic models (Berg and Vance, 2017). The main incentives for using VR among the central concepts are its potential for the visualisation of abstract data (Dam *et al.*, 2000), knowledge transfer for high-risk procedures (Cote *et al.*, 2008), advanced user interface to overcome the complexity of M&S methods (Wilhelm *et al.*, 2005) and an easy-to-use 3D simulation environment (Cueva, 2016). The integration of training in an immersive VR environment, with simulation, modelling and data analytics, is planned to make harmonisation and dissemination of knowledge more accessible.

The existing VF applications presented above generally build on conceptual modelling or pilots rather than being based on real-life data and scenarios. The current article presents research work that aims at contributing to closing the above-mentioned gaps by presenting a VF concept integrating product, process and organisation domains, an integrated design and development approach and demonstrating implementation in a manufacturing plant.

3. Problem identification

There is a growing need to handle co-evolution in terms of reducing ramp-up and design times, improving the performance in the reconfiguration and evaluation of new or existing manufacturing facilities to support management decisions in global industry as well as our case company, Vestas Wind Systems A/S (later Vestas). Therefore, the integration and simultaneous generation of product, process, and factory models remain relevant challenges in the manufacturing industry (Azevedo and Almeida, 2011). In extensive research, VF is recognised as a potential solution to integrate product, process and factory life cycles to be able to adapt to continuously changing demands and technologies in real time. However, there is limited research focusing on the proper design and implementation methods of VF in real-life cases.

Therefore, the problems addressing the gaps in the knowledge base are identified as follows:

- Lack of guidelines for the actual utilisation of technologies and methodologies for integrated design, M&S of products and factories for smart manufacturing.
- Lack of a methodology describing logical steps and requirements for rapid digital virtual design and prototyping of production and factories.
- A gap in the use of VR and computer-aided manufacturing systems for collaboration and communication.

In this respect, the questions raised in this paper are as follows:

Q1. How can VF be designed and developed rapidly for a real-life manufacturing case?

Q2. How can a virtual product model be linked with production processes?

Q3. What are the possible use-cases that promise high value in the manufacturing industry for using VF?

As the above-mentioned problem and questions call for design-oriented IS research, with the aim of discovering the effects of intervention in an organisation, to explore the practical usefulness of a prescription by iterative construction, implementation and evaluation of IT artefacts, design science research methodology (DSRM) is considered the proper methodology, incorporating situational adaptations of the artefacts while covering the broad problem scope (Winter, 2008).

4. Objectives

The objective of this research is to support manufacturing companies in using VF tools to meet the conditions to be able to adapt to evolving business environments by handling the concurrent evolution of the product, process and factory domains. A smart factory is a highly complex system, envisioned as a result of advancements in information and communication technologies. It can be built faster if we have intermediary, stable, complex forms of such systems, which are presumed to be VF. Extensive research has addressed the difficulties in using and integrating the VF tools, as well as the need for application guidelines and methodologies for rapid design and development of VFs. To achieve the research objective, artefacts had to be designed and developed (concepts, methods and procedures to develop VF) for integrating such technologies, to create a VF demo solution for real-life cases and to demonstrate the use of such artefacts. Therefore, as the first phase of the project, particular objectives of our work had to be achieved:

- to design and develop a VF concept and demo that integrates emerging technologies as well as factory and product data, based on a real-life case;
- to demonstrate the use of VF as a modelling simulation, data analytics, factory design, and training application;
- to discover the potential value of such a VF in real-life implementations; and
- to understand the barriers and enablers for the digitalisation of manufacturing operations.

We rely on Herbert Simon's theory about the speed of evolution in complex systems by stating "*having VF as an intermediate stable complex system can accelerate the evolution of more complex systems*". The demonstration of VF for concurrent engineering in terms of design, modelling, simulation, data analytics and training by integrating product, process and production system domains and exploring business cases can contribute to Charles Fine's theory of business genetics by showing the value of adaptation capability. The methodology to achieve this research is discussed in the next section.

5. Methodology

5.1 Design science

Researching the design which integrates diverse technologies, systems and data structures across a manufacturing enterprise brings some challenges. One of the emerging challenges is that the subject IS to be investigated is not just a technological system or a social system, but the phenomenon emerges when the two interact. The IS theory to understand the phenomenon, therefore, links the social world, the natural world and the artificial world which is constructed by a human (Gregor, 2006). Accordingly, the body of knowledge capitalises on social science, natural science and what has been called "*design science*" (Hevner *et al.*, 2004). Herbert Simon is known to be a supporter of the "*theory for design and action*" (Simon, 1996) as well as others (Gregor, 2006). However, Hevner *et al.* (2004) recognised design science as a research activity instead of a theory. By any means, design science is the knowledge that can take forms, including constructs, methods, models, and theory, to create artefacts that comply with sets of functional requirements. Design science in IS, therefore, explores the creation of innovations or artefacts, which represent the ideas, actions, technical capabilities, and products required to carry out the design, analysis, implementation and use of IS. Thus, DSR uses design, analysis, reflection and abstraction to create missing knowledge (Vaishnavi *et al.*, 2017).

Therefore, compared to traditional experimental approaches, design science is more suitable for discovering the effects of interventions in an organisation and explore the practical usefulness of a treatment to deal with the theory–practice gap (Van Aken *et al.*, 2016). Such interventions to highly complex, dynamic and evolving socioeconomic environments, however, cause some complications and internal validity confusion while evaluating the impact of the artefacts to the environment (Lonati *et al.*, 2018). Some of the practical reasons behind this include difficulties in isolating highly complex environments for experimental or quasi-experimental methods, as well as a large number of interdependent/dependent variables contained in such environments. Therefore, many empirical studies of VF sacrifice the aspect of complexity and focus on narrow aspects of capability, case scenario, technology or data. Although the results of these works provide us with valuable evidence for the various capabilities of the VF concept, they are generally uncomprehensive at factory scale and have limited application guidelines for real-life scenarios. To deal with such challenges, various studies have been carried out to provide a nominal, and consistent methodology which incorporates the practices, principles and procedures required to conduct DSR in IS. In the next section, the DSRM for IS (and how it is performed in this research) will be articulated.

5.2 Design science research methodology

It is commonly considered that the origins of DSR go back to the work of Herbert Simon (1996), titled "*The sciences of the artificial*", in which Simon clearly distinguishes the science of artificial (design science) and natural science. Therefore, DSR is a comparatively new approach in the field of IS. Several frameworks, guidelines and methods have been proposed for design science research in IS (Peffers *et al.*, 2007; Holmström *et al.*, 2009; Drechsler and Hevner, 2016). This study was performed on the trail of these guidelines. Figure 2 shows the adapted process model, which consists of six process elements of DSRM for IS (Peffers *et al.*, 2007). Each activity is discussed further in the context of this research.

5.2.1 Problem identification. DSR focuses on both the design and deployment of its innovative artefacts, which makes it ideal for contributing research and practice to the field of digital innovation (Hevner *et al.*, 2019). Therefore, problem identification activity is performed based on the knowledge originating from the requirements characterised by the application domain, as well as the gaps addressed in the knowledge domain. The problems, opportunities and motivations of the application domain are defined and built on the results of various analysis, discussions and interviews with experts from the case company, supported by the existing knowledge and gaps in the literature.

5.2.2 Objectives of the artefact. Our research engaged the real-life problems, motivations and opportunities in operations management to create knowledge by solving such practical issues with pragmatic methods. Therefore, we are trying to discover knowledge to be used in an instrumental way for designing and implementing actions, systems or processes. DSR artefacts evolve through multiple designs and evaluation cycles (Sonnenberg and Brocke, 2012) until they are mature enough to introduce to the problem space and contribute prescriptive knowledge as a technical solution artefact. Our research also requires iterative cycles for the design and implementation of artefacts for achieving our objectives to solve the defined problem.

Therefore, as already stated, the first work package of three focuses on:

(1) concept design;

(2) rapid development procedures and methods for the concept; and

(3) its evaluation for future improvements.

The objectives to be achieved by the design and development of the artefacts, however, can be listed as:

- integrating state-of-the-art technologies;
- product, process, system data for; and
- enabling demonstration and evaluation of the VF concept.

The objectives and designed artefacts will be updated in future work packages, based on expert evaluations, as well as feedback from the dissemination activities.

5.2.3 Design and development of the artefact. The activity of design and development of the artefact (conceptually, any designed object that a contribution is embedded in) covers

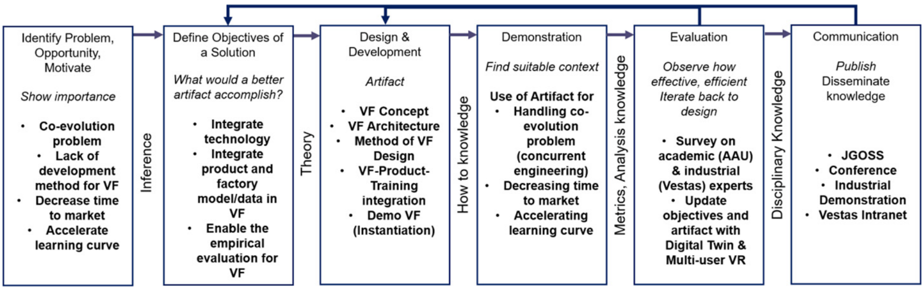


Figure 2.
Adapted design science research methodology

determining the artefact's functionality and its architecture, as well as the creation of the actual artefact. Knowledge derived from theory, existing artefacts in the knowledge base and requirements from the actual case study can be considered as main resources to move on from the objectives to design and development. Although one of the main objectives of the artefact is to solve problems in a particular context, the concept is designed at a generic level, relying on particular requirements and state-of-the-art literature.

In this regard, generalisation in DSR is quite different from explanatory research, in which generalisation or generic design comes from the findings of well-defined random samples from larger populations, as it is the whole population. In DSR, on the other hand, a generic design should be able to transfer into different contexts without losing its necessary effectiveness. Therefore, testing the generic design in different contexts gives knowledge about the particular and enables the evaluation of deviations specific to each context. Giving such deviations is not always possible or necessary but general "*user instructions*" can be sufficient for experienced professionals (Van Aken *et al.*, 2016), depending on the context. The complex nature of the demonstration and application context, as well as the limited number of tests, prevent us from having a comprehensive discussion on possible deviations in the form of "*if-then*" for each different context. Future works will meet such needs by implementing the concept presented in this work into other contexts.

5.2.4 Demonstration. Demonstration of the designed and developed artefacts involves various activities such as experimentation, case study, proof or simulation for solving one or more instances of the defined problem. Therefore, demonstration activity relies on knowledge and defines how to use artefacts effectively in particular contexts. Such knowledge about the particular context can also enable discussions on variations for utilising the artefacts in different contexts.

The wind turbine industry provides various types of production and manufacturing environments, such as fibreglass composite material production (blades), electronic and electrical systems production (control and grid infeed systems), heavy metal manufacturing (towers) and complex and heavy parts assembly (nacelle, gearbox, generator, etc.). Such variety allows industry experts from diverse production areas to assess our generic design. Moreover, we intend to take this opportunity to demonstrate our design in different types of manufacturing and production scenarios in future work. A hub assembly is preferred for the initial demonstration because of its higher proportion of common manufacturing characteristics with other industries, such as the automotive industry.

5.2.5 Evaluation. DSR evaluation has been addressed by researchers(Hevner *et al.*, 2004; Sonnenberg and Brocke, 2012) as a particular concern. The essence of design science research focuses on the pragmatic validity and practical relevance of generic designs (Van Aken *et al.*, 2016). In other words, despite the explanatory research approach explains the present or past, design science focuses on improving the present. Therefore, the justification of design does not interest the truth but the effectiveness, utility, novelty, simplicity, ease of use and consistency. Herbert Simon (1996) recognised "*interestingness*" as a valid claim indeed. Furthermore, considering that this work is the first phase of a comprehensive VF research project, evaluation activity does not aim at a conclusive outcome but focusses on demystifying the direction of future enhancements of artefact development, as well as promising business cases.

6. Concept design and methods

This section discusses the aspects of design processes and methods used to develop VF. The methods presented in this section cover the design and development of the VF model of a real manufacturing plant within the physical plant constraints, operations data and product model. Several different digital tools were used to facilitate different integration mechanisms for the design and development processes. These processes cover the following:

- designing the concept and architecture;
- identification of technology and data requirements;
- (re)modelling the virtual manufacturing/VF environments; and
- performing data analytics, 3D model validation and training in a runtime VR environment. The overall procedure is shown in Figure 3.

The integrated VF model development is focused on the development of the 3D model of a manufacturing plant using a DES tool with VR capability. The overall methodology is shown in Figure 4. The VF, as a digital counterpart of a real plant, includes the main data

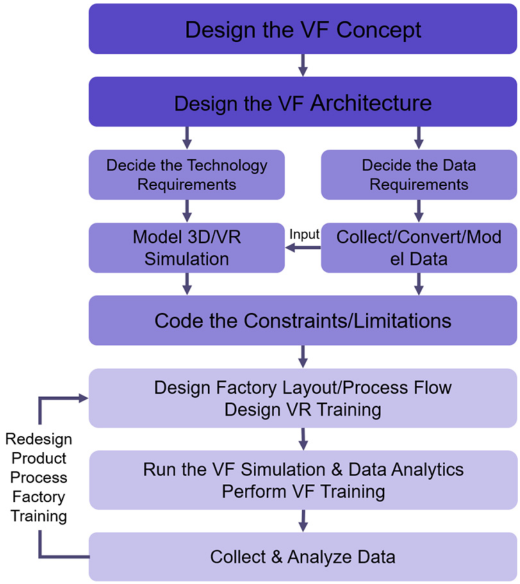


Figure 3. Design and development procedure for virtual factory

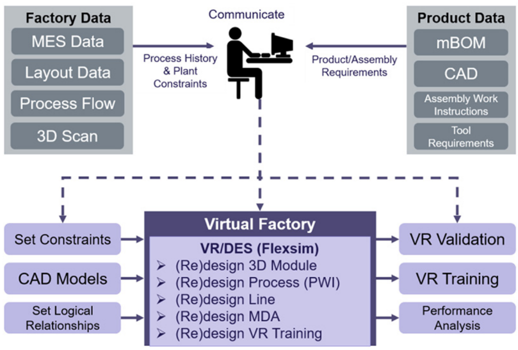
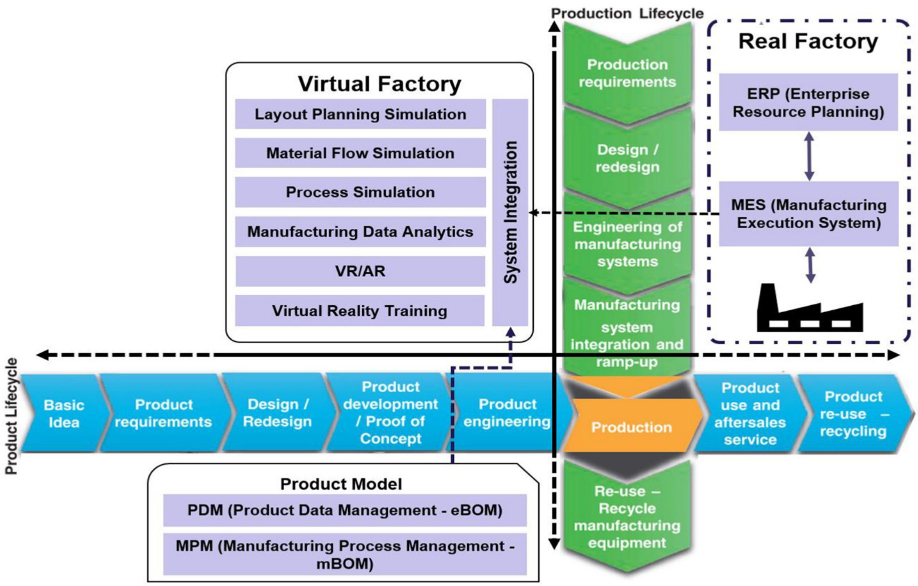


Figure 4. General methodology for VF development

from two different areas of the enterprise. These are the factory and the product area, which includes the manufacturing operation history data from the MES, plant layout, process flow, product parts (CAD) and resource requirements (tools, skills). The constraints in a manufacturing plant mainly stem from the physical plant and product model. However, some limitations are not always stored in the digital model, such as the height or speed limit of a crane. Such constraints as logical relationships between the factory entities, processes and sub-systems were provided as inputs during the modelling of the VF, in cooperation with the relevant stakeholders.

Designing the VF model in the 3D DES tool is an iterative process that includes developing 3D modules, processes, sub-systems (assembly line, material handling, etc.), data analytics and training based on the production and product life cycles shown in Figure 5.

Creating the concept and architecture of the VF were the initial activities required to decide and define the role and functionalities of the VF. Details of the concept (Figure 5) and architecture (Figure 6) are discussed in the next section. Capturing the requirements for the technology utilisation and data conversion to facilitate different integration techniques were carried out according to the expected functionalities, which were inherited from the concept and architecture design. Modelling the 3D VR simulation based on real factory and product data encompasses the as-is model of the manufacturing plant, including the logical relationships. In this phase, the entities in the VF can be considered as digital models of their physical counterparts because of bidirectional *manual data utilisation* (Kritzinger *et al.*, 2018). The following activity of the general methodology applies the constraints and limitations from real manufacturing to VF. At this stage, the VF will attempt to mirror a real factory, including its operational history, processes in logical relations and constraints, buffers and sub-systems. Real-time and automated VF-MES data synchronisation were out of the scope of the current demo because of limited time and skill resources. Bidirectional,



Source: Adapted from Mourtzis *et al.* (2014)

Figure 5.
Virtual factory concept

automated data integration is planned for future developments which will enable facilitating DT s in the VF environment.

The use of VF for product and production life cycle processes is performed after applying the constraints and limitations phase and redesigning the product, process, and production systems and corresponding training conducted in the VF. Data analytics can provide statistical results for the planned changes. 3D VR can support the validation processes for changes. VR training can be designed and performed as embedded in the VF simulation. This enables the coordination of VR trainees with other factory operations. The purpose of the VF can be redesigned, according to the results or changes in products, processes and systems.

6.1 Virtual factory concept and architecture

The VF concept, architecture and framework have been proposed in several different academic works in slightly different ways from each other (Jain *et al.*, 2001; Sacco *et al.*, 2010; Tolio *et al.*, 2013; Choi *et al.*, 2015). We adapted some aspects of these artefacts while designing the concept and architecture of the VF demo.

The academic works pay attention to different aspects of the VF concept, based on its role and functions along with the product and production life cycle processes. This article attempts to position VF among the product and production life cycle processes in Figure 5. Using VF as a virtual mirror of a real factory has the potential to support the creation of product and factory models in an integrated virtual environment. The engineering of manufacturing system design and product development in particular virtual prototyping (Wang, 2003) activities, can be supported by VF tools. VF can also be used for in-situ simulation of production to support real-time operations, production and maintenance planning (Terkaj *et al.*, 2015). Positioning VF between the product and production life cycles allows us to define its potential use cases coherently, especially in the context of a very sophisticated product or production system, such as wind turbine manufacturing. It is also considered that such positioning can be useful in identifying the role of VF for enterprises in which there is an uneven level of digitalisation in product development and shop floor systems. Our VF concept leads to efforts for prescribing the VF architecture shown in Figure 6. Mourtzis *et al.* (2014) outlined the key enabling technologies in product and production life cycles. We borrowed their map and integrated the simulation solutions and some technologies such as VR and 3D DES in the concept design.

Jain *et al.* (2001) proposed a definition of VF and presented a VF concept based on its role in the factory lifecycle, including design, installation and operation stages. The VF vision of Jain *et al.* (2001) built on (re)designing factory subsystems and managing factory operations

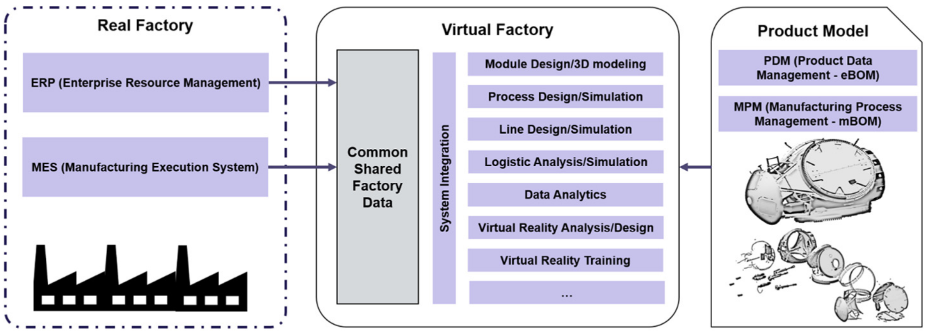


Figure 6.
Virtual factory architecture

subsystems in order to reduce the time to market. This approach encompasses the objectives of our work. The attributed functionalities of VF in Figure 5 and its role in enterprise architecture, defined by Jain *et al.* (2001), were the inspiration to form our scope of the VF architecture. Choi *et al.* (2015) presented a VF implementation strategy for manufacturers and a diagnosis method for the establishment level of VF. Their work also included a VF concept and a VF architecture. We mainly adopted their VF architecture, combining the system integration with the reference model presented by Sacco *et al.* (2010) as a common shared factory DB. Choi *et al.* (2015) classified the VF technologies and linked them with the factory design and development processes, however, they did not cover the product life cycle processes. They also extended the real factory model comprising the enterprise management platforms for manufacturing such as enterprise resource management (ERP), supply chain management, product life cycle management (PLM) and MES. We partially embraced this approach by segregating the platforms as a real factory and product model based on their functional role in our case company. The concept and architecture design in this article attempts to reduce the weakness of the link between the product design, process planning and production system design phases addressed by Tolio *et al.* (2013).

The term "*virtual factory*" has been commonly used by both scholars and practitioners. However, there is no consensus on the definition of VF. Jain *et al.* (2001) 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*", which is the definition mainly used by Sacco *et al.* (2010), in defining their VF Framework (VFF). There are several different terms in the literature (such as *digital factory*) which are used in a similar way to VF (Bracht and Masurat, 2005; Kim *et al.*, 2010). Kuehn (2006) defined the digital factory as "*a comprehensive approach, which consists of the VF and its integration in the real factory as well*". Four different connotations of VF were presented by Jain and Shao (2014), including high fidelity simulation, virtual organisation, VR representation and an emulation facility. However, contemporary developments in 3D DES, VR and IoT technologies and their use in VF concepts are extending the role of VF and its capabilities. Real-time synchronisation capabilities of VR DES with data providers and sensor networks are becoming pre-eminent (Turner *et al.*, 2016). The role of VF is expanding with *in-situ* simulation (Terkaj *et al.s*, 2015) and becoming a real-time digital counterpart of real factory assets, processes and systems. As Møller, Chaudhry and Jørgensen have shown, using advanced DES to develop Virtual Enterprise Architecture, as a system emulator, brings immense benefits in the development, testing or adoption of software algorithms (Møller *et al.*, 2008). Moreover, emulation capabilities promise a substantial role for VF as a testbed for developing and testing AI and machine learning algorithms through learning factories. These advances may lead to a need to redefine the visual and data depiction of real factory entities in VF, which represent their physical counterpart, as DTs. If we embrace the proposal by Hegel about the existence and definition of concepts which states: "*things are what they are through the activity of the Concept that dwells in them and reveals itself in them*" (Hegel, 1991), there is a need to redefine what VF is through the activity of the concept today. It can be considered that VF is evolving from an integrated simulation model of a whole factory to "*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*". This may enable the semantic definition of such twins based on their relationship with each other. Hence, the evolution of VF's role will possibly empower a higher-level definition of VF and allow us to realise smart factories.

7. Model development

The integrated model development aims to build a "*virtual factory*" including its VR model of an assembly line, together with a mixed production VR training scenario in a 3D DES tool. The product model from a PLM solution and VF model, were integrated into the DES tool and simulations were performed using the data from a real shop-floor system. The use of simulation tools is essential, not just in optimisation but also to reduce the time to market by supporting the (re)engineering, (re)designing and decision-making processes.

7.1 Modelling and simulation

In this research, the FlexSim simulation tool (FlexSim, 2020) was used to develop a simulation of the VF. FlexSim is a 3D DES software which has a general purpose and health-care-focused products. Its user-friendly drag-drop and comprehensive visual capabilities were considered valuable for rapid experimentation. FlexSim's embedded VR capability allows users to model, run and manipulate the simulations and collect the statistical data in a 3D graphical VR environment. This capability brought significant advantages in reducing the time for validation after each reconfiguration/redesign of the VF. However, the unique syntax of the tool makes it challenging to develop customised models.

Modelling work started with geometric modelling, followed by mathematical modelling. During the geometric modelling, the current factory layout was used as a base frame on a real scale. Other primary considerations were machines, operators, tools, buffers, materials, transport and other significant objects in the factory. Mathematical modelling covered the simplification of the current production process flow and line.

7.2 Discrete event simulation and virtual reality

Employing simulation modelling tools, such as DES and its 3D capabilities, together with data analytics for a decision support capability, constructs a stage through VF to the smart factory. Moreover, to deal with increasing complexity and shortening life cycles of product, process and system models, VR technology can provide a more advanced user interface for the design, verification and interaction of such models. Therefore, DES and VR had a crucial role to perform in using the VF in the design of the manufacturing process, such as module design, layout design, process flow and factory design and operations management such as planning, simulation and training. To enable VR user interaction with the DES model and VR training capabilities, the public warehouse demo and touch demo models of FlexSim (Cueva, 2016) were borrowed and adapted to our VF model. VR input devices enable VR users to interact with the DES models while the simulation is running. The customised event handler class enables the model to capture user events and links them to other discrete simulation events. Therefore, a VR user can become a part of DES. A crane control operation with touch controls in VR was designed for a crane between assembly line operations (Figure 7). VR users could become a part of the manufacturing processes by using the crane while other manufacturing operations are running. The colour selection scenario of these demo models was also borrowed and adapted to our VF demo as a simple mixed production scenario.

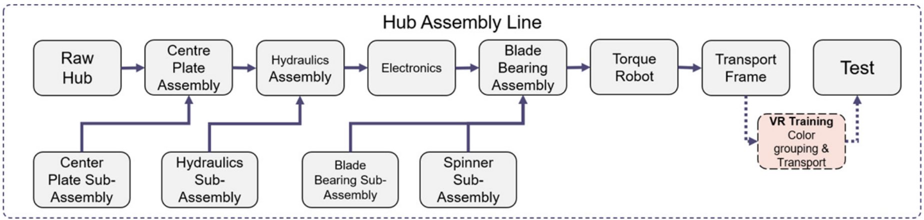


Figure 7.
Flow of processes in the hub assembly line

7.3 Manufacturing data analytics

The roles of simulation for manufacturing data analytics (MDA) in three major areas (diagnostic, predictive and prescriptive analytics) were extensively demonstrated in previous studies (Jain *et al.*, 2017). Therefore, the data analytics capability was not the main focus on model development and demonstration. However, the DA capability of the simulation tool was used to generate standard diagnostics for the shop-floor operations. The simulation enables users to make changes in the manufacturing line design and observe the effects of these changes in the model in real time. Moreover, VR user activities regarding the interaction with the simulation were recorded and analysed in real time.

7.4 Product model and factory model integration

In order to create a simplified product model, data from the PLM solution were used. The assembly operations defined in the manufacturing bill of materials (mBOM) were linked to the same assembly operations in the MES system when integrating the product and factory model. Buffer capacities and required tools in the factory were some examples of defining constraints and limitations in the VF model development.

The MPM and PDM link, which contains the engineering bill of materials (eBOM) and mBOM, respectively, provided the product architecture and product CAD data. 3D CAD software, Creo (PTC, 2020) was used to process the product CAD models. The engineering CAD model size was reduced by deleting non-visible and insignificant layers due to limited rendering capacities of the hardware and software. Heterogeneous levels of detail in the DES were modelled at different levels of detail to increase the efficiency of analysing the model. For example, a robot arm movement in a sub-assembly operation is modelled with specific, precise movements because FlexSim's default library has a robot arm with six joints and allows users to define multiple motion paths and speeds without any custom code. This allows VF users to analyse the performance of a certain activity in detail, which contributes to the mainline performance. However, the rest of the line was modelled at a low level of detail. The multi-resolution modelling capability offers higher efficiency for analysis and saves time for modelling, verification and computing resources (Jain *et al.*, 2017).

