The International Journal of Advanced Manufacturing Technology (2022) 121:2317–2333
https://doi.org/10.1007/s00170-022-09462-z

ORIGINAL ARTICLE

Conceptual foundations and extension of digital twin-based virtual factory to virtual enterprise

Emre Yildiz[1] · **Charles Møller**[1] · **Arne Bilberg**[2]

Received: 9 December 2021 / Accepted: 30 May 2022 / Published online: 10 June 2022

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 Fig. 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

---

✉ Emre Yildiz
ey@mp.aau.dk

[1] Center for Industrial Production, Aalborg University, Fibigerstraede 16, 9220 Aalborg, Denmark

[2] Mads Clausen Institute, University of Southern Denmark, 6400 Sønderborg, Denmark

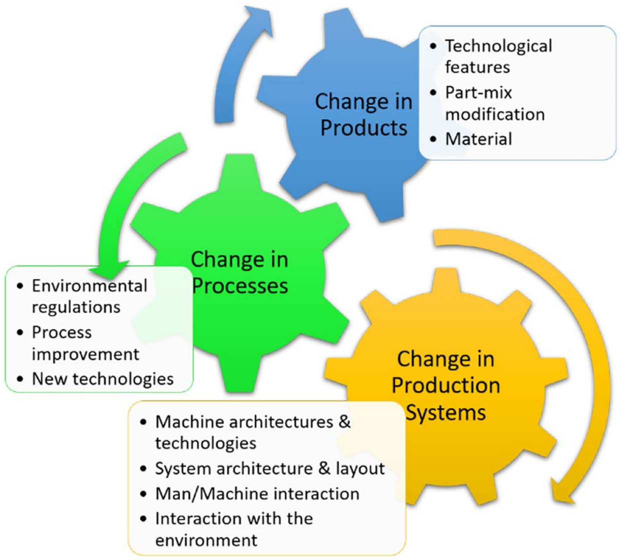

Fig. 1 Co-evolution paradigm (adapted from [1])

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 demand integration of know-what, know-how and know-why forms of knowledge [5] for the design, management and maintenance of models in the process and system domains. Scholars have also studied various approaches, 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 the early modelling, design and planning stages remain among the most relevant challenges for manufacturing enterprises [9].

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 to invent, transform or modify more efficient "to-be" models is becoming vital to deal with co-evolution in complex manufacturing operations. Moreover, handling such evolution at the enterprise-level increases 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]. Nevertheless 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 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 the 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 the DT-based VF concept in industrial cases demonstrate that DT-based VF stands out as a promising CPS to support manufacturing enterprises for handling co-evolution [16–18]. Since this article is formed on a collection of previously published papers, each of which articulates on various interdisciplinary and transdisciplinary empirical issues, we strongly advise the reader to refer to such works [11, 12, 16–20] for extensive knowledge on pragmatic validity and practical relevance. In addition, because the visual contents conceivably have more potential to convey far-reaching knowledge to the audience, we also strongly recommend readers to review the public media documents on (1) integrated VF simulations [21], (2) collaborative and coordinated VR training [22] and (3) outbound supply chain simulation demo [23], which is incorporated by the extension of DT-based VF to the virtual enterprise.

Moreover, DT-based VFs have 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 [24].

1.1 Problem statement and objectives

In regard to adapting manufacturing enterprises to evolving conditions, various studies are focusing on 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 [1]. 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" [25].

Therefore, there is a need for (1) discussions and reflections on previously uncovered contextual knowledge [16–18] 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 the 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 the 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, 16–20]. Although some conceptual and theoretical aspects presented and extensively discussed in this work were 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, Sect. 3 frames and interprets the conceptual and theoretical foundations of the DT-based VF concept. Section 4 presents the concept shortly before Sect. 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 Sect. 8.