7.5 Limitations

Effort was aimed at creating a DT -based VF, which has real-time data synchronisation with shop- floor operations. However, the initial demo was limited, in terms of real-time synchronisation, because of time constraints for the development. Nevertheless, it was confirmed by both Vestas' IT department and FlexSim developers that this capability is available and feasible. A common shared factory data model is included during the design of the VF architecture; however, the subject of the VF demo is limited to implementing a common data model due to the focus on realising and capturing the industrial value of the VF capabilities. 3D laser scanning technology was intended to use the design and development phases because of its effectiveness in capturing accurate spatial data on existing production plants (Lindskog *et al.*, 2017). However, the lack of a proper software licence was a reason to limit the first demo for converting point cloud data to CAD models. Industry experts primarily addressed the value of animations covering the manual assembly of parts in the same role as process work instructions (PWIs), to increase the understanding of complex processes. However, because of the lack of adequate skill sets for advanced simulations at the initial stage, the subject demo was limited, without advanced and complex animations.

8. Demonstration

The demonstration was performed on a Vestas manufacturing plant to realise the functional capabilities of the VF presented above. Over 40 experts from industry and academia assessed the VF demonstration, which took place in February 2019. Semi-structured surveys were conducted regarding the VF users' experience.

Vestas is a Denmark-based global leader in sustainable energy solutions (wind power plant and wind service solutions). The company aims to maintain its competitive position as a market leader by offering a combination of the lowest energy costs, technological leadership and global market reach. Competitive cost levels are achieved through operational excellence, fast product introduction and ramp-up. Therefore, Vestas, like other industry players, needs to be robust to digital disruption and determine long-term targets based on the Industry 4.0 agenda. In this respect, it is considered that the future digitalisation of manufacturing processes is leading to DT s as a VF replication of all manufacturing processes.

Vestas is a global wind turbine manufacturer which also provides relatively mature, digitalised products, processes and production systems, in terms of all-inclusive PLM, ERP and MES platforms. However, Vestas is still improving the integration of such complex domains and faces difficulties in handling co-evolution problems which affect its long-term decisions in operations management. Accordingly, synchronisation and simultaneous engineering of the design and modelling of products, processes and factories remain a critical challenge for Vestas. Such challenges endorse the similarities between our case study and other manufacturing enterprises in different industries.

However, there is a need for feasible design and implementation methodologies to achieve full-scale VF and to investigate its potential value for different use cases.

8.1 Production layout and process flow design

A hub assembly line of a wind turbine manufacturing plant, consisting of eight main operations and four sub-assembly operations, was demonstrated in the VF (Figure 7). The hub assembly is a mainly labour-operated assembly line accompanied by several machining tools. Traditional labour-oriented work and low level digitalisation in the production line make it difficult to predict the effects of changes in the product, process or system during the design and planning phases of manufacturing. Therefore, in this research, the focus was on manual assembly line-type manufacturing to investigate the requirements and outcome of implementing VF.

The current production layout design was imported into the simulation tool as the primary 3D design reference. Processes for each operation were added to exact locations on the layout and time distributions were set, based on real data collected from the MES solution. Other necessary 3D objects were manually imported into the simulation. In the beginning, the product CAD files were embedded in the simulation model, which allowed the migration of the simulation model file to be independent from any other data file. However, the large volume of data required extensive graphical processing power. Because of this, the "Embed media with model" option was disabled, which caused a remarkable improvement in the 3D processing performed while the simulation was running. However, detaching the media files from the simulation meant that simulation imported all of the media files every time the model was opened, as well as requiring migration of all media files together with the simulation model, in case migration was needed.

The movements of a robot were modelled in detail as a proof-of-concept in the multi-resolution modelling. Transport vehicles, buffers, and operators were also added to the VF model and the 3D model of the assembly line is shown in Figure 8.

In order to have a practical understanding and reference point, the simulation experiments were performed 42 times under the guidance of Vestas' experts. Layout design and process flow changes were performed in the VF demonstration while manufacturing was running and the effects of the changes on the statistical results were observed and evaluated by industry experts. The location of *spinner and blade bearing sub-assembly* operations were changed and the effects of this change on the craning process, and consequently the line operations (Figure 8), were observed. The MDA, DES, and VR capabilities allowed the simultaneous analysis of a vast spectrum of indicators in the manufacturing system, including 3D product, process and layout geometry, throughput, state, time, zone, people (operator state, distance, etc.), and financial. The performance of the factory, together with its sub-systems (including the manufacturing, material handling and logistics systems), were analysed quantitatively and visually. The reconfigurability of the VF entities allowed us to test different layout configurations with little effort. The limitations, dependencies and restrictions enabled the VF users to have a more realistic environment for design and planning.

8.2 Virtual Factory training

A mixed production scenario was added between the assembly operations (as shown in Figures 8 and 9). While the whole line operations were simulated as a virtual twin, a VR training operation which required VR user interaction to be completed, was added between the *Transport Frame* and *Test* operations. After the *Transport Frame* operation, hubs in the line were given 3 random colours (red, blue, green) and sent to a queue at which VR users

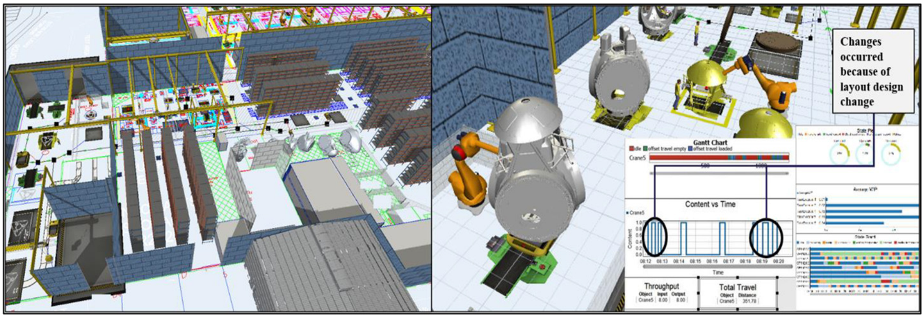


Figure 8.
3D hub assembly in a virtual factory

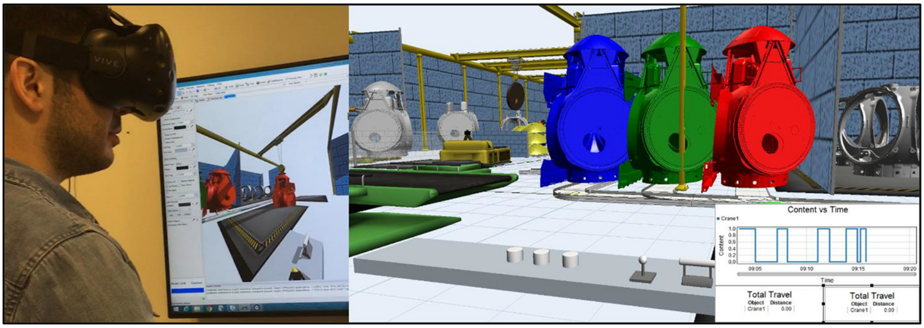


Figure 9.
Mixed production and crane control in VF-integrated VR training

had to interact with the simulation by pushing buttons to select which coloured hub must be processed. Then, the VR user had to carry the selected hub to the next operation by a crane controlled by a virtual handler and a control stick (Figure 9). The three differently-coloured hubs shown in Figure 9 were selected by users based on randomly given priorities (e.g. 1st priority: red, 2nd priority: blue, 3rd priority: green) for each user to perform the crane control task of carrying the hubs to the next operation area. The VR users' performance and learning curves were recorded and displayed in real time (right bottom corner in Figure 9). Performing VR training as a part of VF allowed not only a realistic training environment but, also, a better prediction of operator performance for production planning. Users also had a chance to observe and understand the effect of their performance on the whole manufacturing system. The VF environment allowed users/trainees to coordinate their tasks, based on related operations on the shop-floor. For example, upon completion and after finishing the given mixed production task, some users processed all queued parts and created extra buffer time for themselves to walk through and analyse other production operations in the simulation. Eighteen possible use case ideas for VF in the industry were raised by the VR users and are presented in the next chapter.

9. Evaluation and discussion

The proposed approach in this paper is an integrated VF design and development which combines data from the factory and product domains as well as technologies such as 3D DES, VR and data analytics for (re)designing and (re)configuring the VF, as envisioned in the concept design and methods section. The iterative and simultaneous design and development of the VF enables more flexible and dynamic processes. Such flexibility and dynamism call for retrospective analysis and a redesign/update of the initially planned methods and procedures. The integrated nature of the VF enables a vast spectrum of use cases for model design, development and analysis in the product, process and factory domains. VF was demonstrated and evaluated for the M&S, data analytics, factory design and planning processes in terms of factory layout, process, process flow, manufacturing system design, as well as VR training for mixed production. Through the integrated system, the performance of different configurations and combinations of the manufacturing systems can be examined both visually and quantitatively. A semi-structured survey was conducted with 18 experts from the industry and 16 scholars. Moreover, semi-structured interviews regarding the VF demonstrator were conducted with 4 project managers experienced in new product introduction processes in Vestas. 66% of the industry experts and 56% of the scholars had more than five years' experience in their field. The survey focused on discovering the potential use cases for VF that promise high industrial value and business impact. From the design science research angle, the artefacts created during this study can be listed as follows: the VF concept, VF architecture, a general methodology and procedure for VF development. The VF architecture and the developed VF simulation can be described as an instantiation of the VF concept in a particular context. We also extended the proposed VF concepts in the literature by positioning the VF as a system between the product and production life cycle processes which allowed users to model and simulate such processes in a more efficient and effective way, with respect to the link between the VF, PLM solution and the real factory.

According to our design, development and demonstration efforts, we consider that the artefacts ensure that this work contributes to the successful and rapid design and development of VF for real-life industrial cases, within the limitations defined in the subject section. The design and development procedure (Figure 2) and the general methodology (Figure 3) provide conceptual guidelines for the actual utilisation of technologies and methodologies for designing and developing smart production systems. The design and development process presented in this paper is intended to extend the understanding of the barriers and enablers for VF design and development.

The industry experts, who worked in ten different departments in the manufacturing area, were asked which use cases they saw as being of significant value. The 17 different use cases which promised an industrial value for utilising VF within the wind turbine manufacturing context were captured and evaluated by the industry experts. 10 out of 17 use cases which were considered to be of high value by more than 50% of the industry experts are presented in Table 1. Project managers, who are more experienced in overall product and factory life cycles, were interviewed to rank all use cases according to the expected business value for each use case. As a result of these ranking discussions, some high value use cases were grouped in Table 1, based on the type of process (left hand column) and context of operation in the factory (right hand column) for clarity. Table 1 shows that the majority of industry experts confirmed its value in the factory and its sub-system design, in terms of virtual prototyping, optimisation, VR training, new digital standards and replacing process work instructions. It should be kept in mind that the definition of value differs between the industry experts and scholars.

Overall, the project objectives of design, development and demonstration were achieved within three months by one developer who did not have any previous experience of practising VR, M&S or 3 D modelling. This fact, together with the ease of using VF, can be considered as one of the main factors that can increase the acceptance of both the development and use of VF. The easy-to-use simulation tool for the process was an essential element for accelerating the design and development process. The VF model and associated method presented in this article were considered by experts and scholars to be a valuable solution, in terms of ease of use, simplicity, efficiency and effectiveness.

Scholars considered that automated bidirectional data integration between VF, MES and PLM promised to be of huge potential, incorporating manufacturing engineering knowledge by executing product and production life cycle processes in an integrated virtual environment. Moreover, such integration of advanced product design processes with a VF environment promises huge value for virtual prototyping. The experts stated that VF could have a significant role in performing process prototyping and 0-series prototyping, promising substantial savings in terms of reducing physical builds and the time to market by accelerating learning curves. An increase in distributed manufacturing and cultural differences with local content manufacturing are considered the main reasons for potential use cases using VF for knowledge transfer in the global manufacturing network. Blade manufacturing, in which

Table 1. Value of VF according to industry experts

Where do you see the value of virtual factory?

Rank	18 industry experts	
1	(Re)design	Layout Line Process Flow Factories
2	Simulate prototype (virtual prototyping)	
3	Optimise	Production Line Factory Processes
4	VR training	
5	New digital production process standard	
6	Replacing PWIs	

quality, optimisation and production performance mainly rely on craftsmanship skills, was considered to be the most suitable area for VR training and knowledge dissemination via multi-user VR technology. Replacing important PWIs with custom animation in VF simulations is also considered a way to accelerate learning. Using VF during joint venture business setups was among the use cases suggested by industry experts.

Sixteen scholars from the Department of Material and Production (7 from the Center for Industrial Production, 4 from Robotics, Automation and Machine Intelligence, 3 from Mass Customisations, 1 from Logistics and Supply Chain Management, and 1 from Operations Research) at Aalborg University used the VF, performed the VR training and evaluated the demonstration. The results are shown in Figure 10. They see the highest academic value in using VF for training purposes, factory design and virtual prototyping. Using VF to support *design for manufacturability* and to emulate reconfigurable manufacturing algorithms is also stated as promising high value by scholars. The need for a method for the systematic design of a VF, which is defined by the industry domain, is also recognised as significantly valuable.

The proposed approach and artefacts presented in this article addressed the problems defined in this study:

- Lack of guidelines for the actual utilisation of technologies and methodologies for integrated design, M&S of products and factories for smart manufacturing. The proposed VF concept contains new properties which provide a new perspective to VF by considering product, process and system models in a more distinct way, as well as a new approach to supporting the design, development and utilisation of VF tools and technologies. The demonstration shows that the utilisation of the proposed concept for the reconfiguration of new or existing factory layouts can reduce the ramp-up through integrated VR training and design times, and support management decisions.
- Lack of a methodology describing the logical steps and requirements for rapid, digital virtual design and prototyping of production and factories. Design and development procedures, as well as a methodology, can be considered as the main artefacts which comprise the research knowledge as a contribution to the knowledge base. Moreover, although these artefacts were designed for generic purposes based on the knowledge from a particular context, they can provide general user instructions for experts in the industry to utilise VF solutions.
- A gap in the use of VR and computer-aided manufacturing systems for collaboration and communication. Industry experts' comments indicate that using 3D DES and interactive VR capabilities have a significant potential for enhancing collaboration capabilities, in terms of knowledge transfer and communication. During the development and demonstrations, it was observed that immersive VR and 3D process simulations also decrease the cognitive load of highly complex models and scenarios. Enabling DT and multi-user VR simulation may exploit the collaboration capabilities of the VF concept in the future.

This work presents instrumental knowledge that contributes to solving practical problems on the design and development of a VF in a real-life manufacturing case. The concept presented in this work could be adopted by any enterprise that needs to deal with the co-evolution problem by data integration, in order to support decision making processes on complex operations. The work shows an example of linking the product model and production processes that can support the integration of data and systems across the value chain. Companies performing both discrete and continuous manufacturing operations can adopt the VF concept presented in this research paper. Like every engineering discipline, our

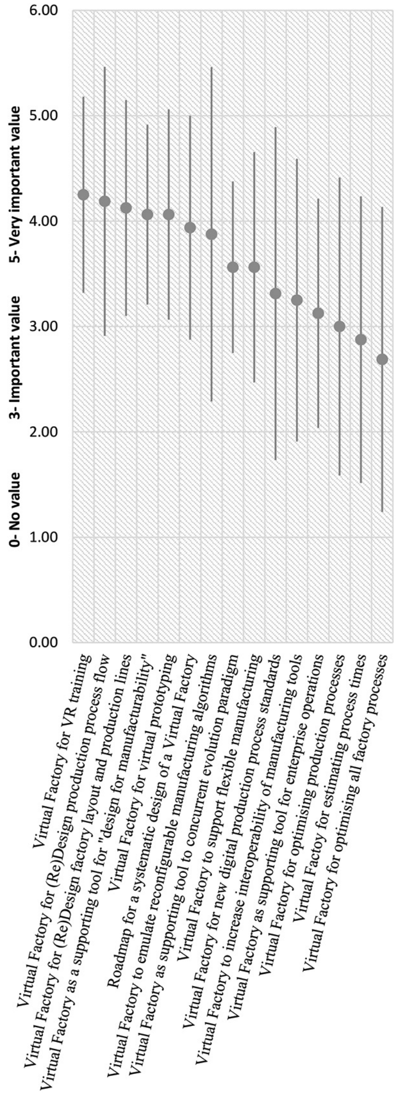


Figure 10.
Value of virtual factory according to scholars

designs lean on a pair of previously important concepts and artefacts, and we hope this work will encourage further research into better designs. Briefly, the work cultivates a meaningful outcome to respond to the questions stated at the initial stage of the research. Moreover, the evaluation made by industry experts also shows the value of adaptation capability provided by VF.

However, an extension utilising new technologies and demonstrations in different contexts in the manufacturing domain is needed to increase the knowledge about the context-driven differences of our generic design. The details are discussed in the next section.

10. Conclusion and future works

This article supports the development of a "*smart factory*" which was envisioned as a part of the Industry 4.0 agenda, by presenting an integrated VF concept which is demonstrated in a wind turbine manufacturing plant. The study is performed in the framework of DSRM from the IS field by presenting a novel approach for the design and development of a VF, as well as its demonstration.

The integration of product and process models in DT -based VF environments has potential in assisting simultaneous engineering, including the generation of product, process, and factory models, as well as in saving on time and cost by virtual prototyping. VR DES integration enables the validation of both the virtual and physical state of objects, including internal and external communication and collaboration throughout the organisation. VR training capabilities can reduce the time taken to market by accelerating learning curves and the ramp-up time. In the light of the evaluation by scholars and experts, this work will be extended with a detailed data integration architecture and relevant procedures for real-time, bi-directional data synchronisation, 3D laser scanning, and advanced VR training.

With the support of MES real-time data from shop-floor operations can be utilised in the VF simulations to develop DTs (Ding *et al.*, 2019; Yildiz *et al.*, 2020b). Such a digital counterpart of a manufacturing system can also provide real-time support for manufacturing performance evaluation, possible system reconfigurations, or maintenance decisions. The need for a working method to utilise terrestrial 3D laser scanning technology along with manufacturing system redesign methodologies was addressed by Lindskog *et al.* (2017). Future work will cover the use of 3D laser scanning technology for the realistic visual redesigning of manufacturing environments (Lindskog *et al.*, 2016). Such extensions in utilising advanced technologies will be demonstrated in improved VR training scenarios in future work.

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Paper 2. Demonstration and evaluation of a digital twin-based virtual factory

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ORIGINAL ARTICLE

Demonstration and evaluation of a digital twin-based virtual factory

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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 bidirectional 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 abovementioned 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

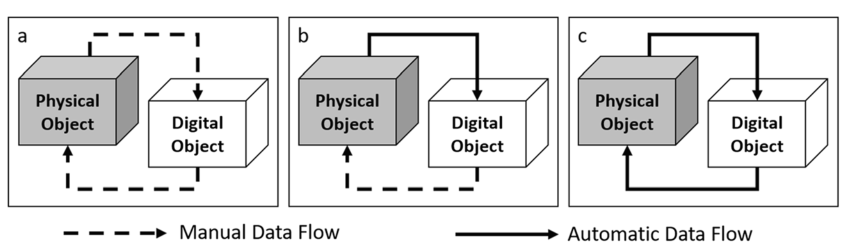


Fig. 1 **a** Digital model (DM). **b** Digital shadow (DS). **c** Digital twin (DT) [48]

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.

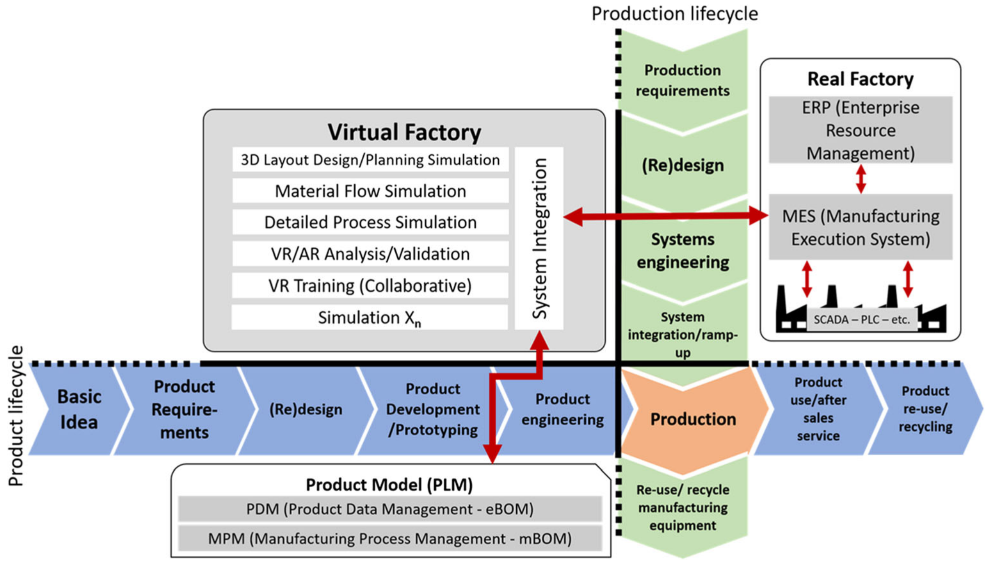
Before presenting the demonstration and evaluation results, the DT-based VF concept is shortly presented and discussed in the next section.

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.

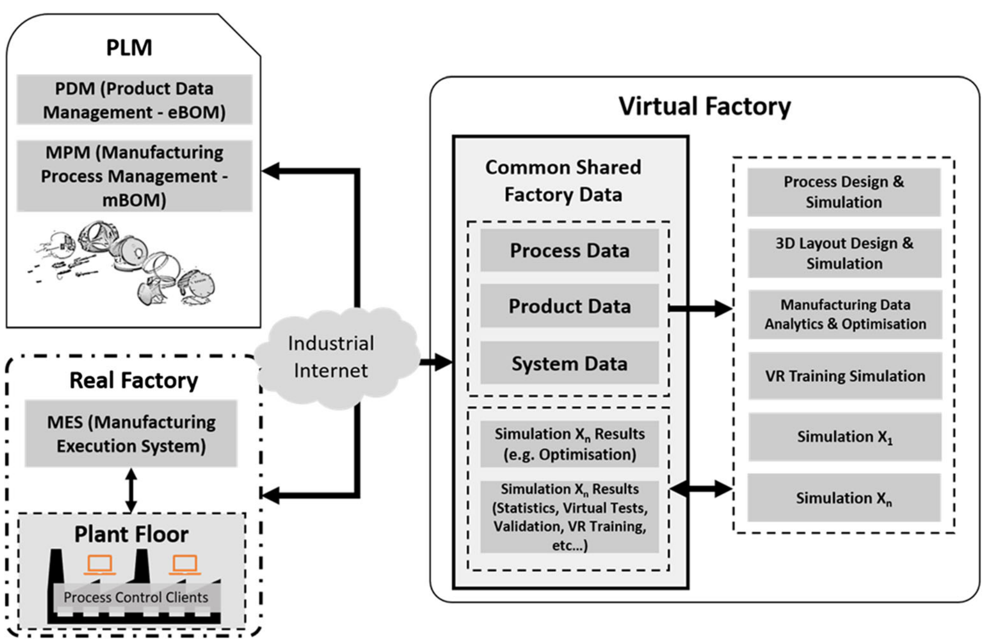
Dynamic representations of product, process and manufacturing systems in 3D DES decrease the cognitive load both vertically and horizontally for diverse experts. Integration of different simulations enables co-simulation of complex systems in different resolutions and more holistically.

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])



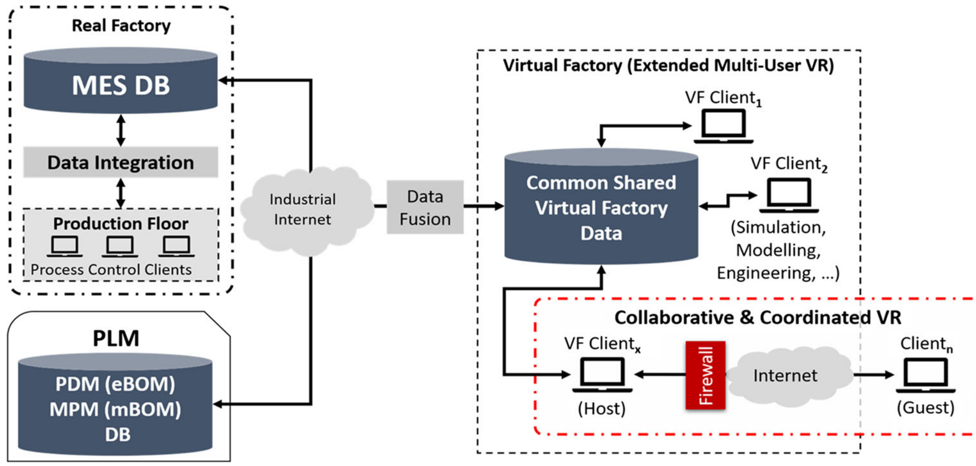


Fig. 4 Data synchronization architecture of DT-based VF extended with multi-user VR (adopted from [10])

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

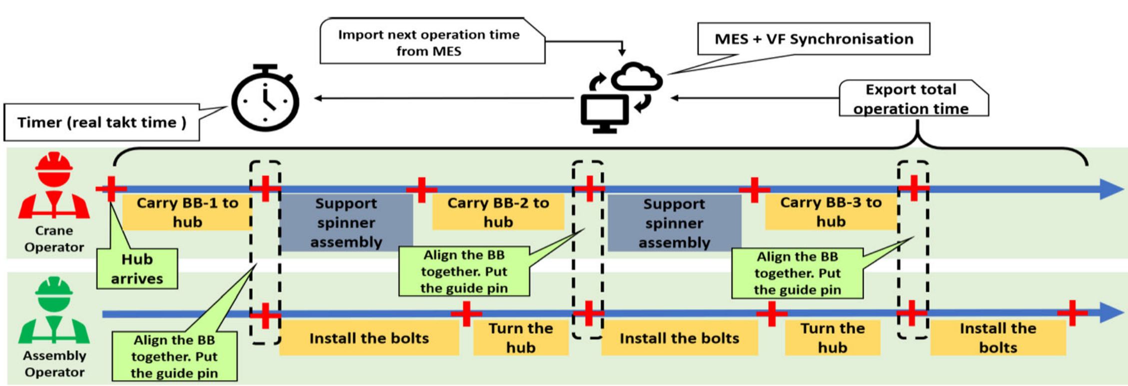


Fig. 5 Collaborative and coordinated VR training scenario (adopted from [10])

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.

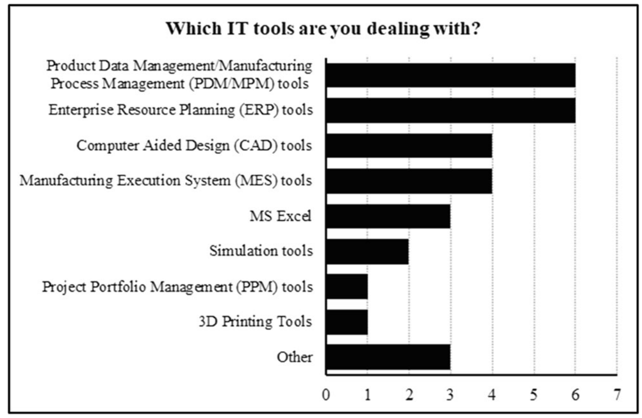


Fig. 6 Familiarity with IT tools

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

Do you see VF as a dynamic system?	Yes	Yes	Definitely	Definitely	Yes	Definitely	Yes	Definitely	Yes	Yes	Definitely	Yes	Yes
Do you see VF as an open system?	Yes	Yes	Yes	Definitely	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes
Is VF a cognitive (sense making) system?	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
Is VF a holistic system?	Yes	Yes	Not sure	Definitely	Yes	Yes	Yes		Absolutely	Yes	Yes	Yes	Yes
Can VF help save time during new product introduction (NPI)?	Yes	Yes	Absolutely	Definitely	Yes	Yes	Yes	Yes	Absolutely	Yes	Yes	Yes	Yes
Can VF support concurrent engineering?	Not sure	Yes	Yes	Yes	Yes	Definitely	Yes		Exactly	Yes	Yes	Yes	Yes
Can VF enable virtual prototyping?	Yes	Not sure	Yes	Some of it, definitely	Not sure	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Can virtual prototyping in VF help decrease physical builds?	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" (In. 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

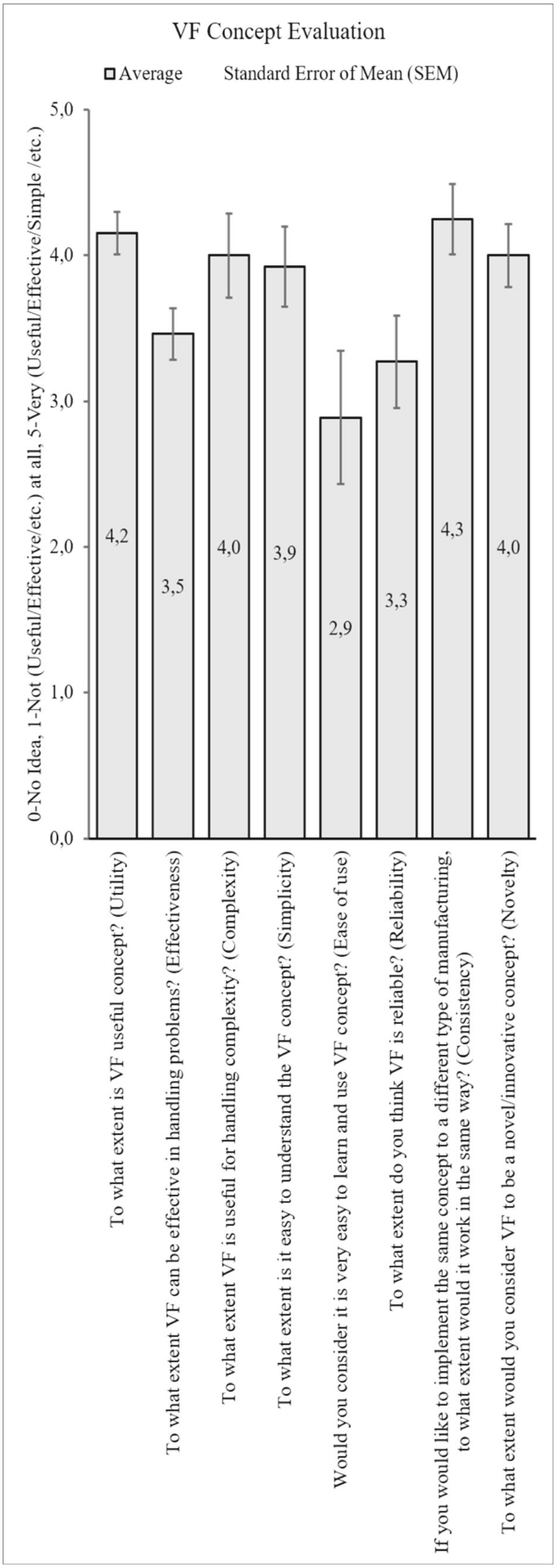


Fig. 7 VF artefacts evaluation

[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 strategic 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

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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.

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Paper 3. Virtual Prototyping: Evaluating the Digital Twin Based Virtual Factory for New Product Introduction

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Virtual Prototyping: Evaluating the Digital Twin Based Virtual Factory for New Product Introduction

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Abstract. Shortening lifecycles and increasing complexity make product and production lifecycle processes more challenging than ever for manufacturing enterprises. Virtual Prototyping (VP) technologies promise a viable solution to handle such challenges in reducing time and physical builds as well as increasing quality. In previous studies, the Digital Twin (DT) based Virtual Factory (VF) concept showed significant potential to handle co-evolution by integrating 3D factory and product models with immersive and interactive 3D Virtual Reality (VR) simulation technology as well as real-time bidirectional data synchronisation between virtual and physical production systems. In this article, we present an extension to the paper "Demonstrating and Evaluating the Digital Twin Based Virtual Factory for Virtual Prototyping" presented at CARV2021. The study presents an evaluation by industry experts of the DT based VF concept for VP in the context of New Product Introduction (NPI) processes. The concept is demonstrated in two cases: wind turbine blade manufacturing and nacelle assembly operations at Vestas Wind Systems A/S. The study shows that the VF provides an immersive virtual environment, which allows the users to reduce the time needed for prototyping. The industry experts propose several business cases for the introduced solution and find that the phases that would have the most gain are the later ones (production) where the product design is more mature.
Keywords: Virtual Factory, Digital Twin, Virtual Prototyping, Virtual Reality, Simulation and Modeling, Industry 4.0.

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1 Introduction

Forces like innovation and technology, competition, changing demands, and regulations are among the main dynamics that shape the evolution of industries [1]. The specific rhythm of the evolution in each manufacturing industry occurs in three domains: products, processes, and systems [2]. Therefore, companies need to handle concurrent evolution (co-evolution) of product, process, and system models to achieve the capability to adapt to their respective industrial environments [3]. However, the increasing frequency of changes results in shorter product and production lifecycles and shifting of decision-making from companies to customers, which results in higher complexity. Thus, achieving architectural isomorphism across the product, process and organisation (system) architecture required to maintain effective alignment of an organisation with its evolving environment [4] is becoming a significant challenge for manufacturing organisations.

Physical prototype building activities during the introduction of a new product can be considered among the most critical activities to achieve and ensure architectural isomorphism. However, physical prototype builds are often highly time-consuming, costly, and complex due to the uncertain and genuine nature of models and operations. When it comes to the wind industry, wind turbine generator (WTG) manufacturing covers a wide variety of production and manufacturing operations, such as heavy metal manufacturing (towers), large-size fiberglass composite material production (blades), complex and heavy parts assembly (gearbox, nacelle, generator, etc.), and electrical and electronic systems manufacturing (control and grid infeed systems). Therefore, physical prototype builds during the New Product Introduction (NPI) are becoming much more challenging for companies such as Vestas Wind Systems A/S (later Vestas). Moreover, despite the particularities of the WTG manufacturing operations, there are significant similarities with various other industries, which can provide a sound basis for the generalisability of the knowledge discovered in this study. WTG tower manufacturing, for instance, incorporates noteworthy similarities with the heavy steel fabrication operations of the aerospace, construction, maritime, and oil and gas industries. WTG blades manufacturing contains unique characteristics, reaching 107 meters in length for a single piece of fiberglass composite product, which is one of the largest in the world [5]. In terms of size, WTG blade production has some similarities with maritime production, such as superyachts [6]. Meanwhile, the global fiberglass market value reached 13 billion USD as of 2020 and is expected to reach 18.6 billion USD by 2027, mainly driven by the automotive and construction industry [7]. While gearbox, generator, and nacelle manufacturing shares similar genetics with the automotive and heavy machinery industries, the converter and control systems of WTGs incorporate similar approaches to those of various electrical and electronic manufacturing industries.

Although there are significant affinities between WTG manufacturing operations and other industries like the automotive, aerospace and maritime industries, WTGs are still not mature products and are continuing to evolve rapidly, together with the associated manufacturing systems and processes. In terms of size and weight, for instance, modern cars, ships, and planes are not substantially different from the same products manufactured in the 1980s. WTGs, however, have now reached rotor sizes of over 200 meters from 10 meters in the 1980s, and over 400 tons of nacelle weight from 5 tons in the 1980s [8], [9]. Despite the tremendous increase in the sizes and weights of WTGs during the last four decades, the (onshore) wind energy cost per kilowatt/hour decreased to 0.05 USD from 0.4 USD during the same period [10]. Thus, the cost per megawatt oriented tendering approach results in significant pressure on WTG manufacturing companies to improve the performance of their turbines by redesigning their products, together with the associated processes and manufacturing systems. In this regard, the Digital Twin (DT) based Virtual Factory (VF) concept [11] is becoming a highly relevant solution by enabling integration, interoperability, and interaction capabilities across product and production lifecycle processes in virtual environments [12].

In recent studies, the DT based VF is considered a promising solution to deal with co-evolution problems with its potential to achieve dynamic, open, holistic, and cognitive system capabilities [12], [13]. Moreover, industry experts considered Virtual Prototyping (VP) among the highest value promising industrial use cases for the DT based VF concept [12]. Although a virtual prototype as a computer simulation of a physical product covers all product lifecycle aspects, including service and maintenance [8], building and testing, the virtual prototype of NPI processes is particularly challenging due to the need for concurrent engineering and complex and ambiguous models and operations. However, due to the same challenges, VP maintains a significant potential for high value by enabling (1) early testing, (2) expensive or impossible tests, (3) fewer physical builds, (4) safer builds, (5) increased agility, (6) reduced cost, (7) complexity handling, and (8) reduced time to market [14]. Thus, the need for evaluating the DT based VF concept in more particular VP use cases was raised in [12].

It should be noted that this article is an extension to the conference paper titled "Demonstrating and Evaluating the Digital Twin Based Virtual Factory for Virtual Prototyping" presented at CARV2021[†][15]. This article is distinguished from the previous one by extending the evaluation and discussion, amongst other additions.

Following the next section, which frames the scope and objectives of the work, Section 3 summarises related works on VP and VF. Section 4 describes the research methodology. Section 5 presents the results and evaluations of the industry experts, followed by the discussion and implications in Section 6 and conclusions in Section 7.

2 Research Scope and Objectives

In this study, we respond to the need addressed in [12] for evaluation of the DT based VF concept (introduced in [5]) in particular VP cases and thus present an evaluation of the concept in the context of NPI processes. The evaluation is established on the data gathered during group interviews with industry experts. In order to support the rigour and novelty of the work in hand, there is a need to clarify the differences between the scopes and objectives of the previous works [12] and the present work. The study in [12] was conducted to evaluate the DT based VF concept in terms of (1) achieving the cornerstones of the competence-based strategic management concept (dynamic, open, cognitive, and holistic), (2) enabling concurrent engineering of products, processes, and systems, (3) supporting shorter product and production lifecycles, (4) the usefulness, effectiveness, and consistency of artefacts [3]. Therefore, the essential premise for the arguments in [12] "is that DT based VF can support competence-based strategic management of manufacturing organisations during their adaptation to dynamic and complex environments." While performing the evaluation of the concept broadly in the scope of competence theory, knowledge about the particular aspects of the concept, including implications of collaborative VR and VP, was discovered. Discussions on VP in [12] provided some pieces of evidence for the potentially high value of using DT based VF during the NPI processes. However, there was a need for in-depth discussions and data on "how" the concept could be utilised during NPI and contribute to each phase of prototyping. Moreover, due to the comprehensive and complex nature of coordinated engineering operations during the NPI, none of the individual interviewees in [12] was confident enough about their judgements on extensive utilisation of the concept for VP operations.

Therefore, the present study is conducted by narrowing down the scope of the DT based VF evaluation and discussions on the VP context with a particular focus on NPI activities. Due to (1) the high level of coordinated engineering during NPI, which causes a limited view for an individual engineer, and (2) the diversity of manufacturing operations of WTGs, it was decided to conduct the interviews with focus groups with distinct engineering (tooling, training, design, etc.) and manufacturing (tower, blade, assembly, etc.) backgrounds. Group interviews were

[†] https://carv2020.com/

established to instigate richer arguments and discussions on an issue or a proposition by enabling the collision of diverse experiences and approaches on the same subject. Thus, *the objective of the study is to conduct an exploratory work to discover knowledge on (1) how the DT based VF can be utilised in VP operations of WTG manufacturing, and (2) what benefits can be gained from such industrial implementation.* Therefore, the concept is demonstrated in wind turbine blade manufacturing and nacelle assembly cases at Vestas, as in the previous work [12]. However, the evaluation was performed by a more specialised and experienced group of interviewees. In contrast to the previous evaluation, which included both higher- and lower-level experts, the interviewees in this work were mostly medium-level and technical experts with more (14.8) years of experience (compared to 11 years in [12]).

Therefore, the study draws upon previous research, including concept design and development of the VF [16], its extension with DT [11], [12] and collaborative VR capabilities [17]. Thus, we spare the reader from prolonged discussions on the concept and its design and development methodologies. However, we would strongly recommend the reader to refer to the subject studies for in-depth discussions on practical and theoretical aspects of the work.

3 Related Works

3.1 Virtual Prototyping

With the advances in Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM) and visualisation and interaction capabilities, the development of virtual environments and realistic virtual representations of product models has gained more attention from scholars and industry experts. Thus, development and interaction with such virtual models become viable solutions promising significant advantages for the industrial processes in terms of reducing time, decreasing costs, and increasing quality [18]. As a result of this, VP, a key aspect from the application point of view, is starting to get attention in both the application and knowledge domains. However, there have been many different interpretations of VP techniques, which have caused some confusion. To prevent such confusion, Wang defined a virtual prototype as "*a computer simulation of a physical product that can be presented, analysed, and tested from concerned product lifecycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (VP)*" [19]. Wang also addressed the needs for concurrent design, analysis, optimisation, and integration of simulation tools. Some studies consider VP to alleviate the shortcomings of rapid prototyping (RP) [20], while others stress the difference between RP and VP [21]. Alongside early adoptions in the aerospace and automotive industries [14], VP technologies are also promising significant value in different industries such as construction [22], the maritime industry [23], and heavy machinery industries [24].

Studies about VP techniques focus on different product lifecycle aspects, including product design, analysis, testing and assembly process design [25]–[28]. However, there are limited studies focusing on the VP of products from a manufacturing aspect [29]. Although scholars concentrate on various VP simulations such as structural material and structural behaviour simulations [28], [30], recent studies show more attention to immersive VR integrated simulation tools [31]. Recent review studies show that advances in simulation technologies, including real-time data integration, realistic visual representations and embedded VR and augmented reality (AR) capabilities, can make simulations a proven enabler for digital integration and access to data across the product and production life cycles [32].

In this respect, the VF concept, as high-fidelity integrated factory simulations representing factories as a whole, can provide viable virtual environments for constructing and testing virtual prototypes, since they enable the experimentation and validation of the various product, process, and system models concurrently [11]. Therefore, we will briefly present some studies focusing on VF in the next section.

3.2 Virtual Factory

Since Onosato and Iwata [33], [34] introduced the integration of product and factory models as an integral aspect of VF and virtual manufacturing, various definitions have been given for VF, including emulation facility, integrated simulation and virtual organisations [35]. Jain et al. 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*" [35]. An integrated VF framework concept which can synchronise the real factory and VF was introduced by Sacco, Pedrazzoli, and Terkaj [36]. While Jain et al. [37] stressed the multi-resolution capabilities of VF simulation models, Yang et al. [38] introduced the VF concept for collaborative design and analysis of manufacturing systems. There is also a higher level of utilisation of the VF concept as a collaborative business process monitoring environment for achieving business goals [39]. Yildiz and Møller [16] presented the VF concept as a more dynamic and open system by integrating VF into actual manufacturing execution and product lifecycle systems, as illustrated in Figure 1. A more distinct conceptualisation of the product, process and system domains in between the product and production lifecycle processes enables better interpretation of the link between these domains. Such representation is also considered a better way to handle complexity and improve efficiency for DT development and the fidelity of simulation models. The utilisation of collaborative VR training simulations in the VF concept, together with DT capabilities, was also studied by Yildiz et al. [11], [17]. They also 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*" [16]. A comprehensive demonstration of the DT based VF concept in industrial cases [12] showed significant potential for the concept to handle co-evolution and called for more particular evaluation in VP cases.

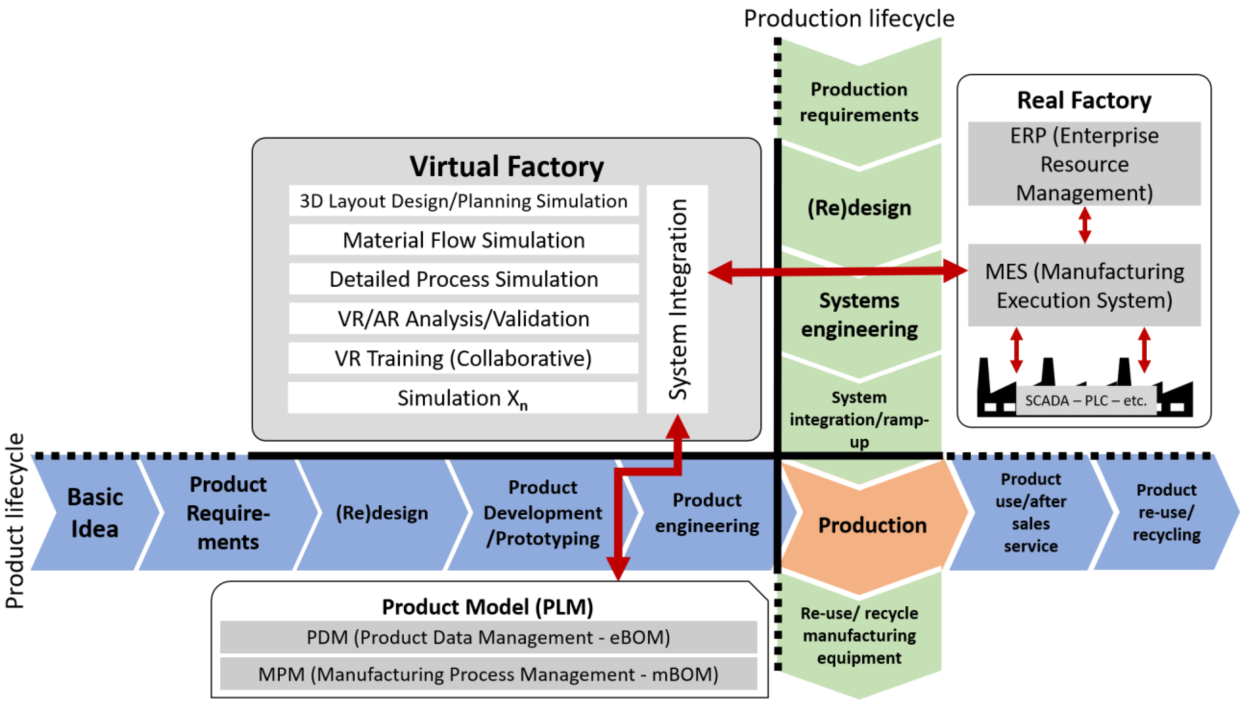

Figure 1. Digital Twin based Virtual Factory concept [12]

In this regard, we further discuss the methodology for the demonstration of the DT based VF concept in wind turbine blade manufacturing and nacelle assembly cases, as well as its evaluation in the context of VP in NPI processes.

4 Methodology

There are two exercises of the knowledge, which are (1) creation of the knowledge and (2) applying the knowledge [40, p. 3]. Knowledge about natural phenomena is discovered/created by applying scientific methods like experimentation, observation, and empirical evidence collection. Such descriptive knowledge about nature enables the manipulation of the same nature by utilising purposefully designed physical (tools, machines, etc.) or conceptual artefacts (models, methods, etc.) [44]. When such artefacts take physical forms, it is usually called technology. The consequence of manipulating natural phenomena is the emergence of new scientific methods, discoveries and thus new knowledge [45]. Since it is not possible to provide an in-depth discussion on science–technology dualism in this work, it is important to stress that the subject study aims to discover prescriptive knowledge, which is demonstrated in the utility, effectiveness, reliability, consistency, etc. of the designed artefact.

Since this study aims to explore the practical usefulness of a conceptual design in empirical cases, Design Science Research Methodology (DSRM) is considered a well-suited methodology. Thus, the research demands instrumental knowledge to uncover the effects of interventions on a manufacturing enterprise's specific (NPI) operations. Various research works which have been carried out over the last three years were conducted on the trails of guidelines, methods, and frameworks of DSRM [41]–[44]. However, this article covers only the demonstration and evaluation activities of six DSRM activities. Since the designed artefacts should have an impact on the practice, the design science research objective of the present paper is to report the kinds of impact of the IT artefact and design theories.

Four demonstration and evaluation sessions were conducted, each with five participants, with a total of 20 participants. A session covered (1) presentation of the artifacts, tools, and capabilities, (2) live demonstration of DT based VF, including VR interaction, and (3) semi-structured group interviews. Therefore, the demonstration and evaluation methods are briefly articulated in the following sub-sections.

4.1 Demonstration

Demonstration of general artefacts (concepts, architectures, methods, demo) delineates how to use the developed artefacts effectively in particular contexts. Therefore, although the discovered knowledge will be about the particular context, it should be able to transfer into various contexts within the same application domain without losing its necessary effectiveness [43]. In this study, DT based VF is demonstrated in two diverse cases, including large composite manufacturing (blade) and complex and heavy parts assembly (nacelle) at Vestas. Although such cases are unique to the wind turbine manufacturing industry, there are significant common aspects with various industries such as shipbuilding, automotive, and aviation. Thus, the knowledge can provide guidelines for experienced professionals in the industry and enable the evaluation of deviations in the form of "if–then" specific to each context.

Since the DT based VF is a generic concept, and the capabilities and implications of the implemented concept depend on the context-specific tools, data and IT infrastructure, a short presentation was made to explain and distinguish the concept, tools, technologies, demo, and methods. Some parts of the data about the demonstration are subject to the intellectual and financial interest of Vestas. Thus, a significant part of the data is covered by the provisions given to Vestas by the research collaboration agreement. However, we strongly advise the readers to access the part of the demonstration video that is publicly available via [46]. The video shows examples of DT based VF simulations that are synchronised with process data from the real factory via the manufacturing execution system. The synchronisation allows the reflection of changes in VFs to produce manufacturing data analysis based on timings from the real factory. Furthermore, the video shows that you can manipulate the VFs in a VR environment and even have multiple users in the same VF simulation environment to perform collaborative and coordinated manufacturing (assembly) operations. This enables operators to train together in the virtual environment on products that may not be in production yet.

4.2 Group Interviews

The group interviews aim to collect data to evaluate the DT based VF concept in the context of VP during the NPI processes with well-grounded pieces of evidence and arguments by exploring the interpretations and perspectives of industry experts. During the group discussions, the interpretations of the experts were critically examined by instigating a process of reflection to gain more specific, accurate and grounded pieces of evidence. Moreover, group discussions with diverse technical expertise on similar operations in different manufacturing domains allowed the experts to reach more reliable judgements or demonstrate independence through slight disagreements.

Since the purpose of Design Science Research (DSR) is to discover the practical usefulness of a solution to deal with empirical challenges with practical methods, DSR focuses on the pragmatic validity and practical relevance of a generic design [43]. Therefore, justification of a solution concerns, including but not limited to, the effectiveness, usefulness, and consistency. In this regard, group interviews were initially planned as physical meetings to enable interviewees to experience first-hand a DT based VF demo with immersive and interactive VR environments. Unfortunately, due to the COVID-19 pandemic, live demonstrations had to be performed during an online meeting which allowed the interviewees to see the physical and virtual environments but not fully experience VR. The interviews were recorded with the Microsoft Teams software tool and transcribed with services provided by the Microsoft Stream platform. The guidelines for designing and conducting interviews by Kvale [47] were followed. The number of interviewees was limited, with five in each session to avoid uneven participation in discussions, and to acquire more valuable knowledge with more intensive interviews and penetrating interpretations. Participants were intentionally mixed for each session based on their background and department (NPI, Blade, Manufacturing, Nacelle, etc.) to increase the diversity of expertise in each session. A list of the expert interviewees is available in the appendix.

5 Results and Evaluation

In total, 20 interviewees participated in the demonstration and evaluation of the DT based VF concept in VP. Four sessions each included five experts and covered the introduction of the concept, demonstration, and evaluation/discussion sections, which took approximately 4 hours. Only the evaluation part of each session was recorded and took 50 minutes on average. The average years of experience of the experts were 14.8 and ranged from a minimum of 3 years to a maximum of 24 years. As anticipated, the expert discussions on the evaluation of DT based VF roamed around four terms, representing some of the main activities of NPI. These terms are (1) mock-ups, (2) design prototypes, (3) process prototypes, and (4) 0-series production. Therefore, the results and evaluations are organised and presented under the respective headlines.

One of the recent product introduction operations at the case company comprised four mock-up builds, five design prototype builds, and four process prototypes. Although the cost of the prototyping depends significantly on the magnitude of the design modifications, the cost of prototype activities of a new wind turbine on such a scale can easily reach over 10 million €. Some of the comments, critiques, and arguments from the industry experts are referenced to the respective participant number in the appendix. For instance, interviewee number 5 is referenced as (Int. 5).

5.1 Mock-up Builds

A mock-up is an early build of the concept design, which aims to verify the functionality of the early design before the detailed design is finalised. A mock-up can be a physical or non-physical build, including a 3D model, computer simulation, hardware in the test, or a mock-up in the factory. However, if the difference in the new design is not minor compared to previous product variants, mock-up activities usually involve a significant number of physical builds. Shifting to the containerised products under the scope of modularisation, for example, could require significant changes in product design, production processes and, thus, the shop floor systems.

Most of the participants agreed that the DT based VF simulations could solve many problems and errors before early builds, but could not eliminate physical mock-up builds completely. This is mainly because NPI procedures dictate some early tests, such as a fatigue test on the physical build and a turbine test for legal certifications, requiring a minimum of three blades. Therefore, for the blade production case, it is considered that a minimum of four mock-up builds are inevitable under the present circumstances. However, 3D model simulations in factory environments were considered significantly beneficial due to increased confidence in the models (Int. 2). In addition, the majority of the experts considered that reducing the time spent on mock-up builds and errors found while using VF simulations would provide sufficient value for the business case. Some stated that the significance of the time spent on design and process changes is due to the high number of issues found during the mock-up builds (Int. 10). Quoting one of the experts: "*Even in early stages, this (DT based VF) could be beneficial to at least anticipate some issues that might occur in production due to design mistakes or miscalculations in design. I think that would be a great help in the decision making (on design.)"* (Int. 14).

Moreover, extending the tools with a detailed and specific process and material simulations, such as material behaviours and resin injection, is considered highly valuable for the blade manufacturing case. Thus, one expert stated, *"There are 1800 pieces of plies in each blade. If VF could be able to predict the tolerances, that would be a great business case."* (Int. 18). Simulating the resin injection process during the WTG blade production is conventionally considered significant for the design and performance of the product. However, experts highlight that such high-resolution production processes and low-resolution factory operations have significant mutual impacts. Heat and humidity originated at the geographical location, for instance, can have a significant impact on such processes as resin injection or torque processes and, eventually overall factory operations. Thus, integrated VF simulations could enable both analyses with high-resolution simulations and synthesis with low-resolution simulations.

5.2 Design Prototypes

A design prototype is a physical build that represents the final design documentation and aims to verify functionality and requirements at the system, product and component level. Ideally, the design prototype should finalise and freeze the Engineering Bill of Materials (eBOM), but most likely, some corrections on the design will be made later on.

DT based VF simulations were considered more beneficial for design prototypes than mock-up builds by the majority of experts since design prototypes are focused less on specific/critical materials behaviours and performances and more on the overall design integrity. It was stated by (Int. 18) that the majority of the issues (failures, corrections, improvements) faced during one of the late blade introduction processes were design-related (drawing corrections 40%, cutting file corrections 24%, bill of materials corrections 14%, among others). Therefore, aiming to find such issues in DT based VF simulations is considered a better approach (Int. 18). On the other hand, one expert stated that *"Replacing the (physical) model is not something we should consider for the near or medium future. But I think that if we could go that way, we could put a good CAD model of the product into the VF environment to do the same prototyping. So, we can play with it and test it in the weeks before the design prototype. Then I think we can lower the* *time that we spend on making the design prototype. But avoiding the design prototype completely is a bit optimistic as it is now. Considering the last design prototype, I guess VF would possibly help to decrease the time to market. We probably have several 100 issues in a design prototype. They are mostly product-related. My guess is around 10% is the space issues (which can be solved by VF).”* (Int. 11). Furthermore, the commonly agreed statement made by (Int. 17) was, *“I do not think we should reduce the number of blades that we built (in prototyping processes). Yes, I know they are expensive, but I think we can improve the quality and perhaps improve the speed.”* Such stress on increasing quality could link to the increasing cost of downtime due to quality problems in WTGs in recent years [48].

In the nacelle assembly case, cable routing and measurements in 3D CAD models are considered a highly challenging process. *“It is supercritical, especially when we try to design a cable bundle from point A to point B, and it goes above the four different cable trays and bins. It is very difficult to draw them laying correctly on the cable tray and all the way, and that is where we see the most of the errors.”* (Int. 20). The impact of such challenges on the production process on the shop floor can also be considered a sign of the importance of multi-resolution simulations of the factory operations.

5.3 Process Prototypes

The process prototype is a physical representation that has the full functionality of the final design. The purpose of the process prototypes is to verify the various documentations of the design concerning the Health, Safety and Environment (HSE), manufacturability, production process (mBOM; Manufacturing Bill of Materials), production setup, transportation, installation, and service (sBOM; Service Bill of Materials).

DT based VF is considered highly useful for process prototypes. *“Designing and modifying the production layout to find out: How to execute? How big a part of a nacelle we build and try to join them with the crane at the states. That is something we could definitely figure out in (VF) for new products.”* (Int. 20). However, most experts also considered the output of physical process prototypes and previous prototypes as very useful for simulating what-if scenarios and optimising 0-series and serial production processes (Int. 2). One expert stressed the importance of specific/detailed process simulations with high-level simulations by stating, *“if we were be able to integrate other simulations like the infusion process with VF simulations, then we could run the blade production process right from lay-up till the curing process. The infusion process includes the material properties, the curing properties, the heating, and the moulds conditions. So, if these applications could talk to each other, then we could run the entire process within a single platform.”* (Int. 18).