2 Methodology and vocabulary

2.1 Case research as theory elaboration

The work on hand is the final outcome of 3-year-long research on VF. Since the previously designed demonstrated and evaluated VF artefacts emerged as a phenomenon when artificial, natural, and socio-technical systems interact, the theories to interpret the phenomenon link the social, natural, and artificial worlds [26]. Thus, the body of knowledge discovered and disseminated during the previous studies in industrial cases [16, 17, 19] capitalises on social, natural and design (artificial) sciences [27]. Previous case studies were conducted on the trails of the design science research (DSR) approach [28] and corresponding methods, frameworks and guidelines emerged to support DSR in IS [29–32]. Since the objectives of the VF solution are to deal with practical challenges with pragmatic methods, the justification of the designed artefacts incorporates the question of practical relevance (*In what way does the design make a valuable contribution to addressing a significant field problem or exploiting a promising opportunity*? [32]), and pragmatic validity (*How strong is the evidence that the design will produce the desired results* [32]*?*).

However, the essence of case research relies on the duality of being "situationally grounded" (*empirically disciplined and minds the contextual idiosyncrasies*) while seeking "a sense of generality" (*reaches beyond the empirical context and inquires extensive theoretical understanding*) that has been called duality criterion [33]. A case study on a Vestas' manufacturing plant, for example, focuses on collecting contextual data by analysing the empirical and structural patterns of the proposed solution within a particular case. However, the research questions to be answered and knowledge to be created by utilising case-specific data cannot be just about Vestas' manufacturing plant but need to be more general. On the other hand, a sense of generality does not focus on whether the solution (or questions) can be generalised to different empirical contexts (contextual deviations) but focuses on to what extent the sense of generality can be met in terms of theory. Therefore, the duality criterion calls for balancing contextual peculiarities of the case research with an investigation of more conceptual and theoretical implications. Three modes of duality criterion, including (1) theory generation, (2) theory testing and (3) theory elaboration, were determined by Ketokivi and Choi [33].

VF research is not positioned in the mode of theory generation because it is considered that the existing theories and literature maintain a sufficient basis to formulate research questions in previous empirical studies. Moreover, the VF study is not considered as theory testing since it is not feasible to derive explicit a priori theoretical hypotheses and conduct experimental research to test such hypotheses in very complex and dynamic manufacturing organisations. Yet, it is considered conceivable to contextualise a priori theories in more general ways, and the new knowledge discovered from empirical context can lead to more new and general theoretical insights. Thus, the VF research and particular study presented in this paper can be positioned as theory elaboration which concentrates on contextualised logic of general theories. Instead of testing the logic in a certain context, this work attempts to elaborate on the logic by exploring the contextual peculiarities with more serendipity and latitude. A successful theory elaboration requires an investigation of general theories and the contextual idiosyncrasies simultaneously [33]. Thus, the aim of this study can be described as "reconciliation of the general with the particular" by interpreting and elaborating on empirical peculiarities through more theoretical abstractions. Therefore, the discussion in this work lies hovering between contextual/empirical and conceptual/theoretical perspectives.

2.2 Vocabulary

Before articulating the concepts and theories on which the 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 [34]. 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. As an essential system of a manufacturing enterprise, the factory 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 and 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 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].

Thus the DT-based VF may 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 [35, 36] 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 complex manufacturing organisations' internal and external nature to provide descriptive knowledge as a language to describe the design principles of the 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" [37]. 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" [38]. 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 the 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 aims 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 Fig. 2. 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, and 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 provide relatively universal laws of evolution in the industries. Eventually, competence-based strategic management concepts, also known as competence theory, incorporate the principles of systems theory and complexity theory and introduce 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, from different perspectives [39, 40]. 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.

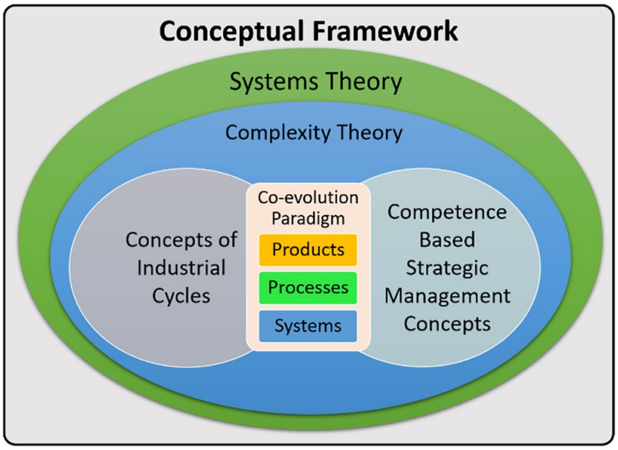

Fig. 2 Conceptual framework

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 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 [41]. Since early studies in the 1950s, there was a gradually increasing interest and recognition of 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 [42]. 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 [43].