5.4 0-Series Production

0-series production is nominally the same as the serial production on the line. However, it represents the design in the line to verify the production capacity in terms of resources, tools, space, etc., and the processes capabilities to achieve the expected takt time with the proper quality requirements. The number of physical builds in 0-series production generally depends on accelerating the learning curve and the ability to reach the target takt time.

0-series production is considered the most effective use case for DT based VF since the design and processes are more mature in this phase. Thus, DT based VF promises high value by enabling the Vestas experts *“to start up with the right sequence, the right staffing, right factory layout, and have a shorter time to market,”* (Int. 5) since the *“use and distribution of labour throughout the blade production is extremely time-consuming.”* (Int. 4). Accelerating the learning curve, which represents how to produce faster, is considered highly possible. One expert stated that reaching the actual takt time for a nacelle may take three to six months and added, *“VF would help to save 25% of the time of 0-series.”* (Int. 11). The criticality of this issue is that *"as soon as we get into 0-series and very short takt times, then we will notice (for example) the lack of crane capacity very quickly. The lead time for getting a new crane from the day we realise it – if we are very lucky – is four to six weeks. So that can be a very serious limiting factor. It is very valuable to see if the crane capacity is a limiting factor and it would be very useful to try out various scenarios in VF simulations*." (Int. 11). Thus, DT based VF is considered very useful *"to understand what the bottlenecks are to identify the risk of moving the paths or fixing the assembly sequences,"* (Int. 13), as well as *"lean optimisations on the operators."* (Int. 17).

5.5 Other Reflections

DT based VF is also considered for various capabilities besides simulating various prototype activities during NPI. The VR capabilities of the DT based VF were considered valuable for pre-training for large scale production roll-outs: *"what if we have a new factory starting up where 1000 people are in the organisation (facility). Then we can do pre-training before we actually put them out on the mould."* (Int. 17). Moreover, collaborative VR shows a sign of higher value for communication with suppliers, and it is considered very *"useful to have VF during technology transfer between factories."* (Int. 1). However, one expert argued that *"when implementing VR, we need to be very focused on who will use it, because not everyone can work with it and that requires change management – a change of mindset."* (Int. 11).

One interviewee also addressed the risk of a rapidly increasing volume of data that needs to be input to the models for achieving close-to-reality models and stressed the importance of DT technology (Int. 20). Another argued that *"Approximately every 6 to 10 years we have a new generation nacelle. In between these years, the designs are very similar, and of course, it is easy to create a digital twin. But if we are introducing a new generation nacelle, it is more difficult to have a digital twin of the production."* (Int. 1).

The possibility of disrupting the product development process based on the VF concept was discussed during the evaluation. Here it was mentioned that the development process follows a strict gate/tier process, where the product design is locked by the time it reaches production development. This means that tools and processes are not defined and might not be available. To reduce this issue, one expert stated that *"it would be beneficial if we went as soon as the design is finished or maybe even before that, when we have the model of the product, we could start simulating the process. Maybe we should change the way we look at it and start with the tools earlier."* (Int. 10).

It was also mentioned that the concept could provide safety benefits in that *"there are so many safety aspects within a nacelle building, a blade building, a tower where we could utilise the safety aspects in VF as well. Also, the system could capture if VR trainees had the right safety behaviour."* (Int. 17). This was further reinforced by the expert: *"I have seen examples (…) where workers did the safety training through the virtual reality headset. (…) They reduced from 32 days to seven or eight days by having virtual reality training sessions."* (Int. 17).

6 Discussion and Implications

The research work presented in this paper achieved the demonstration and evaluation of the DT based VF concept in the context of VP cases, particularly NPI processes. While the previous works evaluated the concept in terms of supporting the co-evolution of manufacturing enterprises, the present work focuses on the potential implications of the concept, particularly in the mock-up build, design prototype, process prototype and 0-series production processes, which are articulated based on expert comments. The expert comments provide valuable pieces of evidence and data on how and to what extent DT based VF can support complex manufacturing operations during the NPI processes.

Since the introduction of a new WTG into the renewable energy market is critical to compete for market share, reducing the time to market is considered strategically vital for WTG manufacturers. Therefore, there is significant pressure on coordinated engineering operations during NPI. However, the expert comments give signs that such pressure also creates significant quality problems later in the manufacturing operations and product performance. NPI engineers are simply aiming to mature their product, process, and system/organisation models from mock-up build to 0-series production. Physical prototypes provide better evidence and greater confidence to make decisions during the NPI process yet lead to significant time and cost issues. Thus, the majority of the experts assert that reducing the time to market should not be a performance indicator for utilising a solution like the DT based VF in early NPI, but instead reducing the number of issues/problems during the NPI operations. Moreover, the limitations on decreasing the physical prototype builds mean that taking this as a basis for fully eliminating physical prototypes in the near future is not realistic.

Since the bidirectional real-time data integration is inherent in the DT based VF concept, questions are raised on how to utilise the historical data of a digital twin technology for a fast-changing model. For example, the historical data of a DT could simply be irrelevant in a totally new production setup. Therefore, DT based VF is considered more valuable for later phases of NPI operations due to the larger volume of data and more mature models. Moreover, this may support the view that easy-to-use DES tools without advanced integration (with MES and PLM), and the DT capability could still be more valuable for early concept/idea simulations by enabling rapid iterations of lightweight model development and simulations.

Overall, the integration of multi-resolution simulations to represent a manufacturing system including its subsystems stands as the core capability of VF to handle evolving complexity. Such integration enables greater confidence in the impacts of major changes in overall operations from both the bottom-up and top-down approaches. Changing the WTG towers from steel to wood [49], for instance, could cause significant changes in material processing and thus the rest of operations assembly, transportation, etc. A dedicated simulation of wood processing (high resolution) could give reliable results to model and simulate the operations at the respective production line, factory, transportation, or installation (low resolution) level. Thus, the chain of reactions triggered by changes at various levels could be modelled and simulated to handle complexity in a flexible and agile way.

6.1 Limitations and Future Work

The work presented in this article covers only the demonstration and evaluation activities of the DSRM. The other DSRM activities, including the problem identification, definition of the objectives of the solution, design, and development activities, that were performed during the previous three years, were covered in previous studies. Thus, the reader should refer to those studies for more information to close the gap between the initial claim, which is the design and development of the DT based VF solution [11], [16], [17], and demonstration and evaluation.

Moreover, conducting a study to evaluate such a comprehensive solution in dynamic, social, and complex organisations carries the risk of internal validity confusions [50]. This is mainly rooted in the difficulty of isolating dynamic and complex manufacturing organisations that inherit a large number of interdependent variables. Such challenges limit us to performing experimental or quasi-experimental studies. Therefore, it should be kept in mind that the data in terms of articulating the capabilities of the solution and other interpretations provided by experts during the interviews are context-specific, relying on the demonstration.

It is observed that the participants were finding it hard to articulate the implications of DT based VF in high resolution manufacturing operations like specific machining, drilling, welding, and resin injection simulations. Therefore, increasing the scale of resolution in the DT based VF concept in future works could make it possible to capture more quantitative data and cases promising tangible value for the concept.

Moreover, due to increasing size and weight, together with regulation and localisation requirements in the wind energy market, more radical solutions like moveable/containerised factories or containerised WTGs are attracting attention. Therefore, implementing the DT based VF concept in a moveable factory concept while extending the simulations with transportation, on-site assembly operations, etc. to simulate the concurrent evolution of the product, process and system/organisation as well as its impact on the value chain, promises a significant potential.

7 Conclusion

This article addresses the need for thorough case evaluations of the DT based VF concept in the context of VP during NPI activities. DT based VF can enable the coordinated engineering of product and production lifecycle processes by enabling the integrated representation of product, process, and systems (organisation) models for designing, verifying, optimising and interacting with such models. Although the VF is not a brand-new concept, recent developments in state-of-the-art technologies like IoT, DT and VR and their integration into modelling and simulation tools are exploiting the potential of the VF concept exponentially. The majority of the studies on VF focus on either very specific cases and technologies or high-level conceptual work. Therefore, the present study aims to close the gap between theory and practice by exploring (1) the implications of the DT based VF in VP operations of WTG manufacturing and (2) the benefits that can be gained from industrial implementation of this concept.

The concept was demonstrated in the wind turbine blade and nacelle production facilities of Vestas and evaluated by industry experts during semi-structured group interviews. The results of the evaluation indicate that the DT based VF concept can have significant value in multiple phases of prototyping. However, the experts agree that the most value would be added in the later phases of product introduction, where this concept provides an integrated representation of the products, processes and system (factory) models. In these phases, the product design will be more mature, but the process is still at a preliminary stage. By providing the integration, the experts can discover design errors in the product and process without creating real-life prototypes. This works towards reducing the prototyping time and increasing the initial quality of the product and process. Finally, the experts address a need for an extension of the demo with more specific simulations focused on material design and behaviour (with higher resolution).

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Declarations

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

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

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

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Appendix: List of Interviewees

List of Expert Interviewees

Interview Date & Time	No	Interviewee Title	Years of experience	Department
18.03.2021 & 14:30	**1**	Industrialisation Lead	12	New Product Master (NPM)
	2	Manufacturing Intelligence	13	Blade Launch & Execution Centre (BLEC), Manufacturing Intelligence
	3	Manager	15	BLEC Blade Launch Team
	4	Continuous Improvement Specialist	15	BLEC, Continuous Improvement
	5	Industrialisation Lead	20	Manufacturing Readiness – Blade (BLA)
22.03.2021 & 10:00	**6**	Senior Specialist	19	Functional Excellence
	7	Senior Specialist, Performance & Execution	24	BLEC, Performance & Execution
	8	Design for Excellence-Lead Professional	11	Design for Manufacturing
	9	Lead Health, Safety, Environment Specialist	22	BLEC
	10	NPM Lead (Electrical)	12	Manufacturing Readiness – Assembly and Towers (ASSY/TOW)
23.03.2021 & 10:00	**11**	Specialist	11	Manufacturing Readiness - ASSY/TOW
	12	NPM Specialist	21	Manufacturing Readiness - BLA
	13	Specialist	13	Manufacturing Readiness - ASSY/TOW
	14	Design for Excellence Engineer	3	Design for Manufacturing
	15	Tooling Professional Quality Tools	15	Manufacturing Readiness - BLA
29.03.2021 & 14:00	**16**	NPM Lead (Blades)	14	Manufacturing Readiness - BLA
	17	Sr. Manager, Training & Global Transfer	10	Global Training & Knowledge Transfer
	18	NC Tech Continuous Improvement lead	13	Manufacturing Readiness - NC TECH
	19	NPM Lead (Towers)	13	Manufacturing Readiness - ASSY/TOW
	20	Specialist	21	Manufacturing Readiness - ASSY/TOW

Paper 4. Conceptual Foundations and Extension of Digital Twin Based Virtual Factory to Virtual Enterprise

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Conceptual Foundations and Extension of Digital Twin Based Virtual Factory to Virtual Enterprise

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Abstract

Manufacturing organisations must compete with each other while adapting to the ever-changing conditions by building and strengthening their chains of competencies to survive. Therefore, companies are challenged to reform and reconstruct their product, process and system models as well as to define new goals conforming to evolving complex and dynamic environments. Recent advancements in technologies such as modelling and simulation (M&S), digital twin (DT), and virtual reality (VR) promise new ways for remodelling organisations' resources, processes and architectures. Moreover, comprehensive concepts like DT based virtual factory (VF) exploit the potential for utilising such technological concepts in the application domain by enabling the integration of various tools, methods and processes. There are a variety of empirical studies focusing either on the distinct use of technologies, methods and processes or very generic concepts and approaches. However, studies focusing on both conceptual and practical aspects for such comprehensive and integrated solutions to handle co-evolution in the complex manufacturing domain are limited for defining, designing, and utilising novel technologies. In this paper, therefore, we attempt to close this gap by (1) framing and discussing the conceptual and theoretical foundations of DT based VF, (2) introducing and discussing the extension of the DT based VF to virtual enterprise and, (3) generalising and interpreting the prescriptive knowledge discovered during the previous VF demonstrations performed at Vestas Wind Systems A/S. Systems and complexity theories, concepts of business cycles, and competence-based strategic management are discussed to frame descriptive knowledge as a language for depicting the internal and external nature of complex manufacturing enterprise operations. Furthermore, design principles of the DT based VF concept are examined based on framed concepts and theories as well as its potential implications and deviations into different application contexts to provide managerial guidelines for utilising such a concept.

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

1. Introduction

Manufacturing industries are gradually challenged more radically by highly complex socio-political, economic and technological dynamics. These changes have immense impacts on the behaviours of manufacturing enterprises and, therefore, on the research priorities of scholars. Forces like innovation, changing demands, increasing competition, and new regulations can be considered among the external forces that forge the organisations' processes, products, and systems. The evolution of markets obliges manufacturing organisations to re-architect their models in product, process and system domains for more adaptive and flexible operations and organisations in order to stay competitive. Therefore, manufacturing organisations have to deal with coordinated evolution (co-evolution) of their models in product, process and system domains [1]. Thus, the term "co-evolution", as illustrated in Figure 1 Co-evolution Paradigm (Adopted from [1]), represents the challenge of generation and propagation of modifications/changes that initiate a multitude of unpredictable scenarios for dynamic manufacturing operations, which represents a major reason for complexity to be dealt with [1].

In order to deal with the co-evolution paradigm, various approaches took the attention of scholars. Product-oriented solutions such as modular product design are considered beneficial for rapid product evolution [2] and for managing complexity [3]. Moreover, modular product design approaches are considered advantageous for the strategic flexibility of organisations in answering to unpredictable futures [4]. Nevertheless, capabilities for modular product design and organisational strategic flexibilities demands integration of know-what, know-how, and know-why forms of knowledge [5] for design, management, and maintenance of models in the process and system domains. There are also various approaches studied by scholars, such as co-development, co-design, and concurrent engineering, that can help manufacturing organisations deal with co-evolution problems [6–8]. Therefore, synchronisation and concurrent engineering of product, process and system models in early modelling, design, and planning stages remain among the most relevant challenges for manufacturing enterprises [9].

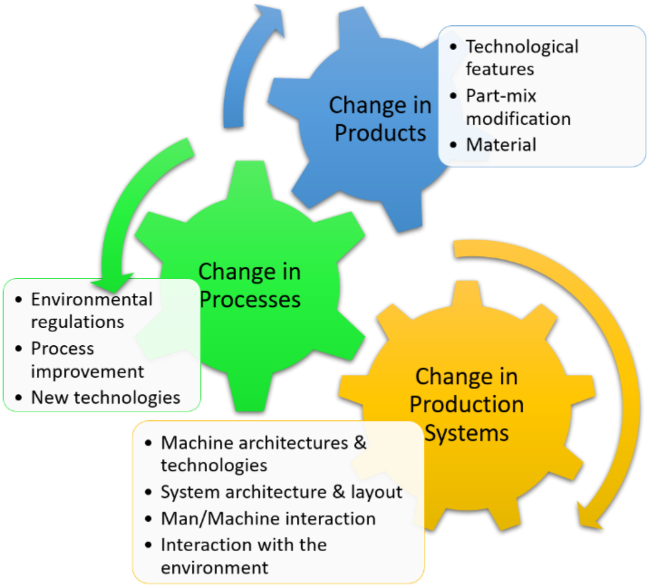

Figure 1 Co-evolution Paradigm (Adopted from [1])

Thus, there is a need for more integration of design, simulation, validation, management and maintenance of product and manufacturing system lifecycle processes which is also called the "era of enterprise integration" by some scholars [10]. However, ever-increasing complexity and ever-shortening lifecycles in product and production domains also challenge organisations while formalising and analysing processes and associated data structures. Therefore, the need for more precise "as-is" models of existing architecture and behaviours in order to invent, transform or modify more efficient "to-be" models are becoming vital to deal with co-evolution in complex manufacturing operations. Moreover, handling such evolution at the enterprise-level increase the importance of Enterprise Modelling (EM) for more effective strategic alignment to dynamic and complex environments. However, enterprise models should not be static models and need to reflect the changes occurring in reality [10]. But still, there is a need for more tangible and concrete artefacts demonstrated in real-life industrial cases to achieve such models.

Recent developments in state-of-the-art technologies like digital twin (DT), 3D modelling and simulations (M&S), and immersive virtual reality (VR) enable comprehensive and integrated solutions to develop and utilise "as-is" and "to-be" models of complex cyber-physical systems (CPS) [11, 12]. In recent years, therefore, empirical works on comprehensive concepts and approaches like VF gained more attention in the application domain. VF was initially introduced as a virtual manufacturing concept where product and factory models can be integrated [13], and later on, defined *"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"* [14]. Recent technological advancements and evolving approaches in developing and utilising VF tools provoked a reconsideration of its definition on the grounds of Hegel's motion regarding the definition and existence of concepts articulating *"things are what they are through the activity of the Concept that dwells in them and reveals itself in them"* [15]. Thus, Yildiz and Møller recently suggested a more inclusive definition for 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"*[16]. Subsequently, they enhanced the VF concept and introduced and demonstrated the DT based VF, which has the potential for more dynamic, open and holistic representations of complex manufacturing systems and operations in immersive virtual environments [17]. Empirical studies on DT based VF concept in industrial cases demonstrates that DT based VF stands out as a promising CPS to support manufacturing enterprises for handling co-evolution [18–20]. Moreover, DT based VFs has the potential to close various gaps regarding context-aware DTs addressed in recent studies, such as DT interoperability, adaptability, human interaction with DTs and real-time data processing for proactive decision making by enabling the integrated context information of the systems and dynamic model interaction [21].

Problem Statement and Objectives

In regards to adapting manufacturing enterprises to evolving conditions, various studies are focusing either the empirical and confined works concentrating on particular technologies or conceptual studies giving attention to a high level and comprehensive abstractions. However, a manufacturing organisation's capability to handle co-evolution is closely related to the market dynamics in which it is operating [22]. Moreover, "existing models for the implementation of digital twins are limited in isolated physics domains inside one enterprise", and "the development of digital twins for automating businesses towards supply chain integration is critical but in absence" [23].

Therefore, there is a need for (1) discussions and reflections on previously uncovered contextual knowledge that leads to new ways of understanding the proposed DT based VF concept, (2) adequate discussions on conceptual and theoretical foundations of comprehensive solutions based on both theoretical and empirical knowledge, and (3) for extending such concept to an enterprise-level for handling co-evolution based on more tangible artefacts and demonstrations.

Thus, the goal of this work is to close the abovementioned theory and practice gap to deal with the co-evolution of manufacturing enterprises in a better way by:

1) framing the conceptual foundations of DT based VF to support co-evolution of organisational systems,
2) proposing and discussing the extension of the DT based VF to virtual enterprise,
3) interpreting and generalising the previously discovered knowledge about DT based VF concept on providing managerial guidelines for utilising the concept.

Discussion in this article is built upon the previously published studies and, therefore, draws its conceptual and theoretical arguments on previous empirical studies conducted in the application domain [11, 12, 16–18, 24]. Although some conceptual and theoretical aspects presented and extensively discussed in this work pointed out in some of the previous studies, there were not well-framed and dedicated discussions on the subject goals.

Following the next section, which provides a vocabulary for further discussions, Section 3 frames and interprets the conceptual and theoretical foundations of the DT based VF concept. Section 4 presents the concept shortly before Section 5, which evaluates and discusses the concept based on four principles of competence-based strategic management concept. Section 6 examines the implementation of four types of changes in organisational architectures by utilising VF tools. Section 7 discusses the generalisation of discovered knowledge, limitations and future works before concluding in Section 8.

2. Vocabulary

Before articulating the concepts and theories on which DT based VF concept was built, we consider that defining and clarifying certain terms and their relationships can be valuable for articulating the nature of complex and evolving phenomena. We adopt a vocabulary to identify the context on which we are conducting our study as well as describe the relationships of the vocabulary [25]. Although we mostly adopt the terms in their current use in the literature, some scholars attributed various meanings to such terms, which resulted in confusion and inconsistencies. Therefore, we aim to provide an internally consistent vocabulary to discuss conceptual matters of the subject.

The terms enterprise, organisation, and firm are used synonymously in this work due to their similar characteristics in terms of openness to larger systems and strategic goal-seeking behaviours as social, natural and artificial systems. The factory, as an essential system of a manufacturing enterprise, contains social, natural and artificial systems and determines the scope of the previous empirical studies we conducted. A manufacturing enterprise is recognised as a system of assets and flows that are open to environmental systems and contains tangible assets such as machines, tools, buildings and intangible assets like knowledge, information capabilities. Capabilities signify repeatable actions which consume other tangible and intangible assets for pursuing specific goals. Goals can be described as a set of interrelated objectives like manufacturing products or semi-products which collectively drive the actions of a manufacturing enterprise. Moreover, goals give direction to a firm's competence leveraging and competence building activities. A manufacturing enterprise can accomplish competence when it maintains the coordinated arrangement of its assets to achieve its goals. Competence leveraging means utilising existing assets and capabilities in existing or new environmental conditions without qualitative adjustment. Competence building, however, means acquiring and using qualitatively different assets and capabilities to pursue goals. "A manufacturing enterprise links, coordinates, and manages various resources which are available, along with useful assets and capabilities, into

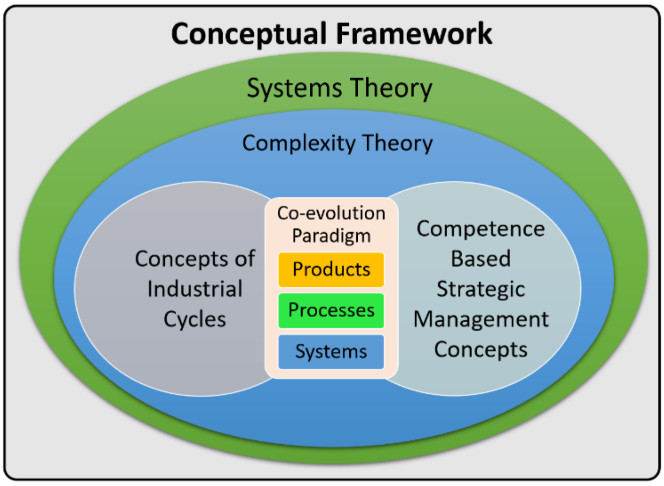

Figure 2 Conceptual Framework

a system to carry out goal-seeking activities. Coordinating and managing systemic interdependencies of internal and external resources of an enterprise may evolve alongside its competitive and cooperative interactions." [12].

DT based VF may, thus, be considered as a virtual twin of a goal-seeking open system that can be employed for competence building and leveraging to achieve strategic goals. The term "virtual twin" is intentionally preferred instead of the term DT due to the definitions of DT [26, 27] and VF [14, 20], as well as the main purpose of developing VFs. The main objective of developing DT based VF is not to achieve a perfect "as-is" model of a manufacturing system but to generate and propagate the changes/modifications in existing systems and processes to simulate unpredictable scenarios for dynamic manufacturing operations by utilising DTs of manufacturing entities. Thus, DT based VF can enable data-intensive simulations of existing organisations for creating and adopting new processes, technologies, and forms of strategies by enabling the predictive capability for complex scenarios. Before the discussion on how this can be achieved, there is a need for more discussions on the internal and external nature of complex manufacturing organisations, which is staged in the next section.

3. Conceptual and Theoretical Framework

This section examines some of the concepts and theoretical principles that can help enlarge our understanding of the internal and external nature of complex manufacturing organisations to provide descriptive knowledge as a language to describe design principles of DT based VF concept. Before diving into the concepts and theories, it could be valuable to put some words about the nature of the knowledge on which we are discussing.

The purpose of modelling enterprise systems, which is simply building forms like "as-is" and "to-be" models of real-world systems, aims at a change in a real-world context through measurable and specific objectives. The relationship between the act of forming "as-is" and "to-be" models of a complex organisation, which incorporates social, natural and artificial systems, echoes in aged discussions among philosophers about changing the world. Demand for a world change is listed in Theses on Feuerbach by Karl Marx as often quoted *"The philosophers have only interpreted the world (die Welt), in various ways; the point, however, is to change it."* [28]. Martin Heidegger argued, however, *"A change of the world presupposes a change of the conception of the world, which can only be established by an adequate interpretation of the world"* [29]. Although we are not trying to interpret and change the World (die Welt), but the environment (um Welt) one (consciousness) can experience. We can presume "as-is" models of a certain environment are the representations of the abstract reflections of a Cognition that relies on the Truth of such environment as its object. Although our cognitions are bounded by empirical and epistemological premises, an adequate conception of the environment can be established by extensive interpretations for facilitating further changes in such an environment. The purpose of addressing such notions is not to set sail to recondite discussions on the epistemic justification of phenomenal knowledge. But, instead, stressing the authors' standpoint that fear of falling into an error while interpreting the environment might reveal itself as a fear of the Truth. Therefore, we simply spare ourselves from prolonged epistemological discussions. But we would like to conclude that the essence of dialectical exercise on understanding and interpreting the evolving nature of complex manufacturing organisations presented in this study aim to affect both its knowledge (the Truth) and its object (the reality).

The theories that are investigated for describing the nature of the co-evolution problem, as well as concepts that are utilised to explore the problem, are framed and shown in Figure 2 Conceptual Framework. General System Theory provides some basic principles and concepts regarding the nature of systems, subsystems, dynamics of systems, parts and interrelations in general. Complexity Theory or complex systems theory reveals some particular propositions on evolving complexity of the social, natural and artificial structure of systems. For understanding the nature of co-evolution in the context of complex manufacturing organisations, there is a need to understand principles of industry evolution as well as the relationship between industry dynamics with internal domains of organisations, namely product, process, system domains. In this regard, the Concepts of Industrial Cycles, also known as principles of business genetics, implement the principles of evolutionary biology to the industries and provides relatively universal laws of evolution in the industries. Eventually, Competence-Based Strategic Management Concepts, also known as Competence Theory, incorporates the principles of systems theory and complexity theory and introduces organisation design concepts for strategic alignment to complex and dynamic environments. Both principles of business genetics and competence-based management concepts emphasise the three domains of manufacturing organisations, namely product, process, and systems, in different perspectives [30, 31]. Therefore, such theories and concepts provide the essential knowledge as a language and founding principles that are used to define and discuss the DT based VF concept for dealing with co-evolution problem as well as its extension to a virtual enterprise.

In this regard, the next section examines the General System Theory and the nature of integration and interaction of different parts and subsystems of a general system, as well as some basic concepts and principles of complexity theory.

3.1. System Theory and Complexity

An increase in disciplinary studies of modern science and knowledge is considered as one of the roots for problems of dynamic interaction, wholeness and organisation in various fields of science. Therefore, the need for a theory, not of a particular kind, but of universal models, principles, and laws applying to systems in general or their subclasses and the relations between their components has emerged [32]. Since early studies in the 1950s, there was a gradually increasing interest and recognition on the relationship between the General System Theory (later System Theory) and various subjects like biology, economics, and psychology. Parallel to this, developments in information theory and cybernetics were availed of principles, terms, and notions of system theory [33]. It is worth mentioning that extant discussions on shrinking disciplinary boundaries coupled with colliding epistemic worlds (academic and public) and led to the increasing call for interdisciplinary and transdisciplinary knowledge production [34].

System theory extended our understanding by formulating and articulating the differences between behaviours of parts and processes in isolation and behaviours of organisation and order unifying them [35]. A system can be defined 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 an independent effect on the whole, and (3) no subgroup of which can have an independent effect on the whole."* [36]. Therefore, the performance and the fundamental properties of a system is not determined by the separate behaviours of its parts but the interactions. Accordingly, a system is *"the product of the interaction of its parts"* [37] 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."* [38]. Over time, scholars identified the distinctions of three types of systems: mechanical, organismic, and social systems, and Ackoff depicted the concept of an enterprise in the context of each type of system [36].

Factories that incorporate social, natural and artificial systems are also embedded in larger systems such as industries, markets and nations. Therefore, when co-evolution is also taken into consideration, factories can be considered as highly complex systems of actively interacting problems. Although there are various approaches proposed to evaluate the complexity of a system [39], a complex system can be defined simply as *"a system made up of a large number of parts that interact in a nonsimple way"* [38]. A fundamental assumption of organisational theory and practice states, *"a certain level of predictability and order exists in the world"* and, thus, encourages simplifications for ordered circumstances [40]. When circumstances change more frequently than ever before and complexity increases, however, predictability decreases significantly. As a result, simplification and conventional management and leadership approaches increasingly start to fail [40, 41].

Therefore, as a complementary approach to analysis which is simply taking parts and processes in isolation, a synthesis which is considering systems and their parts as a whole is required to deal with problems in complex domains [36, 37]. Thus, *"the truth is the whole"* [42].

VF concept does not just enable the wholistic representation of a factory by integrating various simulations of subsystems and essential parts but also enables the integration of the VF platform with its environmental systems. Bearing in mind the recent developments in M&S technologies facilitates advanced digital integration of tools and data across the manufacturing lifecycles [43]. Moreover, whereas integrated DT capabilities allow the creation of more realistic and dynamic "as-is" models of complex organisations, VR capabilities enable the dynamic interaction with complex models in immersive environments [11, 44]. Due to diagnostics, advanced predictive and prescriptive analytics [45] capabilities of simulations, the DT based VF concept can support engineering and management of complex systems in reforming and reconstructing models in an adaptive virtual environment. Thus, the DT based VF concept promises for the analysis and synthesis approaches while redesigning a complex organisation, its subsystems or its environment [12]. Accordingly, the experimental mode of management, which is demanded by a complex domain [40], can be facilitated by the DT based VF concept.

General systems theory and complexity theory provide a basis for understanding and interpretation of "what" is the nature of complex organisations in general and thus how DT based VF can support organisations to handle complexities in evolving operations. The next section investigates some principles and concepts of industrial cycles and interprets the relationship between business environments as an external domain of complex manufacturing organisations in terms of the co-evolution paradigm.

3.2. Concepts of Industrial Cycles

Although different industries have their own dynamics to follow, there are some common laws and forces that can change the industrial cycles permanently. Since manufacturing enterprises are embedded in their respective industry with their supply chain, changes occurring in the industrial cycles are among the main forces that determine the survival matters for enterprises. Charles Fine implemented the principles of evolutionary biology to the industrial lifecycles in his book entitled "Clockspeed: winning industry control in the age of temporary advantage" and outlined relatively universal principles of industry evolution [46].

Just like different species have different lifespans, which are determined by the internal speed of living creatures' metabolism (clockspeed), different industries also have different cycles. For biologists, species like fruit fly is perfect candidates with 10 to 15 days of lifespan for observing and identifying general laws and principles to apply to all species. Similarly, at the spectrum of various industries, the electronic components industry, for example, inherits faster clockspeed with rapidly changing products and manufacturing processes. Industries like mining or automotive, however, follows relatively slow lifecycles [47].

Charles Fine's research enhanced our understanding and interpretations of the nature of evolution in the industries and revealed some laws that include: (1) there is no permanent domination for companies. All domination is temporary, (2) the faster the rhythm of evolution results in the shorter the reign of domination, (3) thus, the ultimate core advantage for the firms is the capability to adapt to evolving industrial environments [30], (4) the rhythm of change in the industries is determined by certain forces and their intensity.

Some of the major forces that shape the evolution of industries as well as internal dynamics of enterprises are identified as (1) technology and innovation, (2) level of competition, (3) regulations, and (4) demography [30, 48]. A significant outcome of the theory of industrial cycles is that the particular rhythm of evolution for each industry takes the place of three angles: product, process, organisation. Recent studies are also examined the concurrent evolution (co-evolution) of product, process and system models [1, 49]. Fine investigated the evolution of systems at a higher level by regarding the manufacturing organisation as a manufacturing supply-chain [50]. He also introduced the Double DNA Helix to illustrate the dynamic forces of supply-chain and proposed 3-dimensional concurrent engineering of the product, process and systems [30]. Tolio et al., however, concentrated factories as manufacturing systems and considered VF as a fundamental tool to handle co-evolution problem [51]. They considered VF as a prerequisite to handling co-evolution problem due to its capabilities for supporting the integration of different digital factory tools as well as the integrated use of various engineering methodologies. Thus, supply-chain systems can be considered as key interfaces between external domains of factories and their internal entities, operations and systems that form the co-evolution.

In so far, the systems theory, complexity theory and concepts of industrial cycles contribute to a basis on understanding “what” is the internal and external nature of co-evolution of complex manufacturing organisations. Nevertheless, there is a need for examination of other concepts to illustrate “how” to study a complex system which can adjust itself to dynamically changing conditions and circumstances. The next section will address such a need.

3.3. Competence-Based Strategic Management

Competence-Based Strategic Management concepts, also called Competence Theory [31, 41], incorporate the principles and concepts of system theory, complexity theory, and strategy theory while characterising organisations and their strategic and competitive actions in a more systemic, inclusive and dynamic way [25]. Competence-based management characterises organisations as complex systems embedded in evolving dynamics of industries as well as strategic goal-seeking behaviours of organisations as products of the interactions of interdepended entities of an organisation [52]. Thus, organisations are goal-seeking open systems that build and leverage their competencies by redesigning their capabilities, resources, and coordination for adapting to and competing in strategic environments. Strategic management of organisations is considered *“as a process of designing organisations as adaptive systems”* in competence theory by Sanchez [41]. Moreover, competence-based strategic management further provides relatively more consistent and feasible organisation design principles for management to sustain competencies [53]. Sanchez illustrates the analysis and synthesis activities of product and production design processes during the architectural transition of an organisation to meet the demands of its environment and suggests a principle of architectural isomorphism [31]. The principle of architectural isomorphism proposes that *“Maintaining effective strategic alignment of an organisation with its environment requires achieving isomorphism across a firm’s product, process, and organisation architectures.”* [31]. Sanchez also maps the four basic types of strategic environments and introduce four types of changes in organisations’ tangible and intangible assets which are characterised “as convergence, reconfiguration, absorptive integration, and architectural transformation.” [31]. We will discuss the forms of changes and how DT based VF can be utilised to support such changes in Section 6 in more detail. An essential aspect of competence theory for our study is that it reveals four cornerstones/dimensions to achieve strategic management of organisations based on an interplay of competence and complexity theories. These cornerstones, namely, dynamic, open, cognitive, holistic, provide a vocabulary to form a conceptual framework that describes how the co-evolution problem should be explored in the context of evolution and modelling of manufacturing enterprises [41]. We discussed each cornerstone and their elaboration on the DT based VF concept in Section 5.

We suggest that DT based VF can achieve four cornerstones and provide a useful solution to design, develop, analyse, simulate, and optimise four types of essential changes in system models to stimulate management thinking and the kinds of flexibility and reconfigurability [12, 17]. Therefore, an essential premise for the discussions in this paper is that DT based VF can assist the co-evolution of complex manufacturing organisations by achieving isomorphism across product, process, and organisation architectures for maintaining effective strategic alignment with their environments.

Competence theory is developed at a high level of abstractions. Thus, it is applicable for any type of organisational processes, including manufacturing organisations. Nevertheless, to the best of our knowledge, the DT based VF research, on which this work was built upon, is one of a kind that attempts to apply the abstractions of competence theory onto a particular manufacturing system context and extends its implications further to broader enterprise-level [12]. In this regard, the next section presents the previously introduced DT based VF concept and its extension to the enterprise level.

4. Digital Twin based Virtual Factory Concept

This section summarises the VF concept history as well as an extension of its implications and role with the utilisation of state-of-the-art technologies to provide more clear foundations for further discussions.

4.1. Product and Production Lifecycle Processes Rendezvous

During the 1990s, VF was described in various ways, including emulation facility, virtual organisation and integrated simulations [13, 14]. Since then, the VF concept was considered for various purposes such as simulation and optimisation [54], system design and modelling [55], production line control [56], sustainability and reconfigurability of factories [57]. Therefore, the concept conveyed its prominence until the present day.

Yildiz and Møller [16] reformed the VF concept by building on the artefacts proposed in previous studies [14, 58] with an effort to distinguish product, process and system (factory) domains and by illustrating its position with regards to product and production lifecycle processes as seen in Figure 3 Digital Twin Based Virtual Factory Concept [17]. Yildiz, Møller and Bilberg further extended the concept and its empirical models with DT and collaborative VR capabilities together with a more inclusive definition [11, 17, 24]. They demonstrated the bi-directional real-time data synchronisation between shopfloor and VF simulations to enable the creation of DTs in VF simulations while utilising interactive VR training in the same models [19].

The separation of product, process and system domains can extend the recognition of the association between each domain as well as an architectural isomorphism of a manufacturing organisation. In other words, VF simulations can provide an integrated virtual environment to incorporate product and manufacturing architectures as well as a rendezvous for product and production lifecycle processes. It is also considered valuable to identify the functional relationship between VF and product development and production execution systems, especially when there is an uneven level of digitalisation. Bidirectional data integration between execution and engineering systems such as product lifecycle management (PLM), enterprise resource planning (ERP), and manufacturing execution system (MES) demonstrated the creation, relation, and manipulation of DTs in comprehensive virtual models as well as control of actual systems via DT simulations. Thus, DT based VF enabled the facilitation of CPSs. Moreover, the DT based VF concept enables extended virtual environments by the integration of various levels and resolutions of simulations that facilitates the alignment

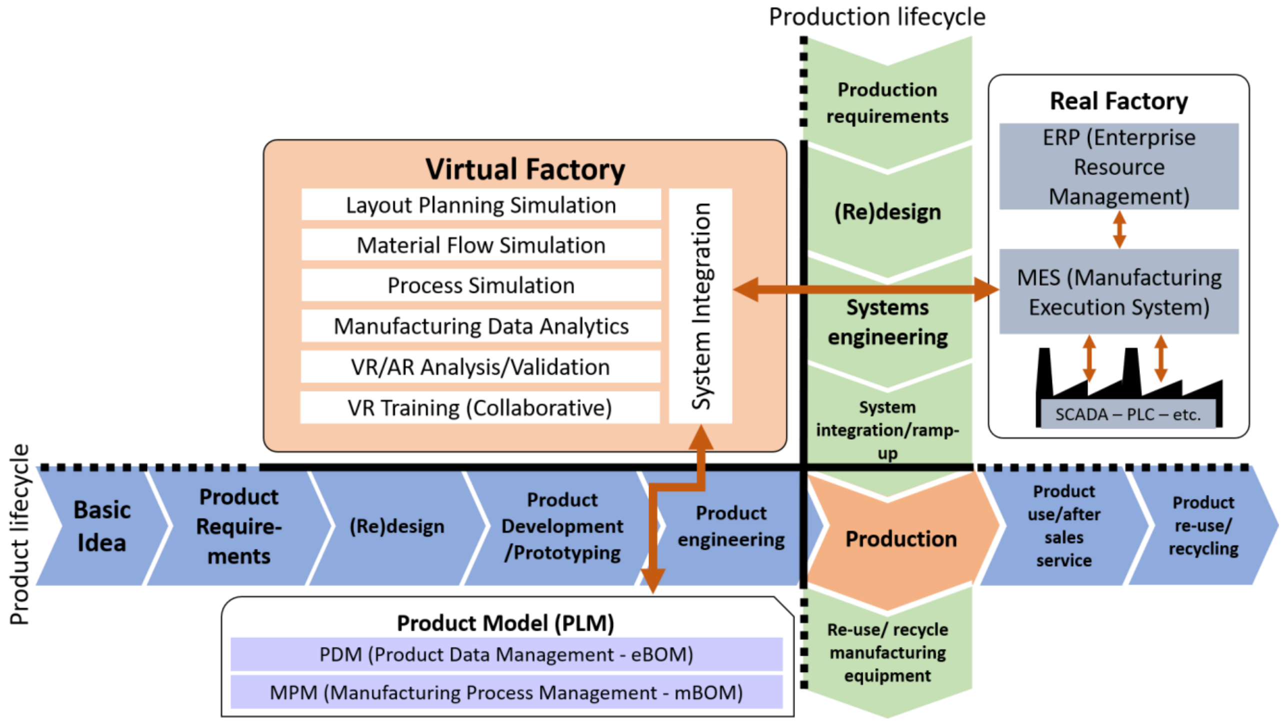

Figure 3 Digital Twin Based Virtual Factory Concept [17]

between product, process and system domains. Together with collaborative VR capabilities, integration of various models, resources, capabilities and processes can provide embedded coordination capability and thus concurrent engineering [17].

While the various level of simulations enables modelling different level of details (multi-resolution) of a system, distinct interfaces such as functional, resource, coordination and governance can be formed and simulated for achieving competence building. Integration between the different resolutions of simulations can facilitate importing objectives and targets from lover resolution, including a line or factory simulation to higher resolution, such as welding or physics simulation, as well as operating states from low resolution to higher resolution. Thus, various changes in simulation models can be reflected in different levels of simulations to test various discrete flexibility or what-if scenarios.

Since the capabilities of the VF platform depend on employed tools, technologies, as well as needs, depending on specific industrial contexts, we do not intend to extend the discussion of penetrating details of the interrelation of tools. However, our endeavours for representing complex manufacturing operations wholistically by integrated simulations led to demand for the extension of the concept to enterprise-level simulations.

4.2. Extension of DT based VF to Virtual Enterprise

It is not a trivial matter to construct the sophisticated inclusion of the supply chain into product development, manufacturing system development, and production execution. Changes that occur both in the product, process and system domain in a manufacturing enterprise calls for a series of coordinated manufacturing operations that require the involvement of a group of manufacturers and suppliers. Although the M&S, DTs, VR technologies enable superior capabilities, the existing implementation of such capabilities is limited in isolated internal domains of one enterprise. Therefore, integration of DT based VF to supply chain models for supporting coordinated evolution of product, process and system models is critical. Such integration can enable DTs integration with supply chains and thus adaptation for holistic optimisation of the manufacturing lifecycles [23].

Figure 4 Virtual Factory Simulations Architecture extended with Supply Chain (Adapted from [12]) illustrates an example of integrated VF simulations architecture extended with the supply chain for a manufacturing enterprise. Different levels and kinds of simulations promise a holistic representation of factories as well as corresponding subsystems of factories. It should be kept in mind that the VF concept can further be extended to particular operations of the value chain out of the factory context by integrating simulation models of diverse

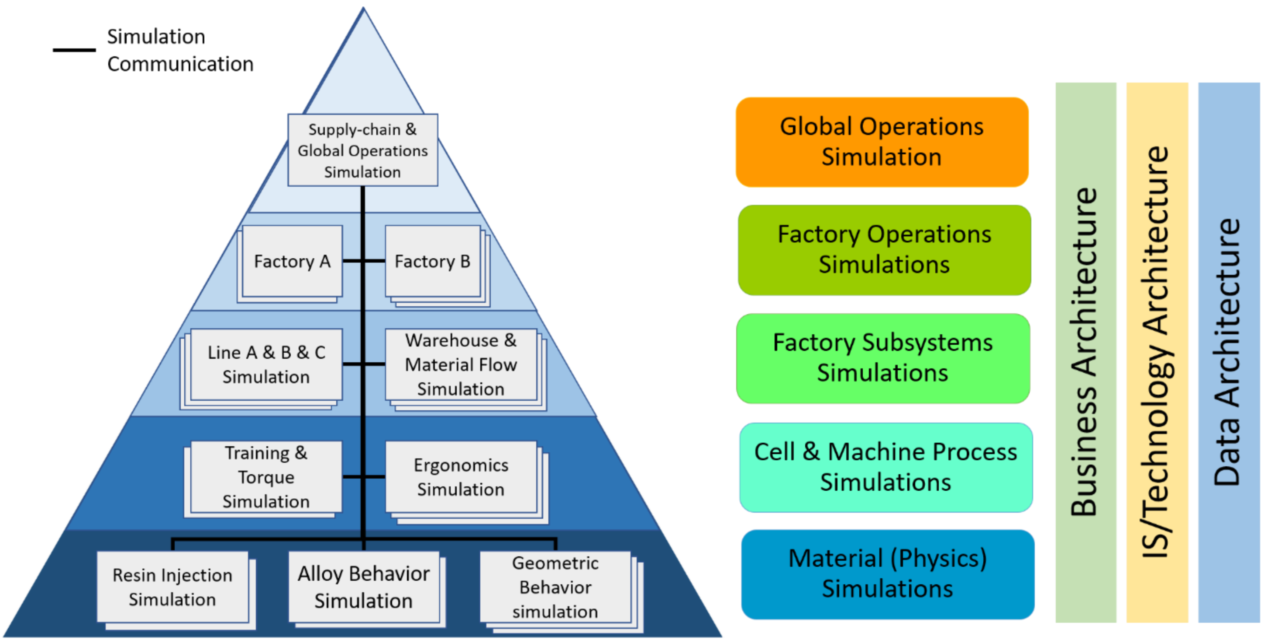

Figure 4 Virtual Factory Simulations Architecture extended with Supply Chain (Adapted from [12])

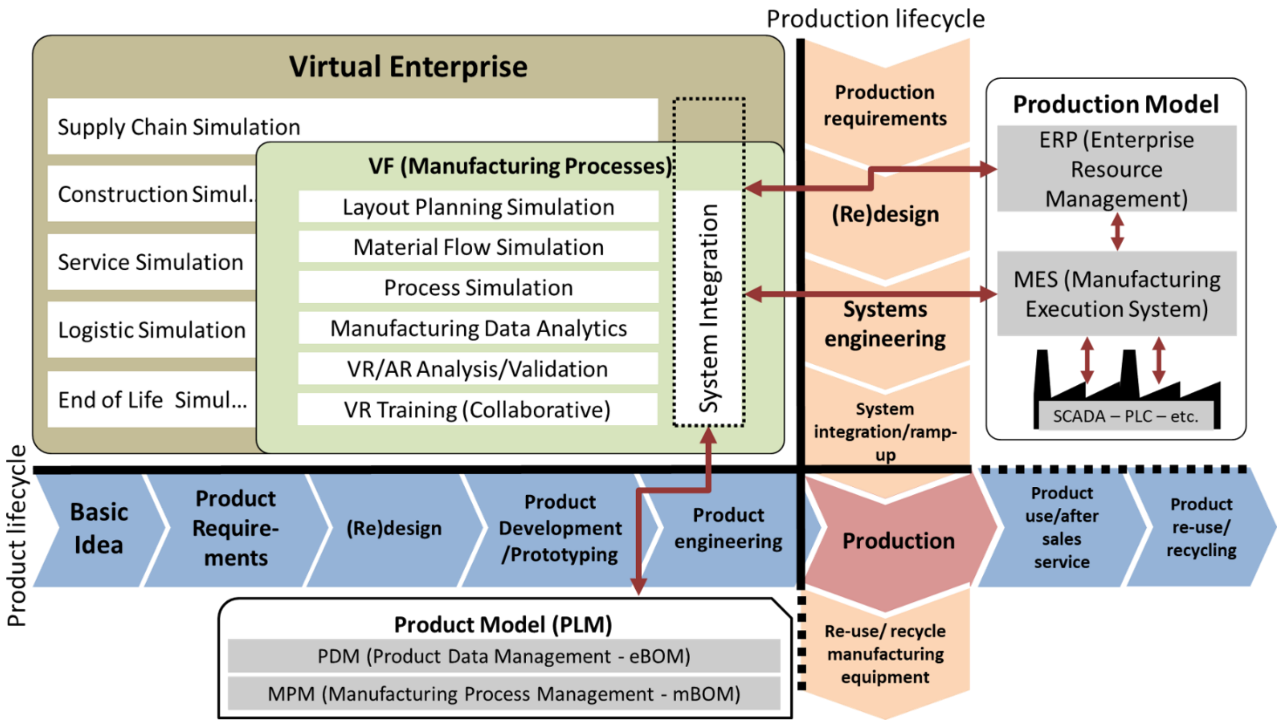

Figure 5 Virtual Enterprise Concept extended from DT based VF

operations. Transportation, logistic, supply chain, service and maintenance and end of life operations, for example, can be integrated into DT based VF as shown in Figure 5 Virtual Enterprise Concept extended from DT based VF. Since the supply chain domain can be considered as an interface between manufacturing enterprises and external industry players, integration of the supply chain system can also support enterprise-level co-evolution based on external dynamics.

There are various purposes and scopes for enterprise architecture [59], but we can define enterprise modelling as *"as the art of externalising knowledge in the form of models about the structure, functionality, behaviour, organisation, management, operations and maintenance of whole or part of an enterprise, or of an enterprise network, as well as the relationships with its environment"* [10]. As a comprehensive model, the DT based VF concept can respond to the need for disseminating the information from manufacturing operations to the whole organisation level. Moreover, VF can also respond to the demand for organisational learning at the enterprise level, which is addressed by Nardello et al. [60]. For each functional component (activity) of a manufacturing enterprise, several models can be designed and simulated for the purpose of experimenting flexibilities. Such capabilities can support strategic decision-making processes for enterprise management. This could be valuable, especially during architectural transformation in dynamic environments, for not only identifying the requirements for existing resources and capabilities but also identifying the capabilities and resources for imagined future environments and scenarios.

Previous studies showed a significant potential for utilising DT based VF concept to enable concurrent engineering, time-saving, virtual collaboration and virtual prototyping in manufacturing operations [17]. Above mentioned discussions and capabilities address that DT based VF concept can be utilised for creating abstractions of enterprise structures, capabilities, governance, etc., in various levels and purposes to deal with complexities and co-evolution. Dynamic, holistic and open system representation of real-world enterprise operations in DT based VF tools can decrease the cognitive load of complex models and support extracting new values from core operations data [61].

Real-time data integration and collaborative VR capabilities of simulation tools enable the dynamic and immersive representation of complex operations as well as interaction with the models in VR environments and the discrete implementation of capabilities, which can be simulated in subsystems or in different resolutions. A public media showing previous demonstrations of DT based VF concept performed in industrial cases as a part of the subject study can be accessed on [62].

In the next section, the DT based VF concept will be discussed in detail based on four cornerstones of the competence-based strategic management concept to provide more grounding arguments on how organisations can build and leverage their competencies for adapting to strategic environments.

5. Four Cornerstones of Competence-Based Strategic Management

5.1. Dynamic System

Sanchez addressed that the need for dynamic representation of a system originates from the gradually increasing frequency of changes occurring in both internal and external domains of organisations in terms of resources, demands, constraints, technologies and infrastructures [41]. Co-evolution of product, process and system models create an increasing pressure on enterprises to adjust their competitive capabilities for adapting to evolving complex environments and conditions. In addition to this, real-life manufacturing processes take place where the product models meet with the system models in a dynamic and complex fashion. However, the legacy engineering tools represents such manufacturing operations in various kinds of static models by isolating the operations into various layers. Moreover, the increasing complexity of operations causes an increase in cognitive loads and calls for more dynamic models. Therefore, the dynamic complexity of the internal and external domain of manufacturing enterprises decreases the predictability of intended changes, their implications and consequences. This challenge is clearly addressed by an industry expert in the following sentence; *"I can see how the system will look like with the current tools, but I cannot see how it will work"* [17]. Thus, to be able to respond to the evolving needs, opportunities and problems in the future, resources, capabilities and processes of manufacturing organisations, as well as their environments, should be represented dynamic way as it is in reality.

DT based VF as a virtual twin of an actual system has the potential to represent operations in actual systems by achieving the isomorphism across a manufacturing enterprise's product, process and organisation architectures. Therefore, it can be capable of simulating and thus performing necessary changes in resources and capabilities dynamically to respond to future changes to stay competitive. In other words, parallel future scenarios can be modelled, simulated and manipulated for highly complex operations by using actual production data, product models as well as constraints of the real world. Real-time data can facilitate realistic representations of actual operations, resources and models as well as changes in such models and operations. Embedded data analytics functions of simulation tools can support the real-time decision, responses and even control of actual systems [63]. Previous demonstrations show that DT based VF can import manufacturing execution parameters of a manufacturing line, for instance, from MES and product models corresponding to such line from PLM in real-time and simulate the operations dynamically according to changes in the real world [18, 19].

5.2. Open System

Characterisation of open-systems is originated from the embedded nature of organisations [41]. Every system is embedded in some environmental systems. Manufacturing organisations, for example, are embedded in nations, industries and markets, from which they obtain resources like materials, skills, imagination, etc., while supplying outputs like products, semi-products, services, etc., to their environmental systems. Such a concept can be applied to subsystems of highly complex manufacturing enterprises including, factories, assembly lines or machines. Therefore, each system needs to access a changing array of critical inputs from its environmental systems while providing competitive outputs to survive. However, the co-evolution of both internal and external domains of manufacturing organisations requires designing systems to be open to robust and flexible connections with their environments. Thus, organisations are challenged for designing open systems comprising dynamic and complex interdependencies to be able to access and organise changing arrays of inputs and outputs.

DT capability of VF tools facilitates the creation, simulation and manipulation of not just internal but also external entities of such complex systems. Integration with ERP or digital platforms of other organisations can facilitate realistic reflections of changing array of inputs from environmental systems to internal domains of organisations. A real-time weather forecast or traffic data, for instance, can be imported and utilised to determine certain simulation parameters in case it has an impact on operations. Recent advancements in the Internet of Things and the Internet of Industrial Things have the potential to facilitate more efficient and effective context-specific real-time data from real-world entities increasingly. Moreover, as previously mentioned, an extension of the VF concept by integrating simulations of environmental systems such as logistics, labour market, maintenance and service can enable the creation and simulation of changing arrays of inputs. Therefore, DT based VF can be considered as a virtual representation of real-life dynamic and open systems which can be embedded into environmental systems and establish new connections with its environment. Thus, the DT based VF concept can support the strategic management of manufacturing organisations to achieve robust open systems for strategic flexibility.

5.3. Cognitive System

Need for the cognitive system dimension of competence theory emerge from the essential need for sense-making given the evolving dynamism and complexity of enterprises' internal and external environment [41]. Managerial cognition is a fundamental requirement for identifying resources, processes and competencies as well as their contextual essence for sustainable competitive advantage [64]. As a result of co-evolution, however, increasing dynamism and evolving complexity of internal and external domains of manufacturing organisations constitutes a growing challenge for articulating new logics to enhance adaptive capabilities. Therefore, organisations and their corresponding digital/virtual models need to be cognitive (easy to make sense of) to support managerial cognition.

The architectural isomorphism between product, process and system models promise for increasing contextual knowledge of DT based VF models. Moreover, integration of simulation tools between horizontally and vertically diverse operations of an enterprise can enable synthesis as a complementary activity to analysis. Partly due to dynamic representation along with 3D, DT, and VR capabilities of simulation tools, DT based VF can support cognitive system representation. Embedded immersive VR capabilities of simulation tools together with collaborative (multi-user) VR and interaction with the simulation models promise for decreasing cognitive loads of complex models during communication [17]. Moreover, utilising DTs in VF simulation increase the precision, accuracy and reliability of models as well as the feeling of responsibility and seriousness to finish the tasks in VR training in the VF simulations [11]. Therefore, the DT based VF concept stands out with its potential for enhanced capabilities for sense-making dynamic models to support enterprise imagination and managerial cognition for designing and simulating a new set of resources and capabilities.

5.4. Holistic System

Sanchez states that the emergence of demand for holistic system view is required for effectively operating organisations as adaptive open systems [41]. In addition to that, basic principles of systems theory which defines systems as the product of the interaction of their parts, entail a holistic view due to the determination of essential properties and performance of a system by interdependencies of its parts. As articulated by the principles of the system theory, *"If each part of a system, considered separately, is made to operate as efficiently as possible, the system as a whole will not operate as effectively as possible"* [37]. Therefore, there is a need for enterprise management to mediate various interdependencies among organisations' internal and external resources and capabilities for the implementation of systematic changes in complex and evolving open systems. In short, a holistic view becomes essential to understand how everything works together and to predict the consequences of changes in highly complex and dynamic environments.