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 [44]. 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" [45]. Therefore, the performance and the fundamental properties of a system are not determined by the separate behaviours of its parts but the interactions. Accordingly, a system is "the product of the interaction of its parts" [46] 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" [47]. Over time, scholars identified the distinctions between 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 [45].

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 [48], a complex system can be defined simply as "a system made up of a large number of parts that interact in a nonsimple way" [47]. A fundamental assumption of organisational theory and practice states that "a certain level of predictability and order exists in the world" and, thus, encourages simplifications for ordered circumstances [49]. 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 [49, 50]. 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 [45, 46]. Thus, "the truth is the whole" [51].

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 [52]. 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, 53]. Due to diagnostics and advanced predictive and prescriptive analytics [54] capabilities of simulations, the DT-based VF concept can support the engineering and management of complex systems in reforming and reconstructing models in an adaptive virtual environment. Thus, the DT-based VF concept promises a potential 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 [49], 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 [55].

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, in the spectrum of various industries, the electronic components industry, for example, inherits a faster clockspeed with rapidly changing products and manufacturing processes. Industries like mining or automotive, however, follow relatively slow lifecycles [56].

Charles Fine's research enhanced our understanding and interpretations of the nature of evolution in the industries and revealed some laws that include as follows: (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 [39], (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 [39, 57]. 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, and organisation. Recent studies are also examined the concurrent evolution (co-evolution) of product, process, and system models [1, 58]. Fine investigated the evolution of systems at a higher level by regarding the manufacturing organisation as a manufacturing supply chain [59]. 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 [39]. Tolio et al., however, concentrated on factories as manufacturing systems and considered VF as a fundamental tool to handle co-evolution problem [60]. 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 key interfaces between factories' external domains 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 for understanding “what” is the internal and external nature of co-evolution of complex manufacturing organisations. Nevertheless, there is a need to examine 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 [40, 50], 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 [34]. 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 [61]. 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 [50]. Moreover, competence-based strategic management further provides relatively more consistent and feasible organisation design principles for management to sustain competencies [62]. 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 [40]. 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” [40]. Sanchez also maps the four basic types of strategic environments and introduces four types of changes in organisations’ tangible and intangible assets which are characterised “as convergence, reconfiguration, absorptive integration and architectural transformation” [40]. We will discuss the forms of changes and how DT-based VF can be utilised to support such changes in Sect. 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, and 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 [50]. We discussed each cornerstone and their elaboration on the DT-based VF concept in Sect. 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, 16]. 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, upon which this work was built, 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 has been considered for various purposes such as simulation and optimisation [63], system design and modelling [64], production line control [65], sustainability and reconfigurability of factories [66]. 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, 67] with an effort to distinguish product, process and system (factory) domains and by illustrating its position with regard to product and production lifecycle processes as seen in Fig. 3. Yildiz et al. further extended the concept and its empirical models with DT and collaborative VR capabilities together with a more inclusive definition [11, 17, 19]. 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 [17].

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 integrating various levels and resolutions of simulations that facilitate the alignment 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 [16].