Since earlier studies, the VF concept has been defined and built upon the integration of various simulations considering the factory as a whole, including its subsystems [16]. Thus, the DT based VF concept facilitates the holistic and dynamic representation of actual complex manufacturing systems. Advancements in co-

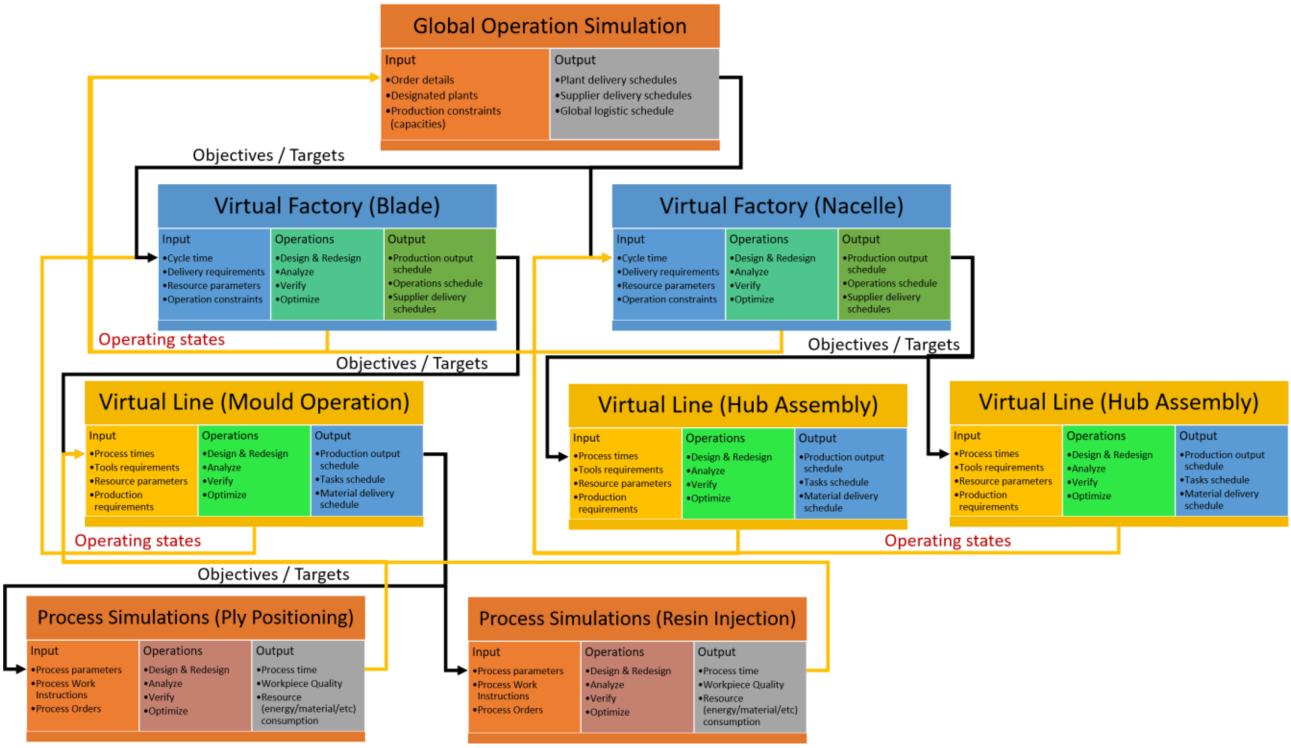

Figure 6 Integrated Simulations Example

simulation capabilities also support M&S of various levels and kinds of internal and external changes of a manufacturing system in a more realistic way. Figure 6 Integrated Simulations Example shows a relatively simplified example of integrated simulations representing a wind turbine manufacturing organisation. Simulation models can share operating states from higher-resolution simulations to lower resolution or objectives and targets from a lower resolution to higher resolution simulations. Thus, changing production requirements from higher-level (low resolution) simulations, for example, can be reflected in a lower level (high resolution) simulation. Moreover, vertically integrated processes, for example, assembly, material handling, and warehouse, can be integrated and represented simultaneously and holistically. When acknowledging the DT capabilities and data integration across the whole value chain [43], DT based VF can support the creation of a virtual environment in which all entities of a complex system can be developed, related and manipulated.

Thus, the dynamic, open, cognitive and holistic nature of internal and external environments of manufacturing organisations can be modelled and simulated in DT based VF tools to reduce the impact of dynamic complexity and uncertainty. Architectural isomorphism can also be achieved while maintaining quasi-stable adaptation to evolving complex environments. Therefore, processes and operations in a complex system can be analysed for sense-making in an evolving environment for modelling and cultivating new internal resources and capabilities, for approaching new external resources, for determining new organisational goals, and for reorganising available resources and capabilities to deal with co-evolution. In this regard, various forms of changes in organisation architecture utilising the concept will be elaborated on the next section.

6. Forms of Changes in Enterprise Architecture

In order to adapt to ever-changing environments and respond to competitive pressures, organisations need to do more than perform their existing tasks. Organisations need to manage changes in their resources, capabilities as well as coordination of their processes. Four types of architectural changes, namely convergence, reconfiguration, absorptive integration, and architectural transformation, are determined for organisations to respond to competitive dynamics as depicted in Figure 7 Types of Changes in an Enterprise's Architecture [31].

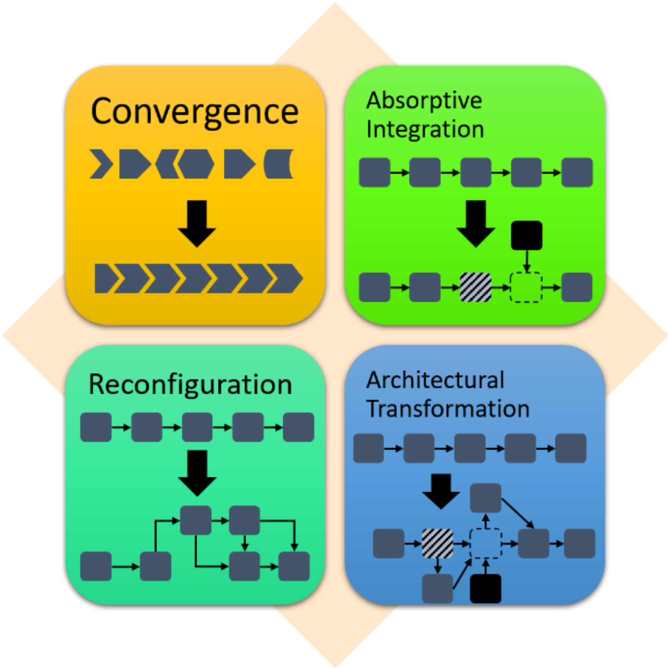

Figure 7 Types of Changes in an Enterprise's Architecture [31]

These forms of changes demand combinations of various flexibilities such as "operating flexibility, resource flexibility, coordination flexibility, and two forms of (managerial) cognitive flexibility" [31]. In the following, the DT based VF concept is discussed in terms of supporting such changes, respectively.

6.1. *Convergence*

Convergence represents incremental improvements to organisations' existing resources and capabilities within a current product, process and system architectures [65]. Therefore, such change focuses on continuous improvements in the efficiency and performance of existing operations.

DT based VF concept, which is built upon multi-level integrated simulation concept, is studied for multidisciplinary and multi-fidelity analysis and optimisation of manufacturing systems and showed its potential for optimisation and efficiency for production systems [66, 67]. DT capabilities and bidirectional data integration also promise real-time analysis, design and planning for unexpected changes in resources and capabilities. Previous demonstrations of the concept show significant pieces of evidence that DT based VF tools can optimise the operations of a manufacturing organisation not just holistically but also respond to the changes occurring in the actual factories in real-time [19]. Therefore, organisations can simulate various firm-specific operating flexibility scenarios, which are critical for improving and maintaining robustness to respond to competitive pressures of their environment.

6.2. *Reconfiguration*

Reconfiguration implies re-arranging the existing functions, resources, and capabilities as well as relationships to develop a new architecture for enhanced or different performance characteristics [31]. Thus, it involves changes in interactions in existing operations such as production processes by redesigning workflows, material flows, or information flows.

Reconfiguring existing resources and operations in VF tools facilitates concurrent engineering of product, process and system architectures by supporting product and production lifecycle processes. Moreover, reconfiguration can be performed in various resolution levels such as production line, factory or enterprise levels. Due to DT capabilities, entities in DT based VF tools can represent not just real-time states of their physical counterparts but also historical data. Thus, organisations can simulate and test resource and coordination flexibilities in terms of identifying, acquiring, accessing or reconfiguring resources and capabilities in various ways.

6.3. *Absorptive Integration*

Absorptive integration represents the integration of new or significantly modified functions, resources or processes into an organisation's existing architecture [4, 31]. Thus, this type of change involves integrating a new type of external resources and functions to an existing organisation to support organisations co-evolution.

DT based VF demonstrations (Fig. 6) performed in the Vestas manufacturing cases covers the integration of VR interactive training scenarios as part of a virtual twin of existing manufacturing lines. While all operations were developed as a DT of their actual counterparts in the production line, a single operation is modified as a mixed production line and assigned to perform by a VR trainee. Thus, a new type of operation is absorbed into the existing manufacturing operations to train labours and observe the impact of change on whole assembly line operations [17, 24]. Therefore, the DT based VF concept showed significant capabilities to support organisation managers for cognitive and coordination flexibilities to identify new opportunities and integrate new capabilities into existing architectures.

6.4. Architectural Transformation

Architectural transformation covers radical innovations by creating new functions, processes and resources as well as interrelating such components in new ways within an organisation's architecture [31]. Architectural transformation can be driven by rapid changes like disruptive technologies within limited opportunities and time. Designing organisation architectures to support frequent changes in processes, resources, goals for maintaining strategic effectiveness are considered the reason for "upheaval" in traditional organisation designs [65].

Since DT based VF concept is shown capable of supporting reconfiguration and absorptive integration, they can be considered to support architectural transformation. Moreover, enabling process rendezvous for product and production lifecycle processes and supporting architectural isomorphism, DT based VF can facilitate an efficient and effective digital platform to evaluate and validate radical changes in existing architectures. Therefore, significant demand for cognitive flexibilities, which are required to create new value creation processes for managers, can be supported by utilising DT based VF concept.

7. Discussion

DT based VF concept is developed and demonstrated in the scope of factory or more specific industrial cases like assembly and production line operations. However, since the concept of a factory relies on social, natural and artificial systems, the VF concept showed significant potential to be extended to the enterprise level. Therefore, the authors used the terms organisation, enterprise, firm, and factory as abstractions of complex, dynamic and open social sociocultural, techno-economic systems. In this regard, the concept is framed and discussed based on four types of architectural changes to provide prescriptive knowledge as managerial guidelines for utilising the DT based VF concept to deal with the co-evolution paradigm in dynamic and complex environments.

Besides, the concept discussed in this study could be used in various development lifecycles (design, development, testing, implementation, maintenance, planning, analysis) of diverse systems depending on the value promising or criticality for each industry. While the clockspeed (speed of evolution) in a certain industry is high, the utility and effectiveness of DT based VF could be higher for more comprehensive what-if scenarios; it could be more valuable for optimisation, maintenance, and analysis for lower clockspeed industries.

The knowledge discovered in previous studies on DT based VF concept [11, 18–20], which is conducted in various industrial cases, provided shreds of evidence and foundation for the arguments presented in this paper. Therefore, we build upon the previous empirical knowledge by framing and discussing the DT based VF concept based on four dimensions of competence theory to achieve adaptive, dynamic, cognitive and holistic systems. Relying on the empirical studies, we hereby attempt to frame and discuss the conceptual and theoretical foundations of the DT based VF concept and its extension to a virtual enterprise. In other words, knowledge generated by exploring the empirical context with more serendipity and latitude is employed for the situational groundedness of theoretical abstractions and concepts.

Thus, in this study, we have attempted to fulfil the so-called duality criterion of case studies, which is (1) situationally grounded (empirically disciplined and comply with contextual idiosyncrasies), and (2) a sense of generality (broader theoretical understanding through abstractions) [68]. Therefore, this article's contribution can be positioned as theory elaboration by a reconciliation of the particular with the general.

Moreover, there is a need for further empirical studies for extending the VF concept by integrating digital tools to represent enterprise operations, resources and architectures out of manufacturing context. Integration of supply chain platforms, as well as modelling and simulation capabilities to DT based VF, can extend the potential of the concept and enable new use cases for industry experts. Therefore, future research activities will be dedicated to extending the knowledge with inbound and outbound supply chain simulations as well as their design, development and demonstration in industrial cases.

Integration of environmental systems enables real-time reflections of the changing reality in a virtual model, and therefore, more agile and rapid responses can be employed. Further improvements in simulation tools by implementing AI algorithms can open up new horizons for organisational learning, efficiency, and optimisation for highly complex scenarios. Therefore, further improvements in the VF concept such as embedding artificial intelligence, machine learning or more comprehensive optimisation algorithms for supporting managerial decisions can be considered in future studies.

8. Conclusion

The concurrent evolution and changing complex dynamics of markets and industries require faster adaptation for manufacturing organisations to survive in highly competitive environments. Although various technological concepts are promising a value to support enterprises during their adaptation, the value of such technologies increases exponentially when they are integrated into a more comprehensive concept/solution. DT based VF factory can be considered among comprehensive concepts to exploit the value of individual technological concepts by enabling the integration of various tools, methods and processes as well as architectural isomorphism across an organisation. Previous studies conducted in industrial cases demonstrate the DT based VF concept on exploring its value and potential for the manufacturing engineering field. In this paper, however, we have attempted to frame and discuss the conceptual and theoretical foundations of the DT based VF concept to articulate design principles of such a comprehensive concept as well as its extension to the virtual enterprise. Building upon that, we tried to frame and discuss the prescriptive knowledge discovered in previous demonstrations to generalise contextual knowledge and to provide managerial guidelines for utilising the DT based VF concept to handle concurrent evolution of product, process and system architectures. Thus, the paper aims to close the gap between theory and practice by providing a theoretical grounding for artefacts tested in various empirical studies as well as conceptualising the prescriptive knowledge discovered during the previous industrial demonstrations.

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Conflict of interest

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Availability of Data and Materials

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

Consent to Publish

The participants provided informed consent for the 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.

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Paper 5. Designing Collaborative and Coordinated Virtual Reality Training Integrated with Virtual and Physical Factories

Designing Collaborative and Coordinated Virtual Reality Training Integrated with Virtual and Physical Factories

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***Abstract*—Rapidly changing customer demands, regulations and technologies drive the complexity of products, processes and production systems, as well as shorter product and factory lifecycles. In order to handle such complexity while decreasing the time-to-market, immersive virtual reality (VR) technologies are increasingly being used in industry to support product and factory lifecycle engineering processes, such as (re)design, validation and verification, learning and training. However, the design and development of multi-user VR training for complex and manual production processes remain a challenge for industry. The integration of VR training simulations with virtual and physical factories could support the handling of such obstacles in terms of efficiency and effectiveness by increasing the precision, accuracy and reliability of data used in VR simulations. In this study, we present a collaborative and coordinated VR training model and its data integration with virtual factory tools and manufacturing execution systems for a wind turbine assembly scenario. A demonstration has been performed and evaluated by industry experts. The preliminary evaluation results show that integrated collaborative VR training has significant potential for more efficient and effective training, as well as enabling new use cases for industry.**

Keywords—Virtual Reality, Virtual Factory, Collaborative Virtual Reality Training, Virtual Reality Simulation

I. INTRODUCTION

The design of a new production process and the corresponding assembly training is a complex and time-consuming process. Moreover, rapidly changing customer demands cause increased complexity in product and production systems, as well as a decrease in product and production lifecycles. The foundations of the industry 4.0 paradigm comprise increasing integration of all the production agents (people, machines and resources) in the form of cyber-physical systems and increasing decentralisation of production processes [1]. Therefore, researchers and industry experts are focusing on virtual factory (VF) tools as an integrated high-fidelity simulation in order to handle the concurrent evolution of product, process and production systems [2], [3]. In this regard, industry 4.0 recommends the adoption of a series of technologies known as the nine pillars of technological advancements [4], including the comprehensive simulation of processes, horizontal and vertical integration of systems, and virtual and augmented reality (VR/AR).

VR is used in various ways, including product and process design, training, remote collaboration and communication in different industries [5]. Using a virtual environment for learning and training is a safer and more cost-effective method, especially for dangerous tasks and training with expensive physical builds [6]. VR training is also essential for knowledge management, especially in distributed and manual collaborative assemblies. Collaborative virtual environments provide advantages for interpersonal coordination for the feasibility of transferring the simulation outcomes to the real world [6]. However, the design and development of sophisticated VR training is challenging and requires serious time and effort. Integrating VR training to virtual and real factory environments with bidirectional data synchronisation, as well as utilising technologies like discrete event simulation, 3D laser scanning and a digital twin, could support the design, development and use of immersive VR training simulations. Environmental simulations, for example, can be generated by discrete event simulations to understand CAD objects interacting with the surrounding environment, which can be created quite realistically by using 3D terrestrial laser scanning technology and objects in the VR simulations can be linked to their physical counterpart for more realistic representations. Such an integration concept can enable entirely new use cases. Data integration of VR training with product and production systems can increase the precision, accuracy, reliability of training and efficiency of the design and development of such training. However, there is a need for proper conceptual models, architectures and methods for the integration and evaluation of such artefacts in real-life cases. Thus, this makes the question of how to utilise such new technologies to improve the design, development and use of collaborative and coordinated VR training a relevant research topic.

Decreasing the time-to-market by utilising VR training to improve learning curves, especially for the ramp-up phase, can be considered as the primary motivation for industry.

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Decreasing physical builds for training can also be considered another significant cost saving and motivation in the wind turbine manufacturing industry. Manufacturing Execution System (MES) provides an interface to the actual physical production by capturing and recording "as-built" data regarding the actual/physical transformation of raw materials on the shop floor (e.g. processes, materials, personnel, machines and support services) in real time. Ongoing research activities at the case company, Vestas Wind Systems A/S (Later Vestas), in the context of industry 4.0, including VF, digital twins and 3D laser scanning, provide an opportunity for the development and demonstration of a multi-user VR training integration with physical (MES) and virtual production systems (VF). Thus, a collaborative and coordinated VR training demo is designed, developed and integrated for physical and VF systems for wind turbine manufacturing scenario of Vestas.

The need to reduce the time-to-market remains an essential challenge, while the complexity of product and production processes is increasing. Improvements in the hardware and software of VR systems enable the use of immersive VR for learning and training simulations to reduce the ramp-up time. However, despite the sophisticated interplay of the technologies used, VR is not a turnkey solution yet. Designing and developing a multi-user complex VR training and sustaining the precision and reliability of the data used in the simulation remain difficult and costly processes.

The identified problems can be listed as:

- The difficulty for utilising VR for complex (collaborative and coordinated) manual assembly training;
- Low precision, accuracy and reliability of data used in VR training;
- Low efficiency of VR training (re)design.

Bidirectional data integration of VR simulation with a VF, which is considered as a potential solution to integrate product, process and factory domains [7], and MES can support solving the problems above. A VF demo, which was developed for the earlier phases of the research work, provides an opportunity for designing, developing and demonstrating a solution.

The work presented in this study aims to support manufacturing companies in utilising immersive VR technologies for complex multi-user learning and training simulations integrated with virtual and physical factory systems. The objective of this work is to explore artefacts (models, methods and procedures) to solve the abovementioned problems. In particular, the objectives of the work can be listed as follows:

- Designing and developing a multi-user VR training simulation concept for a collaborative and coordinated manual assembly operation scenario;
- Designing and developing a bidirectional automated data integration concept between VR training, virtual and physical production systems;
- Demonstrating the design in a real-life case for enhancing the data-centric model-based VR training simulation.

The rest of this study is organised as follows. The second section presents a review of the relevant works in the literature. The third section presents the conceptual model of integrated collaborative VR training and its data integration and implementation. The fourth section covers the case study development, demonstration and evaluation. The fifth and sixth sections contain the discussion and conclusion, respectively.

II. Related Work

In 1965, Ivan Sutherland envisioned "The Ultimate Display", which conveys information not only to the eyes, but to the ears, hands, nose and mouth [8]. Sutherland set the stage for VR research by stating that: ''The Ultimate Display would, of course, be a room within which the computer can control the existence of matter.'' [8]. However, it took almost 30 years to see VR technology in industry and academia [9]. In the mid-1990s, VR was not mature enough but was still investigated because of its potential by companies including Caterpillar, Chrysler, Boeing and NASA, as well as some academic institutions. Just a couple of years later, there was a remarkable adoption of VR in industry for real-work applications [10]. In the following years, research contributions within the VR knowledge base have been exploited both by industrial and academic communities.

VR is generally described as "a set of technologies that enable people to immersively experience a world beyond reality" [11]. Since the 1990s, VR has been adopted by various industries to serve different needs, including concept design, develop and evaluation [5], learning and training for high-risk procedures [12], experiencing virtual spaces before building physical ones [13] and the visualisation of abstract data [14]. VR is also used to support manufacturing simulations to overcome the complexity of generating various modelling and simulation methods by providing better user interfaces [15]. The use of VR technology for the training and design of product, process and production systems has built up over time. Recent improvements in simulation tools provide an easy-to-use 3D simulation environment together with the capability of VR [16].

Several promising works have used VR in a training and manufacturing context. Al-Ahmari et al. [17], for example, developed a virtual manufacturing assembly simulation system (VMASS) to support training operations for assembly operations. Abidi et al. [18] extended the VMASS study by evaluating VR assembly training in terms of the effectiveness and transfer of training. Their study showed that VR training decreases the actual assembly time and error rate compared with traditional training and provides a risk- and injury-free training environment. A training system based on VR and process mining was developed and evaluated by Roldán et al. and the results showed that the system has competitive advantages over traditional systems [19]. A comprehensive literature review was conducted by Feng et al. [20] to understand the developments and implementation of immersive VR in a serious game approach in the context of an emergency evacuation. They proposed a conceptual framework for the effective design and implementation of immersive VR-based serious games. An interactive and immersive VR training system to simulate human-robot cooperation for educational serious game purposes was presented by Elias, Dimitrios and George-Christopher, with the results showing positive prospects for the use of VR in human-robot collaboration training [21].

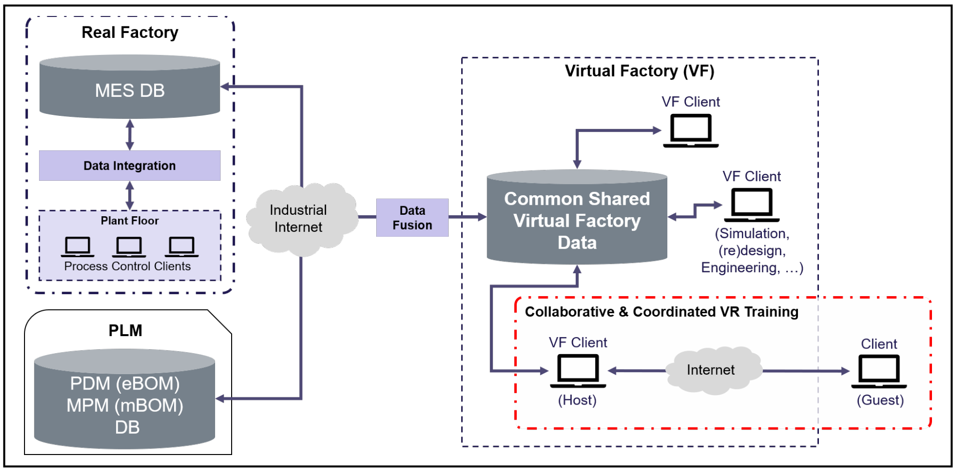

Figure 1 Data integration architecture

Some reviews have focused both on the knowledge base and application contexts, showing the benefits and gaps in the VR training subject. Menin, Torchelsen and Nedel [6] reviewed 63 articles to better understand the impact of VR technology on immersive simulations with serious purposes, to present a taxonomy to VR simulations and to discuss whether methods and participant profiles affect results. Research shows that participants can influence the result of the experiments based on their video gaming experience. Participants who have video game experiences have positive performance in the completion time of the VR training simulation, but such experience does not influence the understanding of the manufacturing operation [22]. Berg and Vance conducted an industry survey covering on-site visits with 18 companies and interviews with 62 people from various companies and disciplines to present the current state-of-the-art of VR, particularly in engineering-focused businesses [11]. They stress that the recent developments in affordable VR hardware and software have increased the potential and strategic importance of VR for investigating questions regarding visibility, ergonomics, quality, data visualisation and communication. They also address several challenges including: 1) the need for environmental simulations that help to understand CAD objects interacting with the surrounding environment; 2) difficulties for model generation in terms of adding colour, texture, kinematic interaction and material properties [11]. Mourtzis, Doukas and Bernidaki [23] investigated the evolution and recent developments of simulation technologies in industry, as well as addressing the gap in the use of VR and computer-aided manufacturing systems for collaboration and communication.

The abovementioned research works show that VR technology has already proved its value in design, evaluation, validation and training. However, there are still challenges in terms of designing and simulating interactive VR environments. The VF, as an integrated simulation environment, provides an opportunity to design and simulate the model in the context of factory, product and process domains. Integrating VR training with virtual and physical factory systems may contribute to handling the challenges addressed above. In this regard, the proposal of a collaborative and integrated VR training system is presented in the next section.

III. Proposal for a Collaborative and Integrated VR Training System

A. *Design Science Research Methodology*

Since the abovementioned problems and objectives call for a design-oriented information system (IS) research approach by targeting the iterative construction, implementation and evaluation of artefacts, DSRM is considered the relevant methodology, incorporating situational adaptations of the artefacts, as well as covering the broad problem scope [24]. Design science in an IS seeks for the creation of innovations or artefacts that represent the ideas, technical capabilities, actions and products required to achieve the design, implementation, analysis and use of information systems. Thus, "design science research (DSR) is research that creates this type of missing knowledge using design, analysis, reflection and abstraction." [25]. DSR is ideal in contributing to the knowledge domain and application context of digital innovation because DSR focuses on both the design and deployment of its innovative artefacts [26]. Artefacts of DSR evolve through numerous design and evaluation cycles [27], and they are introduced to the problem space when they are mature enough to contribute with prescriptive knowledge. The research activity presented in this study also requires iterative design, implementation and evaluation cycles to achieve defined

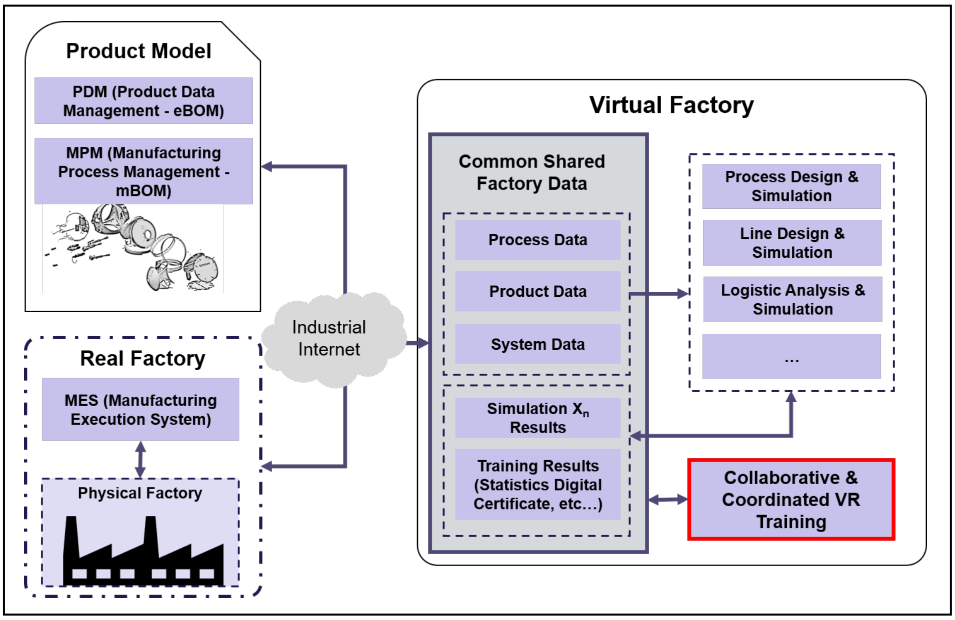

Figure 2. Virtual Factory model extended with collaborative Virtual Reality training.

objectives. Therefore, DSRM is chosen as a primary methodology for this research.

B. Extended Virtual Factory Architecture for Data Synchronisation

A VF, as a high fidelity integrated simulation environment [3], represents a factory as a whole. The VF is also considered as a prerequisite to handling management and concurrent evolution of product, process and production systems [7]. Learning and training are also two of the critical activities in managing changes/evolution in product, process and system domains, mainly to tackle a learning curve and long time-to-market problems. Simultaneous generation of models in these domains becoming more related to designing and developing relevant training in the context of digitalisation. Changes in product models require (re)design of the associated production processes. Such processes generally define the requirements for the corresponding learning/training. The statistical results of learning can be useful for the design and planning of production systems. An increase in the complexity of models created for these activities makes bidirectional data integration significant for efficiency. Thus, it is considered that the integrating VR training to VF architecture, which is also integrated to physical production environment via MES can enable real-time data acquisition in VR training, as well as supporting the simultaneous engineering of models in VF tools.

Integrating physical devices and environments with virtual environments has been tackled by a number of different works [28]. Figure 1 shows the data integration architecture of VF including multi-user VR simulation. The details of the architecture are not disclosed to protect the interests of the industrial stakeholder. Nevertheless, there is no conflict of interest to disclose the number of works for better understanding the integration architectures of physical experimental devices into virtual environments. MIT's iLab Project [29] is focusing the integration of remote experiments and simulations into virtual environments. A remote lab is developed by University of Deusto based on a 3D-based virtual environment Second Life [30] to control remote experiments. An approach for the communication between physical devices and virtual environments was developed by Stevens Institute of Technology [31] and a pilot virtual laboratory system was implemented for remote experiment [28]. An architecture that integrates a number of robotic platforms in immersive virtual environments was presented recently in [32]. The above-mentioned works present integration architectures of VR with physical settings that are examined for the subject in hand.