While the various levels of simulations enable modelling different levels 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

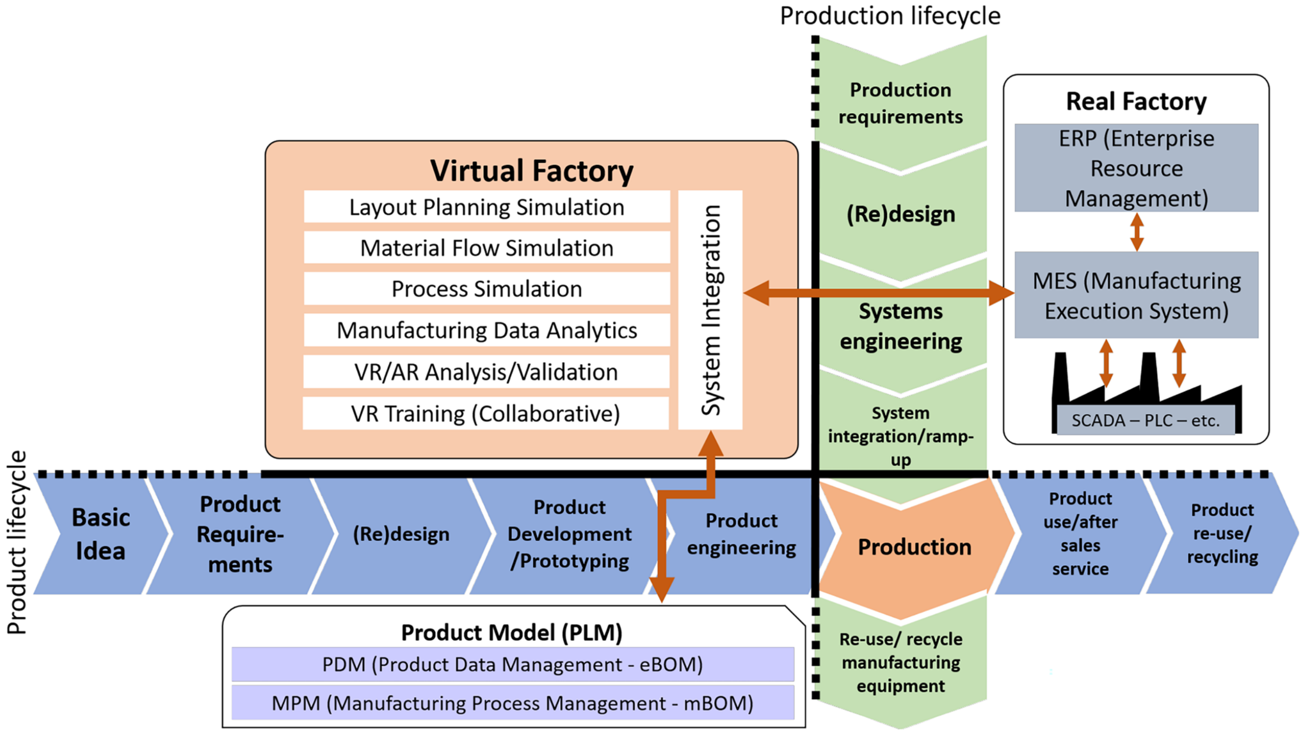

Fig. 3 DT-based VF concept [16, 17]

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 and 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 call for a series of coordinated manufacturing operations that require the involvement of a group of manufacturers and suppliers. Although the M&S, DTs and 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 the coordinated evolution of product, process and system models is critical. Such integration can enable DT integration with supply chains and thus adaptation for holistic optimisation of the manufacturing lifecycles [25].

Figure 4 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 value chain operations out of the factory context by integrating simulation models of diverse 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 Fig. 5 and demonstrated in [23]. Here it should be noted that the auxiliary revision on the extended concept was performed on the grounds of peer reviews and based on recent studies focusing the evolution of MES solutions as well as their advancing integration with the enterprise (supply chain) and shopfloor systems [68]. It is neither easy nor vital to anticipate the long-term evolution of MES, ERP and industrial Internet of Things (IIoTs); the integration of data across such systems is considered essential to achieve smart factories by providing product-centric real-time data across enterprises' operations [68, 69]. Therefore, increasing real-time data integration (vertical integration) and service-oriented infrastructures (horizontal integration) within the manufacturing enterprises [68] is illustrated with added data fusion layer in Fig. 5. 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 [70], but we can define enterprise modelling "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

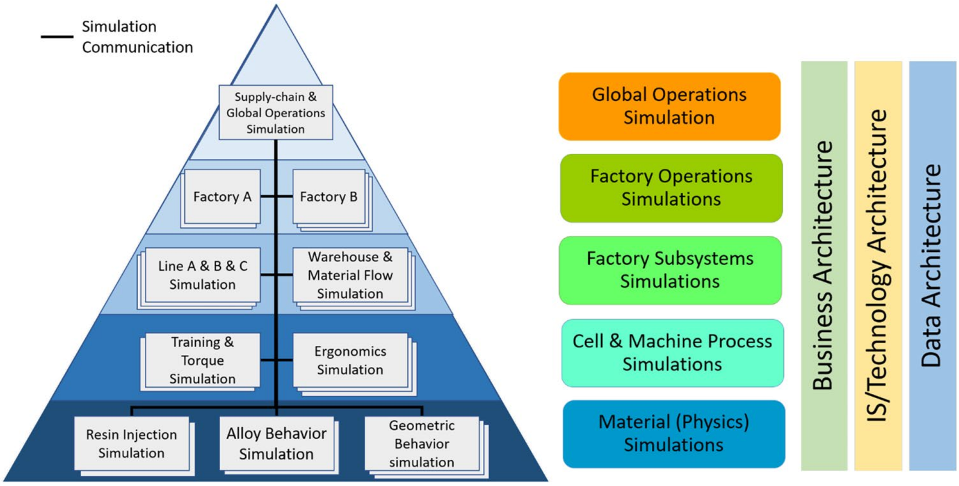

Fig. 4 Virtual factory simulations architecture extended with supply chain (adapted from [12])