Figure 2 shows the VF architecture extended with multi-user VR training simulation. VF system is connected to the MES database and updating the real production data at particular time intervals, which can be set as seconds. Different VF design/simulation tools can import process, product, and production data and/or output data from other design/simulation tools. VR training simulation is designed to import the data from a common shared data repository automatically. The architecture also allows for designing and developing Digital Twin (DT) of physical entities on the shop floor.

A suitable VR training, VF and MES data integration model as a proof-of-concept is decided together with shop floor workers and developers. Details of the integration design are presented in the next section.

C. Virtual Reality Training and Virtual and Real Factory Data Integration Model

The data integration between VF, MES and VR training simulation is shown in Figure 3. VR training simulation and VF line simulation both are connected to MES, which provides real-time shop floor operation data and common shared factory data repository, which stores data from other VF design and simulation tools. This integration can enable the use of data in multiple simulation tools and multiple times. Extension of this integration of simulation tools for multidisciplinary analysis and optimisation of manufacturing

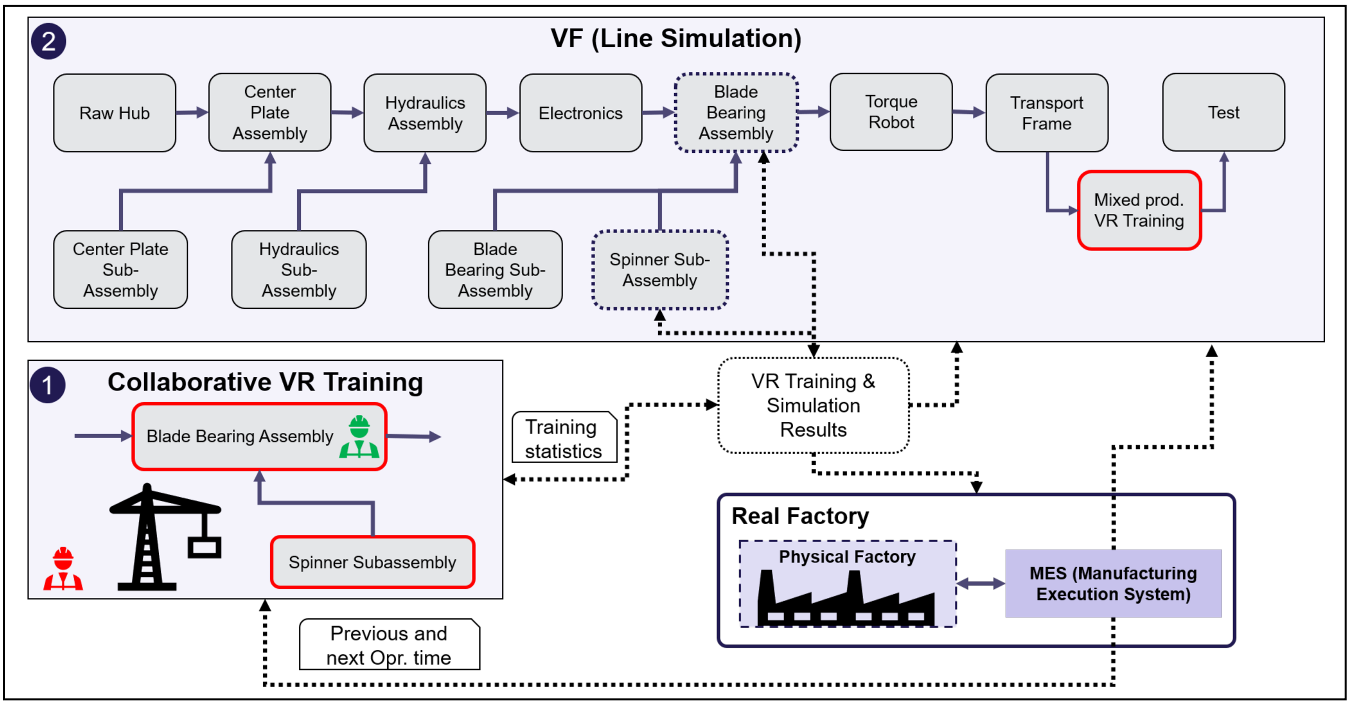

Figure 3. Virtual Reality training, Virtual Factory and Manufacturing Execution System data integration model.

systems and its potentials for optimisation and efficiency is also addressed by Delbrugger et al. [33].

IV. Case Study – Collaborative and Coordinated Training Scenario

The definition of collaborative work is often cited in the literature to be that of Karl Marx "multiple individuals working together in a planned way in the same production process or in different but connected production processes" [34] while coordination is defined as the "management of dependencies among independent activities" [35]. Collaboration virtualisation theory [36], containing three categories of constructs that affect collaboration virtualisability, namely, team, task and technology, was utilised during the design of the scenario. Figure 4 shows the concept of collaboration and coordination work scenarios.

A manual assembly scenario that requires a collaboration of two workers in one task with coordination of one worker between two tasks was suggested by the shop floor workers of Vestas for the design and development of the demo. Figure 5 shows the training scenario of multi-user VR training for blade bearing (BB) assembly operation. The VR training simulation imports the historical operation data directly from the MES and shows the average operation time in the VR training environment (Figure 6). This operation time allows trainees to know whether their performance causes a block or hunger in the assembly line. The operation starts by moving BB to the hub for assembly by a crane operator who has a fixed location in a VR environment. The crane operator is needed to be guided by the assembly operator who can have a better visual of moving parts. When the BB is located, the assembly operator fixes the BB with the first bolt. After the first bolt is assembled, the crane is free to support spinner assembly operation. The crane operator should coordinate his or her time until the assembly operator finishes installing the bolts. As soon as installing the bolts task finishes and the hub is turned for the new BB, the cycle starts from the beginning and repeats three times in total. When all tasks are finished, the training simulation extracts the total training time data to be used in other VF tools and MES. Development and

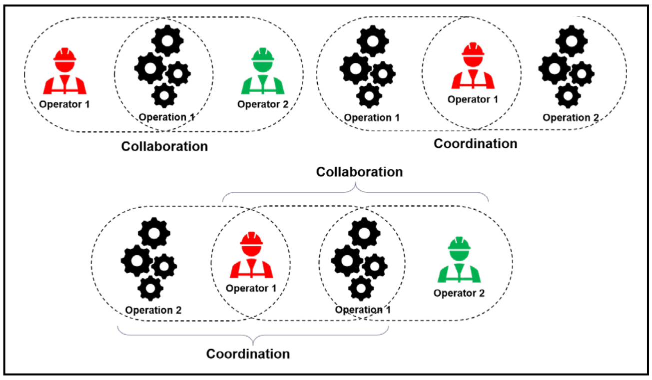

Figure 4 Collaboration and coordination concept

demonstration of the designed system are presented in the next section.

A. Development

The CAD models of the product parts were exported from the product data management system and processed by Creo software to simplify the models. A Unity 3d™ game engine was used for the compilation of assembly, rendering, physics, and simulation of multi-user VR training. Photon Unity networking packages were used to enable multiplayer by integrating multiple builds in runtime. These packages allow us to develop and use flexible, scalable and real-time VR simulations/games just by connecting to the internet. Two immersive head-mounted devices supporting head tracking are used to fully exploit the tracking, navigation and immersion capabilities of the VR training system. SQL server and management tools were used for data integration between MES and VF simulations. In order to connect the industrial internet, one of the PCs provided by the case company with required networking and encryption tools was used.

B. Demonstration

The first version of the multi-user VR training simulation was demonstrated to six industry experts who have more than five years' experience and two scholars at the MASSIVE

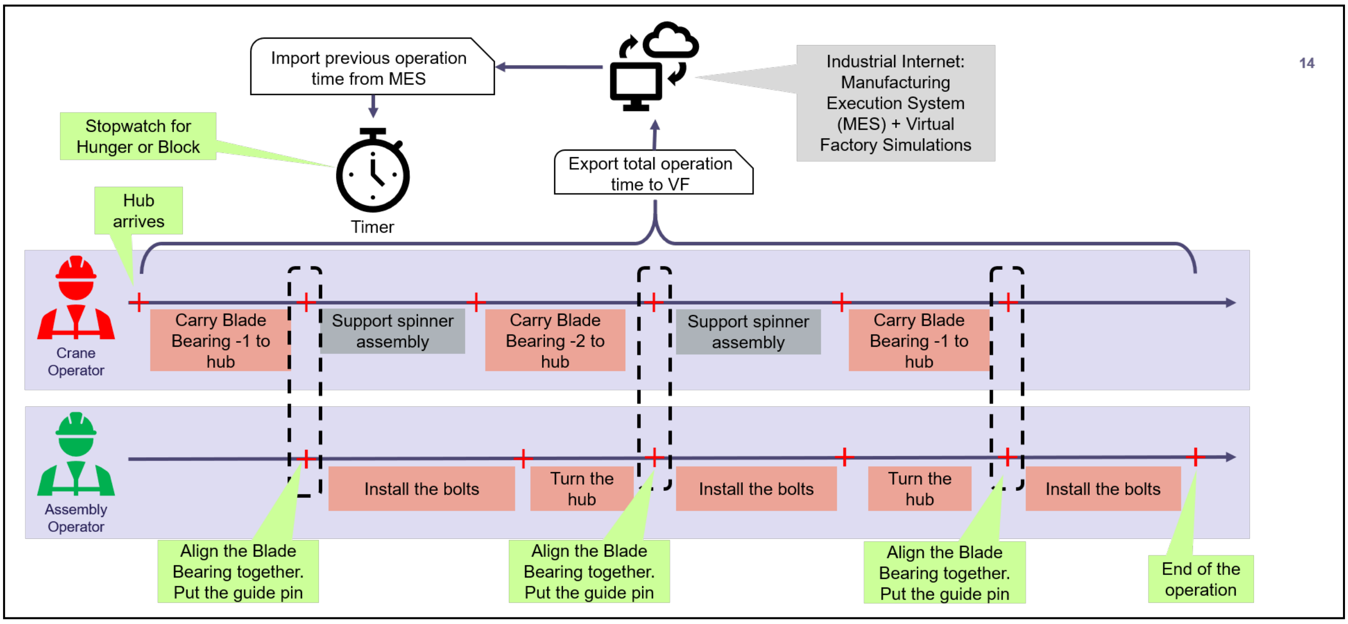

Figure 5. Collaborative and coordinated VR training scenario.

Virtual Reality Laboratory of INESC TEC. The scenario and the system architecture were explained to the industry experts. The VR training simulation requires subjects to individually perform the training that is required to collaborate in a virtual environment while sharing the same physical environment (Figure 6). Training performance data was extracted and used in the line simulation together with the data from the physical production system.

Several demonstrations are planned to be performed at different manufacturing plants of the case company. The objectives of the first demonstration which is presented here are to present the research work to the senior experts from the industry and to enable the evaluation of the design, development and implementation of the artefacts presented in this study. Experts evaluated the demonstration with unstructured interviews.

Figure 6. Collaborative and coordinated VR training demonstration.

C. Evaluation

The objectives of the preliminary evaluation of the demonstration are to understand the potential value of the proposed architecture and approach in terms of solving the problems presented above and to explore the high value promising use cases for integrated multi-user VR training simulation for the industry. The outcomes of the first evaluation are also expected to contribute to the design of forthcoming, developments and more comprehensive evaluation scenarios.

A vice president, a senior director of manufacturing systems, two senior specialists and two expert engineers were among the participants who evaluate the proposed VR training system.

The development work of the VR training was performed in five working days by two experienced developers. Establishing data integration between the VR training system, MES and VF system is achieved in 4 h by one IT expert. During the data integration process for a particular product model used in the VR simulation, MES did not return any results to the SQL query run by the VR training simulation because of the recent production changes in the shop floor. As a result of this, developers had to update the product type based on physical production operations. This unexpected incident showed that the integrated design of the VR training supports the reliability and accuracy of the data used in the VR simulation.

Unstructured interviews performed with the industry experts and their subjective evaluations based on personal experiences, comments and ideas are grouped and summarised below based on defined problems:

- The difficulty for utilising VR for complex (collaborative and coordinated) manual assembly training.

"Photon Unity network packages make multi-user VR development and use a lot easier than we expected."

"While local content production projects are increasing, being able to provide multi-user VR training simulation for users from different production plants can enable more effortless knowledge transfer and support serious cost savings."

- Low precision, accuracy and reliability of data used in VR training.

"Knowing that real operation times utilised in the VR training increase the feeling of seriousness and responsibility to finish the task on time as well as the precision, accuracy and reliability of the VR environment and the scenario."

"We have all actual task/operation times in MES at present. We intend to use VR training for critical new tasks and we will be able to extract training times and send back to MES and/or VF tools with bidirectional data integration. Such data integration enables our engineers to make comprehensive time studies (planned/training/actual time) more effectively and efficiently during the earlier phases of product introduction processes such as product or process design."

"Data integrated VR training can be more effective and valuable, especially for more data-intensive learning and training scenarios such as circuit board assembly."

- Low efficiency of VR training (re)design.

"Creating a common shared data repository and integrating it with VF tools and MES can provide structured and updated data during the design/redesign and development of VR training. This can enable developing and utilising DTs in VR training, and virtual objects in VR training can be adjusted according to their physical counterpart."

"Integration of VR training with VF tools is promising for decreasing the design and development time not just for VR training but also product, process and production systems."

V. Discussion

VR technology has already been adopted by industry and proved its value in design, evaluation and training. Multi-user VR training is promising for expansion for their utilisation areas in industry. Integrating VR training with virtual and physical production systems enables more efficient and effective data utilisation among these systems.

Preliminary discussions with industry experts on an integrated collaborative VR system show that its value lies in the ability to explore possible future horizons. Data integration enables new use cases such as time studies and DT-based VR training, and it also brings the need for more comprehensive evaluations for specific use cases. Such integration could support modular VR training system development in the future.

The approach presented in this study can be used for similar collaborative and coordinated training design and developments in industry. This study also contributes to the VF concept by extending the VF architecture with real-time data synchronisation and multi-user VR training simulation. Research work presented in this work also provides insights regarding industry expectations in relation to a proposed collaborative and integrated VF training system.

Precision and reliability of data collection on the shop floor were out of the scope during the work presented in this study. The number of experts from the industry was limited because of time and geographical limitations. Demonstration of a VR training system to a higher number of industry experts from different manufacturing plants and more comprehensive evaluations are needed. Further demonstrations and evaluations are in progress.

VI. Conclusion

The increase in the complexity of product and production lifecycles and the need for shorter lifecycles requires more and more integrated design, development and the use of technological advancements in industry. VR technology, as one such technological advancement, has a more significant role in supporting the processes of such lifecycles. However, there are some problems related to the utilisation of VR in industry. We present an integrated design and development approach to utilise VR with physical and virtual factory systems and a demonstration.

Early results of the research work show that this approach is promising more efficient and effective development and use of VR in the context of collaborative and coordinated manual assembly training simulation.

More comprehensive demonstrations and evaluation of the VR training together with VF tools in specific product and production lifecycle processes will be performed for the future works. A more conceptualised integration model is also needed. VF data model such as [37] and its applicability for real-life cases should also be investigated.

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Disclaimer

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

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Paper 6. Virtual Factory: Digital Twin Based Integrated Factory Simulations

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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.

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.

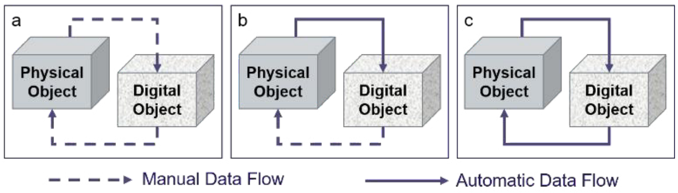

Fig. 1 Data flow in (a) Digital Model, (b) Digital Shadow, and (c) Digital Twin [23].

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.

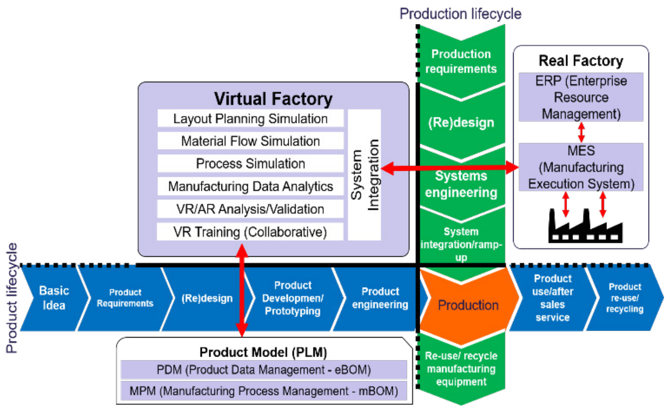

Fig. 2 Digital twin based virtual factory concept [5].

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

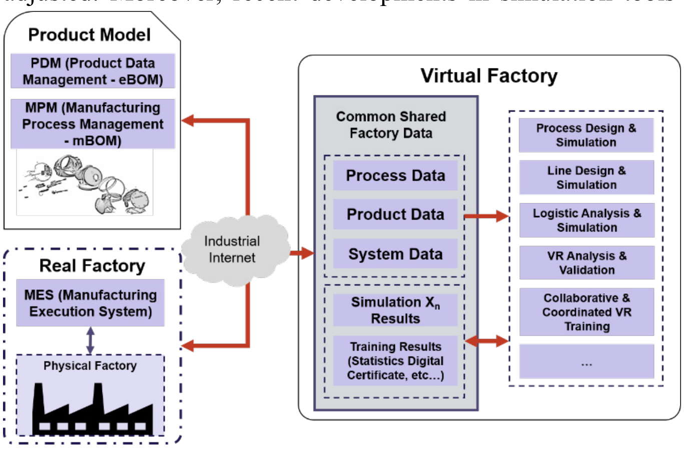

Fig. 3 VF data integration architecture.

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.

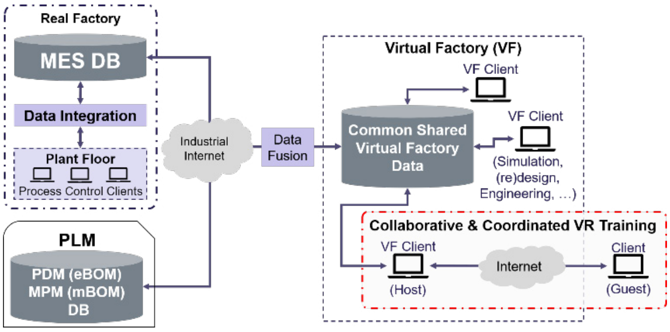

Fig. 4 VF data synchronisation architecture extended with multi-user VR.

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.

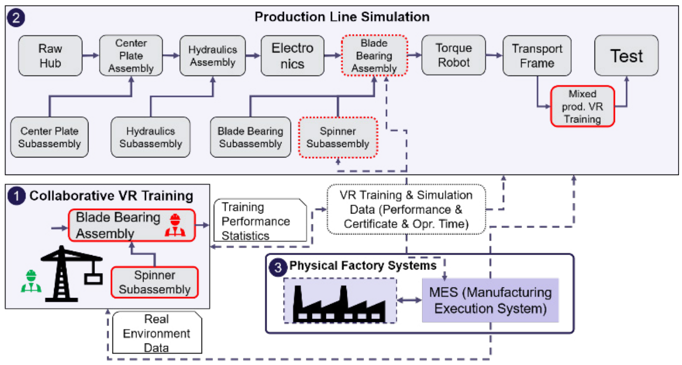

Fig. 5 Integration model for (1) VR training simulation, (2) line simulation and (3) physical factory systems.

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

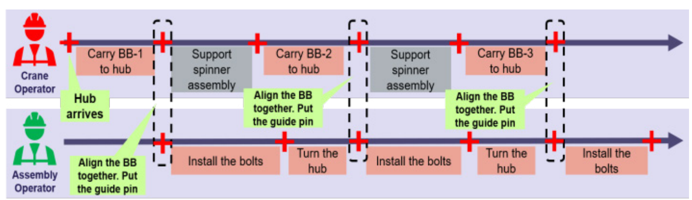

Fig. 6 Collaborative and coordinated VR training scenario.

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:

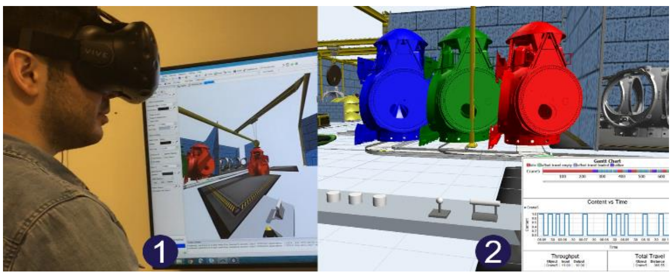

Fig. 8 Line simulation integrated mixed production VR training (refer Fig. 5)

- 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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Paper 7. Virtual Factory: Competence-Based Adaptive Modelling and Simulation Approach for Manufacturing Enterprise

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Virtual Factory: Competence-Based Adaptive Modelling and Simulation Approach for Manufacturing Enterprise

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Abstract. The evolution of industries is constantly forcing enterprises to adapt to ever-changing market dynamics. Companies are challenged by remodelling their resources, processes, and competencies as well as to define new goals in accordance with evolving complex and dynamic environments. Virtual Factory as a dynamic, cognitive, open, and holistic system promises a potential for an adaptive enterprise modelling tool to support manufacturing companies in dealing with such challenges. This short paper attempts to frame the theoretical concepts for evolving markets and adaptive organisations (systems) in terms of the theory of industrial cycles, systems theory, and competence theory. Furthermore, the Virtual Factory concept is presented and discussed based on framed theories and four dimensions of competence theory.

Keywords: Enterprise modelling theory · Enterprise modelling practice · Enterprise modelling tool · Multi-level enterprise modelling · Modelling in industry 4.0 · Digital twins

1 Introduction

In the age of Industry 4.0 and smart manufacturing, innovation, increasing competition, and rapidly changing demands can be considered among the main forces shaping business systems, organisation processes, products, and services as well as new strategies and methods of production. Enterprises need to evolve to adapt to continuously changing market demands, technologies, and regulations in order to stay competitive. This Change is resulting in an ever-increasing complexity in product, process, and system domains which affects organisations' approaches to analyse and formalise business processes and related data structures. Another result of this evolution is ever more integration of design, simulation, management, and maintenance of product/service and system life-cycle processes which is also called the "era of enterprise integration" [1]. The need for more accurate "AS-IS" models of existing enterprise architecture and behaviour in order to revise more efficient "TO-BE" models and solutions is becoming more vital while

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lifecycles are ever-shortening. The modular design of products is considered beneficial for faster product evolution [2] and complexity management [3], and improves strategic flexibility of enterprises in answering to unpredictable futures [4]. However, capabilities for modular products and other strategic flexibilities requires integration of know-what, know-why, and know-how forms of knowledge [5] in terms of design, management, and maintenance of product, process, and system domains. Therefore, one of the most relevant challenges faced by manufacturing enterprises is the synchronisation and simultaneous generation of product, process, and system (organisation) models in the early modelling and planning stages [6].

The above-mentioned needs and challenges make Enterprise Modelling (EM) a more crucial activity for adapting to ever-changing complex environments and developing new competencies for the effective strategic alignment of an organisation to its environment. EM is defined *"as the art of externalising knowledge in the form of models about the structure, functionality, behaviour, organisation, management, operations and maintenance of whole or part of an enterprise, or of an enterprise network, as well as the relationships with its environment"* by Vernadat [1]. The virtual Factory (VF), a concept which was initially defined as an integrated simulation model of a factory and its subsystems representing the factory as a whole [7], evolved in practice over the last decade together with the recent technological developments in modelling and simulation (M&S), digital twin (DT), and virtual reality (VR), as well as approaches in developing and utilising VF tools and models [4, 5]. Such developments and approaches enabled the dynamic, cognitive, open, and holistic virtual representation of actual organisations in digital platforms. This progress provoked a reconsideration of the definition of VF on the grounds of Hegel's motion concerning the existence and definition of concepts articulating *"things are what they are through the activity of the Concept that dwells in them and reveals itself in them"* [8]. Yildiz and Møller suggested that VF is *"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"* [9]. Accordingly, VF promises a potential for an adaptive enterprise modelling tool to support manufacturing enterprises during the evolution forced by smart manufacturing and Industry 4.0.

This work attempts to frame some theories and concepts for evolving complex environments and the evolution of organisations. Furthermore, we discuss the VF based on framed concepts and principles to interpret its impacts on designing, modelling, optimisation, control, and maintenance of enterprise systems and processes. Enterprise models are not static and need to reflect the evolution of reality [1]. Therefore, we aim to contribute to the evolution of EM forced by new research trends and technological developments by addressing the model maintenance and update based on reality.

The paper is organised as follows: Sect. 2 frames the theoretical foundations including the theory of industrial cycles explaining the dynamics of evolving markets; systems theory presents the principles of enterprise dynamics as a system and competence theory grounds the principles for guiding design and management of evolving systems; Sect. 3 introduces the vocabulary and VF concept; Sect. 4 evaluates the VF based on four dimensions of competence theory; Sect. 5 discusses the implementation of basic forms of change in organisation architectures using VF tools, before concluding in Sect. 6.

2 Theoretical Foundations

Charles Fine's work presented in his book called *"Clockspeed: winning industry control in the age of temporary advantage"* helps us to interpret external forces and the evolving nature of industrial forces and their effects on domestic domains of enterprises in terms of products, processes, and organisational systems [10]. The concepts and relatively universal principles introduced in his work, also called *Theory of Industrial Cycles* [11], is based on the idea that the ultimate core advantage for companies is the capability to adapt to ever-changing business environments. He also proposed 3-dimensional concurrent engineering in such domains in order to handle evolution [11, 12]. Evolution of models in product, process, and system domains, which is called the *co-evolution paradigm*, was also investigated in recent studies [13, 14] and some considered VF as the prerequisite to handle this co-evolution problem [15].

Evolution of enterprises from mechanical systems to organismic systems and eventually social systems is depicted by Russell Ackoff [16], and a system is defined 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."* [16]. Such definition and principles of *System Theory* states the fundamental properties of a system taken as a whole stem from the interactions of its parts, not their separate actions. Thus, *"a system is not the collection of its parts but the product of the interactions of its parts"* [17]. Because of this, a system cannot be understood just by separating its parts and analysis of such parts. As a social system, enterprises have their own purposes, and they are open systems that are embedded into larger systems which have their own purposes too. Therefore, Ackoff [16] concludes that situations (or problems) faced in enterprises which are complex systems of strongly interacting problems requires *analysis* (taking apart to understand) and *synthesis* (the opposite of analysis) together as complementary activities and redesigning either the entity, complex system, or its environment to solve a problem [17].

In this regard, the *Theory of Complex Systems* provides some principles which enlarge our understanding about the social, natural, and artificial systems that we are discussing. Herbert Simon chooses to define a complex system as *"a system made up of a large number of parts that interact in a nonsimple way."* [18]. His study on the structure of complex systems reveals the internal dynamics and structure of complex systems and argues that highly complex systems can be built faster when there are stable or quasi-stable intermediate forms of complex systems [19, 20]. Since simulation can facilitate digital integration across manufacturing lifecycles [21] and can be used for diagnostic analytics, predictive analytics, and prescriptive analytics [22], the VF concept can provide a foundation to build intermediary stable complex forms of the smart factories of the future.

The theories addressed above provide concepts and principles to increase our understanding of dynamic phenomena of all types. Finally, *Competence-Based Strategic Management Theory (or Competence Theory)* incorporates the above-mentioned concepts and principles in a more inclusive, dynamic, and systemic way [23, 24] and leads new insights into more feasible and consistent organisation/system design principles and processes [25]. Competence theory extends the systems view of a firm by identifying strategic goal-seeking behaviours of a firm which correspond to real-world cognitive and decision-making situations. Ron Sanchez defines the essential characteristics of system design and proposes a concept of an organisation structure for the effective strategic alignment of an enterprise with its environment [26]. He identifies four basic types of strategic environments and proposes four basic types of change in organisation resources, capabilities, and coordination to respond to changing environments (convergence, reconfiguration, absorptive integration, and architectural transformation). Sanchez also proposed four cornerstones/dimensions (dynamic, open-systems, cognitive, and holistic) to achieve competence-based strategic management in terms of building and leveraging competencies in dynamically changing complex environments [25].

We suggest that VF can achieve these four cornerstones and provide a useful environment to design, analyse, optimise, and simulate four types of essential changes in complex enterprise models to stimulate management thinking at all levels about the kinds of flexibility and reconfigurability that need to be designed into manufacturing enterprises when future demands may differ significantly from past demands. Therefore, vocabulary and the VF concept will be presented in the next section before discussing the concept based on four dimensions of competence theory.

3 Vocabulary and Concept

3.1 Vocabulary: Factory as a Manufacturing Enterprise

The term organisation, firm, and enterprise are used synonymously in this article since the subject theories state that, as a social system, they both have similar characteristics in terms of strategic goal-seeking and openness to larger systems. The *factory* which includes social, natural, and artificial systems defines our scope in terms of a key system of a *manufacturing enterprise* identified as an open system of assets and flows which covers tangible assets such as production tools and intangible assets like capabilities. *Capabilities* represent repeatable actions that are using other tangible and intangible assets in order to pursue specific goals. *Goals* are the set of interrelated objectives such as creating/producing products or semi-products that collectively motivate actions of a manufacturing enterprise and give direction to its competence building and competence leveraging activities. A manufacturing enterprise can achieve *competence* when it sustains the coordinated deployment of its stock of assets to achieve its goals. A manufacturing enterprise can *leverage its competence* by using existing assets and capabilities in current or new environmental conditions without qualitative changes. *Competence building*, however, requires acquiring and using qualitatively different stocks of assets and capabilities to pursue goals. A manufacturing enterprise links, coordinates, and manages various resources which are available, along with useful assets and capabilities, into a system to carry out goal-seeking activities. Coordinating and managing systemic interdependencies of internal and external resources of an enterprise may evolve alongside its competitive and cooperative interactions.

VF may, therefore, be seen as a virtual twin of a goal-seeking open system which supports the competence building and leveraging activities of an enterprise to achieve strategic goals. VF can provide data-intensive simulation models of existing systems and processes to design, management, and maintenance of resources for creating and adopting new technologies, processes, products, and forms of strategies. Thus, VF can contribute effective strategic alignment of manufacturing enterprises to align their environments by enabling the predictive capability to test different flexibility aspects (operating, resource, coordination, and cognitive flexibilities) for highly complex scenarios in manufacturing systems. Therefore, VF can support increasing managerial cognition to imagine, develop, and leverage enterprise competencies which shape competitive environments.

3.2 Virtual Factory

Concept. Yildiz and Møller [27] positioned the VF based on its functions and role in the product and production lifecycle processes more distinctively than previously proposed concepts, as seen in Fig. 1. This separation extends the understanding of the link between the production system and product design as well as process planning. It can also be valuable to identify the function and role of VF for enterprises in which digitalisation in product development and production execution systems are uneven. Bidirectional data integration between engineering and execution systems such as enterprise resource planning (ERP), manufacturing execution system (MES), and product lifecycle management (PLM) enables the creation, relation, and manipulation of digital twins (DTs) using simulation tools as well as control of actual systems. Such capabilities promise a high potential to handle complexity, and to support flexibility and concurrent engineering. This also seems to be useful for strategic management decision processes especially in dynamic environments and during architectural transformation since strategic managers should not only identify the needs for existing resources and capabilities, but they should also identify the resources and capabilities for an imagined future environment to compete effectively.

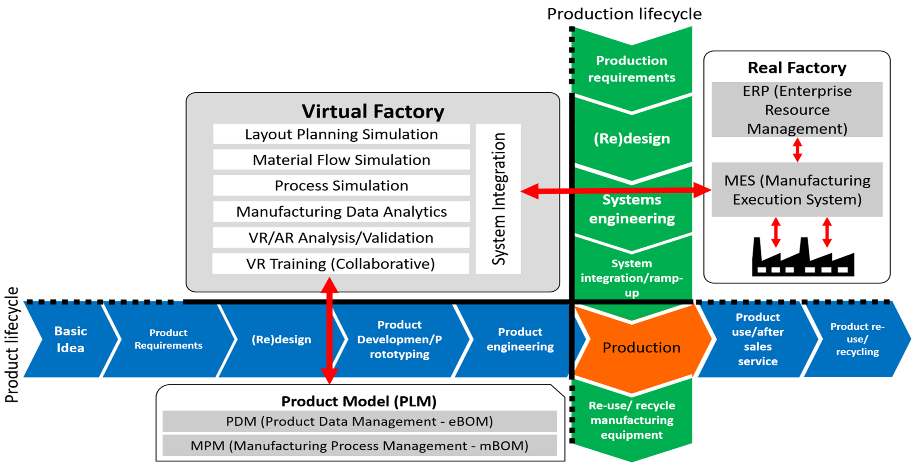

Fig. 1. Virtual factory concept

Modular VF Architecture for Manufacturing Enterprise. Figure 2 shows an example of instantiation to manufacturing enterprise level. Different types of simulations representing the enterprise and its subsystems can be integrated in a modular way to represent the enterprise holistically. Real-time integration capabilities of M&S and collaborative VR increase the dynamic and immersive representation of enterprise operations and interaction with the models [28]. Together with industry or organisation specific interfaces between different levels of simulations and between simulations and actual execution, engineering, and business platforms, the VF concept can achieve predictability/diagnosability, dynamic reconfigurability, and adaptability. Integrating simulations of different subsystems belonging to an enterprise, together with co-simulation capabilities, has the potential to contribute to the increased cognitive and holistic representation of a manufacturing enterprise.

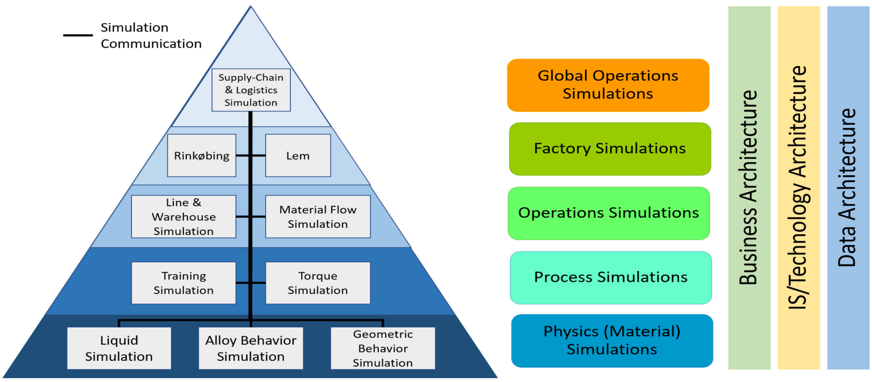

Fig. 2. Virtual factory architecture

An extension of VF simulations by adding more enterprise-level simulations such as business process and data flow simulations can increase the capabilities of VF to support enterprise architecture governance and transition planning. Various opportunities, solutions, and migration scenarios can be simulated in VF to support decisions during transition planning. Similarly, architectural changes and discrete implementation scenarios can be simulated in different resolutions in VF simulations.

4 Virtual Factory and Four Dimensions of Competence Theory

4.1 Dynamic System

One of the first dimensions of competence theory states that organisations/systems must be capable of performing the necessary changes dynamically in their resources and capabilities in order to respond to future needs and opportunities and stay competitive [25]. VF, as a virtual twin of actual systems, can represent the models and process in a more dynamic way and in real-time, as seen in Fig. 3. Therefore, VF simulations can be used to model, simulate, and even respond in real-time to the changes in actual processes, resources, capabilities, and functions of organisations. Such competence enables the dynamic and realistic representation of actual systems of manufacturing enterprises and their environment, which allows changes to occur dynamically. Every time a simulation model of a manufacturing line or a machine runs, for example, a number of parameters can be imported from the actual MES and designing, modelling, and planning processes can be performed more dynamically according to the changes in the real world.

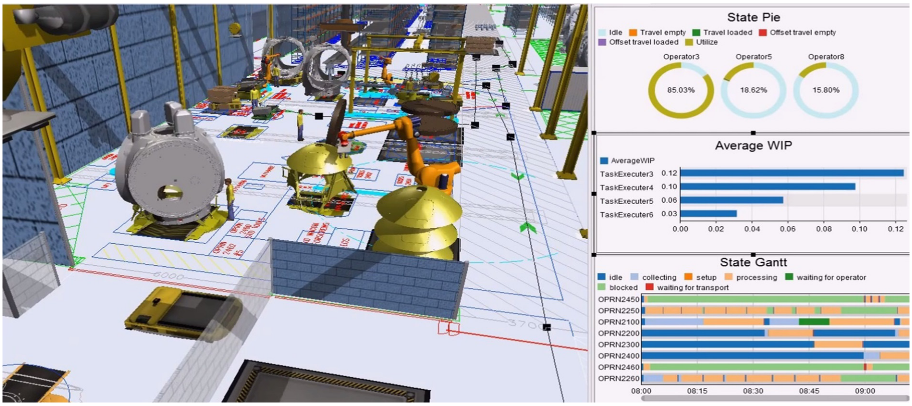

Fig. 3. 3D discrete event virtual factory simulation

4.2 Open System

The second cornerstone of competence theory is identifying systems as open systems which are embedded in larger systems [25]. Manufacturing enterprises are integrated into larger systems like nations and industries from which they get inputs and to which they give outputs. To be able to stay competitive manufacturing enterprises need to be open to set up new connections and relations to their environments to stay competitive while environments are changing dynamically. VF simulations also represent reality both internally and externally. A whole manufacturing enterprise or its subsystems can be represented with a simulation model which is integrated into larger systems such as ERP or a supply chain system as it is in the real world.

Moreover, each subsystem's model is also represented by its relationship with other subsystems, as seen in Fig. 2. VF is also open to creating new connections with its environmental systems through DT and Internet of Things (IoT) technologies. Therefore, VF is an open system which can be embedded into other systems and establish new connections with its evolving environment to access and coordinate a changing array of input resources as well as the creation of changing array of outputs.

4.3 Cognitive (Sense-Making) System

Another aspect of competence theory is to achieve cognitive systems by increasing the dynamic and evolving complexity of internal and external system models of enterprises [25]. In order to support managerial cognition to be able to identify resources and capabilities to achieve goals for sustainable competition in highly dynamic and complex environments, systems and model need to be cognitive (easy to make sense of). As a result of dynamic representation together with technological advancements like 3D discrete event simulation (DES), DT, and VR, the VF concept enables dynamic and cognitive models for both horizontally and vertically diverse managers and engineers. Integration capabilities of technologies promise an increase in information quality. Modelling, simulating, analysing, and interacting with models collaboratively, as seen in Fig. 4, opens up new possibilities for enterprise modelling and management [27, 28]. Therefore, VF can support managerial cognition to support enterprise imagination for developing and exercising new resources and capabilities. Please scan the QR code in Fig. 5 for more visual data on VF demonstrations.

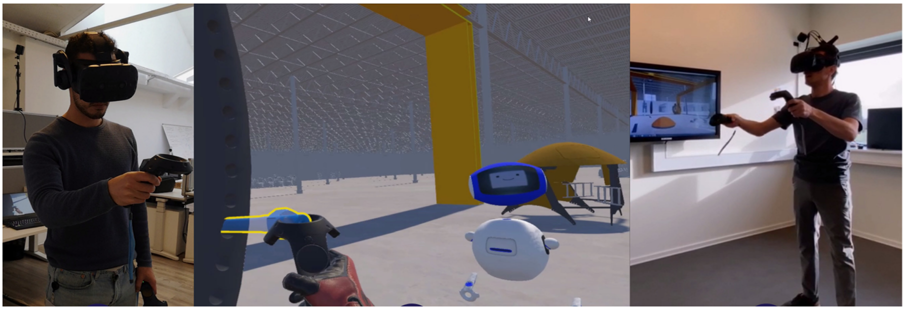

Fig. 4. Collaborative VR assembly simulation [27, 28]

4.4 Holistic System

The fourth and last aspect of competence theory is to achieve a holistic view of the enterprise to function effectively and to adapt to environmental changes as an open system [25]. To be able to implement systematic changes into complex and evolving open systems, management of manufacturing enterprises needs to mediate various interdependencies among its internal and external resources and capabilities. As described by the principles of the system theory *"If each part*

Fig. 5. Scan this for VF demo.

of a system, considered separately, is made to operate as efficiently as possible, the system as a whole will not operate as effectively as possible" [17]. Therefore, VF, as integrated simulations representing a manufacturing enterprise, including its subsystems, enables the holistic representation of existing complex systems. Integration and co-simulation capabilities enable designing and simulating any level of internal and external changes realistically in highly complex and dynamic models. Different level of simulations in VF can be integrated with each other with an interface to share either real-time operating states or objectives and targets (Fig. 2). When a change is made in a manufacturing operations level simulation model, for example, the effect of such change can be observed in material handling, warehouse, or even supply chain simulation models simultaneously.

5 Discussion

The VF concept has the potential to integrate engineering models forming product, system and process domains in a dynamic, open, cognitive, and holistic way. Moreover, VF simulations can be useful tools to design and simulate four types of changes (convergence, reconfiguration, absorptive integration, and architectural transformation) described by Sanchez [26] to respond to different strategic environments. Advanced M&S technologies can efficiently perform convergence as an incremental improvement of existing competencies. Together with advanced data integration across the whole enterprise simulations can have actions responsive to changes in actual reality. Therefore, VF can be adaptive enterprise modelling tool that can support managers and engineers in manufacturing enterprises for remodelling enterprise resources, with capabilities to leverage and build new competencies as well as defining and testing new strategies based on evolving environments. Thus, competence-based adaptive modelling can be accomplished. VF with immersive simulation models can also provide a platform to (re)design new functional components into existing enterprise systems and architecture. It can also be convenient to analyse the chain of reactions of intended changes into related simulation models. VF tools can also provide a viable platform to implement architectural changes in the existing resources, capabilities, and functions, and their interdependent coordination in a simulation model.

Moreover, it is possible to transform the existing architecture while reconfiguring existing functions. All four types of changes can be implemented in the enterprise architectures with VF tools. Automated and manual data integration, as well as capabilities to set constraints, limitations, and collisions in simulation models, can increase the realistic simulations of different scenarios.

Competence theory is articulated at a high level of abstraction. Thus, it is suitable for all kinds of organisational processes, including production systems. Nonetheless, to the best of our knowledge, there has not been any work that attempts to depict the abstractions of competence theory in a production system context.

6 Conclusion

Designing and developing enterprise models as an adaptive dynamic system in evolving complex environments is challenging for managers. The theory of industrial cycles explains dynamic forces and their relations in terms of the evolution of industries. Systems theory and complexity theory defines the basic principles which need to be considered while designing and developing a complex system. Competence theory inherits the principles of complexity theory and systems theory to formulate more comprehensive, dynamic, and practical principles for organisation design principles and processes. These principles and processes form the foundation of the VF concept and its utilisation as an adaptive enterprise modelling tool.

In this short paper, we attempt to frame theoretical concepts and principles of the VF concept as a competence-based adaptive enterprise modelling and simulation tool. The VF concept is also discussed based on four fundamental concepts of competence theory.

Disclosure Statement

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Paper 8. Demonstrating and Evaluating the Digital Twin Based Virtual Factory for Virtual Prototyping

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Demonstrating and Evaluating the Digital Twin Based Virtual Factory for Virtual Prototyping

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Abstract. Virtual prototyping (VP) technologies promise a viable solution to handle challenges in shorter product and production lifecycles and higher complexity. In this paper, we present the demonstration, and preliminary evaluation of the previously introduced digital twin (DT) based virtual factory (VF) concept for VP in the context of new product introduction (NPI) processes. The concept is demonstrated in two cases: blade manufacturing and nacelle assembly operations Vestas Wind Systems A/S. The preliminary evaluation results show that DT based integrated VF simulations provide immersive virtual environments, which allow users to manage complex product and production systems and significant cost savings. Finally, we present and discuss the evaluation of the concept demonstration by industry experts for the proposed solution.

Keywords: Virtual factory · Digital twin · Virtual prototyping · Virtual reality · Simulation and modelling · Industry 4.0

1 Introduction

Forces like innovation and technology, competition, changing demands, and regulations are among the main dynamics shaping industries' evolution [1]. The specific rhythm of the evolution in each manufacturing industry occurs in three domains: products, processes, systems [2]. Therefore, companies need to handle concurrent evolution (co-evolution) of product, process, and system models to achieve the capability to adapt to their respective industrial environments [3]. However, increasing the frequency of chances results in shorter product and production lifecycles and shifting decision-making from companies to customers resulting in higher complexity. Thus, achieving architectural isomorphism across product, process and organisation (system) architecture required to maintain effective alignment of an organisation with its evolving environment [4] becomes a significant challenge for manufacturing organisations.

Physical prototype building activities during the introduction of a new product can be considered among the most critical activities to achieve and ensure architectural isomorphism. However, physical prototype builds are often highly time-consuming, costly, and complex due to models and operations' uncertain and genuine nature. When

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it comes to the wind industry, turbine manufacturing covers a wide variety of production and manufacturing operations, such as heavy metal manufacturing (towers), large-size fibreglass composite material production (blades), complex and heavy parts assembly (gearbox, nacelle, generator, etcetera), and electrical & electronic systems manufacturing (control and grid infeed systems). Therefore, physical prototype builds during the NPI becomes more challenging for companies like Vestas Wind System A/S (later Vestas). In this regard, DT based VF concept [5] becomes highly relevant solutions by enabling integration, interoperability, and interaction capabilities across product and production lifecycle processes in virtual worlds [6].

In recent studies, DT based VF was considered a promising solution to deal with co-evolution problem with its potential to achieve dynamic, open, holistic and cognitive system capabilities [6, 7]. Moreover, industry experts considered VP among the highest value promising industrial use cases for DT based VF concept [6]. Although a virtual prototype as a computer simulation of a physical product covers all product lifecycle aspects, including service and maintenance [8], building and testing the virtual prototype of NPI processes is particularly challenging due to the need for concurrent engineering complex and ambiguous models and operations. However, due to the same challenges, VP maintains the significant potential for high value for including but not limited to 1) early testing, 2) fewer physical builds, 3) reduced cost, 4) complexity handling, and 5) reduced time to market [9]. Thus, the need to evaluate the DT-based VF concept in more particular VP use cases was raised by [6].

Therefore, in this study, we respond to the need addressed by [6] and present the DT based VF evaluation introduced by [5], in VP during NPI processes by industry experts. The concept is demonstrated in wind blade manufacturing and nacelle assembly cases of Vestas. The study draws upon previous researches, including concept design and development of VF [10] and its extension with DT [5, 6] and collaborative VR [11] capabilities. Therefore, we spared the reader from prolonged discussions on the concept and its design and development methodologies. However, we would strongly recommend the reader refer to the subject studies for in-depth discussions on practical and theoretical aspects of the work.

Following the next section, which summarises related works on VP and VF, Sect. 3 presents and discusses the methodology of demonstration and evaluation. Section 4 introduces the summary of preliminary results and discusses the evaluation of the concept before concluding in Sect. 5.

2 Related Works

2.1 Virtual Prototyping

Since the advances in computer-aided design (CAD), computer-aided manufacturing (CAM) and visualisation and interaction capabilities prevailed, the development of virtual environments and realistic virtual representations of product models gain more attention from scholars and industry experts. Thus, development and interaction with such virtual models become viable solutions promising significant advantages for the industrial processes in terms of reducing time, decreasing costs, and increasing quality [12]. As a result, VP, a key aspect from the application point of view, starts getting attention both in the application and knowledge domains. There were, however, many different interpretations of VP techniques which cause some confusions. To prevent such confusions, Wang defined a virtual prototype as "*a computer simulation of a physical product that can be presented, analysed, and tested from concerned product lifecycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (VP)*" [8]. Wang also addressed the need for concurrent design, analysis, optimisation, and integration of simulations tools. Some studies consider VP to alleviate the shortcomings of rapid prototyping (RP) [13], while others stress the difference between RP and VP [14]. Alongside early adoptions in the aerospace and automotive industry [9], VP technologies are also promising significant value in different industries such as construction [15], maritime industry [16] and heavy machinery industries [17].

Studies about VP techniques focus on product lifecycle, including product design, analysis, testing and assembly process design [18–21]. However, pretty limited studies focus on the VP of products from manufacturing aspects [22]. Although scholars concentrate on various VP simulations such as structural material and structural behaviour simulations [21, 23], recent studies show more attention to immersive VR integrated simulation tools [24]. Recent review studies show that advancements in simulation technologies, including real-time data integration, realistic visual representations and embedded VR and AR capabilities, can make simulations a proven enabler for digital integration and access to data across the product and production life cycles [25].

In this respect, the VF concept as high-fidelity integrated factory simulations representing factories as a whole can provide viable virtual environments for constructing and testing virtual prototypes since they enable the experimentation and validation of the various product, process and system models concurrently [5]. Therefore, we will shortly present some studies focusing on VF in the next section.

2.2 Virtual Factory

Since Onosato and Iwata [26] introduced the integration of product and factory models as an integral aspect of VF and virtual manufacturing, various definitions were made for VF, including emulation facility, integrated simulation and virtual organisations [27]. Jain et al. 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.*" [27]. An integrated VF framework concept which can synchronise real factory and VF was introduced by Sacco, Pedrazzoli, and Terkaj [28]. The utilisation of collaborative VR training simulations in the VF concept, together with DT capabilities, was also studied by Yildiz et al. [5, 11]. Yildiz and Møller [10] presented the VF concept as a more dynamic and open system by integrating VF to actual manufacturing execution and product lifecycle systems. They also 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*" [10]. A comprehensive demonstration of the DT based VF concept in industrial cases [6] showed significant potential for handling co-evolution and called for more particular evaluation in VP cases.

In this regard, we discussed the methodology for the demonstration of the DT based VF concept in wind blade manufacturing and nacelle assembly cases, as well as its evaluation in the context of VP in NPI processes.

3 Methodology

This article covers only the demonstration and evaluation activities of six Design Science Research Methodology (DSRM) activities [29]. Four demonstration and evaluation sessions, each of which with five participants, were performed. Each session covered 1) presentation of the artefacts, tools, and capabilities, 2) live demonstration of DT based VF, including VR interaction, and 3) semi-structured group interviews. Therefore, the demonstration and evaluation methods were shortly articulated further on.

3.1 Demonstration

DT based VF demonstrated in two diverse cases, including large composite manufacturing (blade) and complex and heavy parts assembly (nacelle) of Vestas. Although such cases are unique to the wind turbine manufacturing industry, there are significant common aspects with various industries such as shipbuilding, automotive, and aviation. Thus, the knowledge can provide guidelines for experienced professionals in the industry and enable the evaluation of deviations in the form of "if-then" specific to each context.

Fig. 1. Scan the QR code for demonstration

Some parts of the data about the demonstration are subject to the intellectual and financial interest of the Vestas. Therefore, a significant part of the data is covered by the provisions given to the Vestas by the research collaboration agreement. However, we strongly advise the readers to access the part of the demonstration video, which is publicly available, via [30] or scanning the QR code in Fig. 1.

3.2 Group Interviews

The group interviews aim to collect data to evaluate the DT based VF concept in the context of VP during the NPI processes with well-grounded pieces of evidence and arguments by exploring interpretations and perspectives of industry experts. During the group discussions, the interpretations of experts were critically examined by instigating a process of reflection to gain more specific, accurate and grounded pieces of evidence.

The number of interviewees was limited, with five for each session to avoid uneven participation in discussions and to acquire more valuable knowledge with more intensive interviews and penetrating interpretations. Participants were intentionally mixed for each session based on their background and departments to increase the diversity of expertise. Please refer to [31] for the list of interviewees as a public online appendix.

4 Evaluation and Discussion

As anticipated, expert discussions on the evaluation of DT based VF roamed around four types of prototyping activities, representing the main exercises of NPI. These are 1) mock-ups, 2) design prototypes, 3) process prototypes, and 4) 0-series production. Therefore, the evaluation summary is grouped and presented in Table 1 based on the respective headlines.

Table 1. Summary of DT based VF evaluation

Prototyping activity	Summary of evaluation
Mock-up builds	• Most of the experts agree that the DT based VF concept cannot fully eliminate physical mock-up builds due to mandatory physical tests for legal certification • A minimum of 4 mock-up builds for the wind turbine blade is inevitable • 3D simulation is beneficial for higher confidence in the models • Time and error reduction during mock-up build can be promising value cases for DT based VF • Extending the simulation tools with detailed material behaviours and resin injection is considered highly valuable for blade manufacturing
Design prototypes	• The majority of experts consider the DT-based VF concept more beneficial for design prototypes than mock-up builds since it is less focused on specific/critical materials behaviours • The majority of the failures, corrections, improvements faced during the late blade introduction processes were design-related • Some stated that eliminating the physical design prototype for the near or medium future is optimistic • Utilising DT based VF during the design prototype processes is considered useful for decreasing time to market
Process prototypes	• DT based VF is considered highly useful for process prototypes to simulate production execution • Most experts considered the results of physical prototype activities highly useful for 0-series and serial production optimisation • Some underlined the significance of integrating the high- and low-resolution simulations to achieve a holistic view within the single platform
0-Series production	• The 0-series production is considered the most effective use case for DT based VF since the design and processes are more mature in this phase • DT-based VF promises high value by enabling the right sequence, the right staffing, the right factory layout, and having a shorter time to market • Some stated that VF could accelerate the learning curve and achieve actual takt time by reducing 25% time of 0-series which may take three to six months at present • Discovering the limiting factors and bottlenecks such as lack of crane capacity is considered very valuable

4.1 Discussions

DT based VF is also considered for various capabilities besides simulating various prototype building activities during NPI. VR capabilities of the DT based VF was considered valuable for pre-training for big scale production roll-outs. Moreover, collaborative VR shows a sign of higher value for communication with suppliers and is considered very useful to have VF during technology transfer between factories. However, some argued that implementing VR requires a significant focus on change management and competence build.

Some also addressed the risk of a rapidly increasing size of data that needs to be input into the models for achieving close to reality models and stressed the importance of DT technology.

5 Conclusion

This paper addresses the need for more particular case evaluations of the DT based VF concept in the context of the VP of a product during NPI activities. The concept was demonstrated in the blade and nacelle production facilities of Vestas and evaluated by industry experts during semi-structured group interviews. The preliminary results show that the DT based VF concept is more value promising in the later phases of product introduction to its intensity on the integrated representation of product, process, and system (factory) models. Thus, experts address the need for extending the demo with higher resolution simulations like material design and behaviour simulations.

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Declarations.

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

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

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

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SUMMARY

Constant evolution in the global manufacturing resulting from various forces like innovation, changing demands, competition, and regulations is forcing manufacturing enterprises towards more digital and smarter operations to stay competitive in their respective markets. This evolution of manufacturing towards digitalisation led to a new paradigm in the last decade, which has been called the "fourth industrial revolution" or "Industry 4.0". Yet, it is not a trivial matter for manufacturing organisations to deal with the accelerating frequency of radical changes by means of new strategies, methods, and technologies. Evolving dynamic forces have immense impacts on the digital transformation of manufacturing operations as well as the priorities of scholarly works. Nowadays, it is more apparent and easier to comprehend the relation between evolving market dynamics and their reciprocal consequences on products, processes, and manufacturing systems. Accordingly, manufacturing organisations must handle the initiation of change as well as its propagation, which triggers a multitude of unpredictable and complex modifications in production. This challenge is characterised as the concurrent/coordinated evolution of products, processes, and systems, in other words, "co-evolution" in scholarly works. The Virtual Factory (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", enables data integration across the manufacturing value chain as well as the integrated use of technologies and methodologies. Therefore, VF is recognised by scholars as a useful and effective solution to deal with the co-evolution paradigm. However, there are still significant gaps in the knowledge domain as well as empirical challenges in the application domain in terms of designing, developing, and utilising the VF concept. Therefore, the purpose of VF research work is to address such gaps and challenges by designing and developing artefacts and frameworks together with empirical evaluations of designed artefacts in the industrial cases. The VF research work presented in this thesis is the final outcome of a three-year- long PhD study conducted as part of a comprehensive research collaboration project named Smart Factories. The thesis on hand is the final effort to frame the three-year-long research aiming to establish a systemic design and development approach for DT-based VF, employing a collaborative virtual reality capability that can integrate product, process, and system models to support the manufacturing enterprises for handling co-evolution problems during their adaptation to evolving environments. Thus, with this final effort, this thesis is aiming to: Establish comprehensive and methodical foundations for the empirical, conceptual, and philosophical discussions supporting the previously discovered and disseminated knowledge on DT-based VF employing a collaborative virtual reality capability that can integrate product, process, and system models.

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