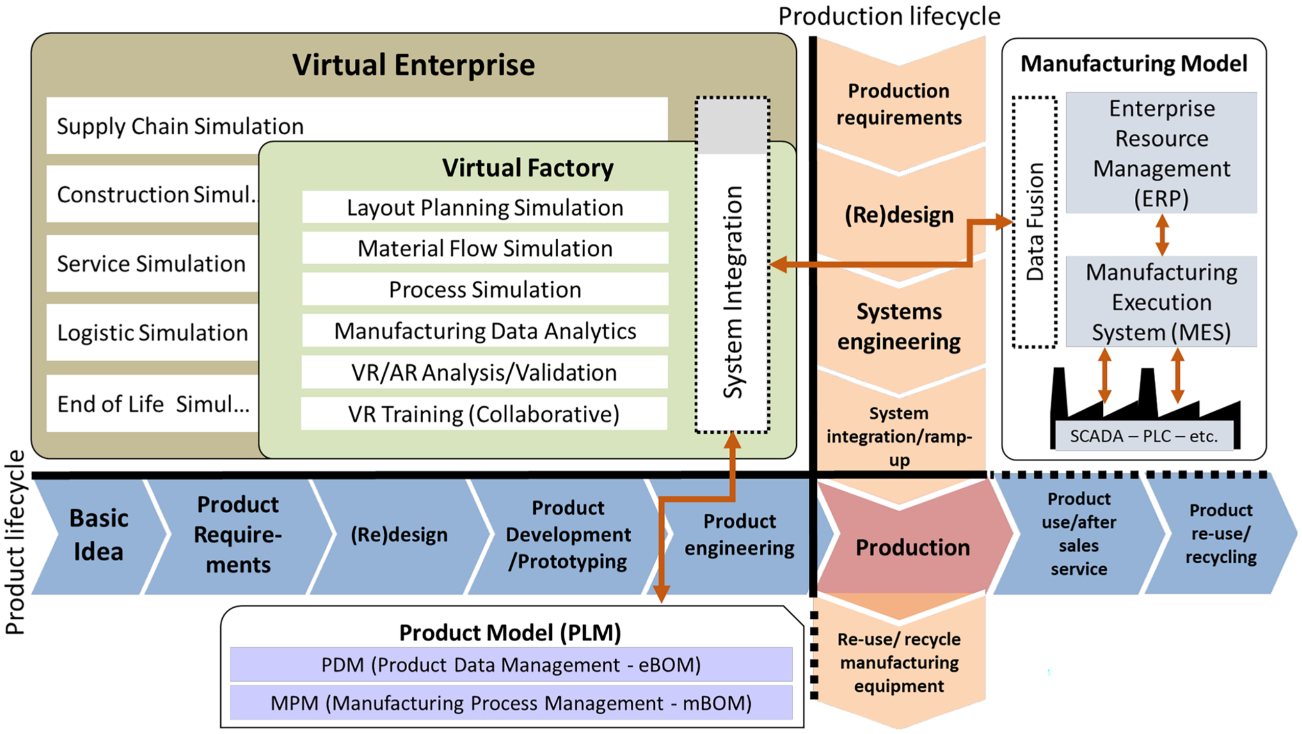

Fig. 5 Virtual enterprise concept extended from DT-based VF

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. [71]. 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 the DT-based VF concept to enable concurrent engineering, time-saving, virtual collaboration and virtual prototyping in manufacturing operations [16]. Abovementioned discussions and capabilities address that the 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 [72].

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 the DT-based VF concept performed in industrial cases as a part of the subject study can be accessed on [21].

In the next section, the DT-based VF concept will be discussed in detail based on the 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 [50]. Co-evolution of product, process and system models creates 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 represent 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 reciprocal consequences. An industry expert clearly addresses this challange 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 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, processes, 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 and constraints of the real-world operations. 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 [73]. 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 [17, 18].

5.2 Open system

Characterisation of open systems originated from the embedded nature of organisations [50]. 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 and imagination, while supplying outputs like products, semi-products and services, 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 to design 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 as well as data integration from virtual back to physical entities. Integration with ERP or digital and cloud-based 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 can potentially 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 emerges from the essential need for sense-making given the evolving dynamism and complexity of enterprises’ internal and external environment [50]. Managerial cognition is a fundamental requirement for identifying resources, processes, and competencies as well as their contextual essence for sustainable competitive advantage [74]. 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 promises for increasing contextual knowledge of DT-based VF models. Moreover, the 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 the 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 the cognitive loads of complex models during communication [17]. Moreover, utilising DTs in VF simulation increases 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 a holistic system view is required for effectively operating organisations as adaptive open systems [50]. 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” [46]. 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-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 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 [52], DT-based VF can support the creation of a virtual environment in which

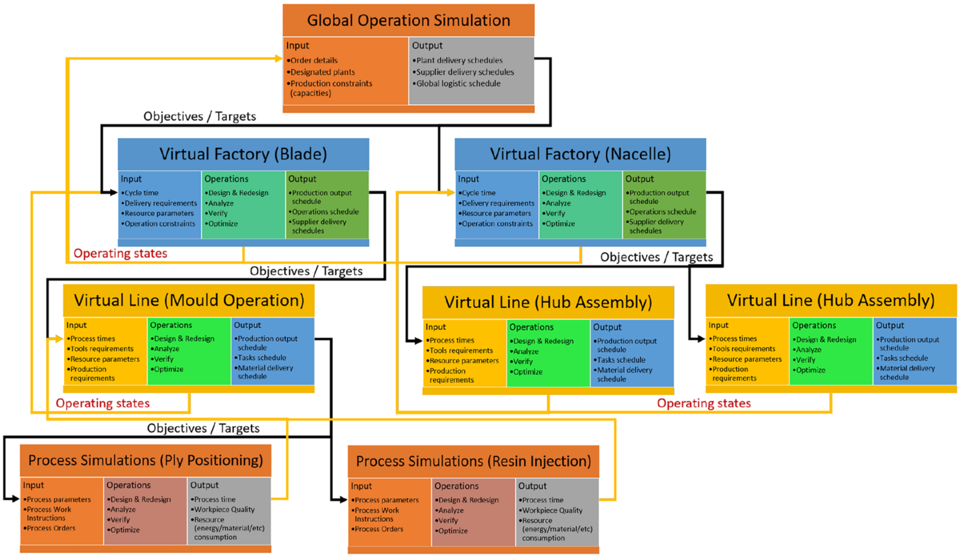

Fig. 6 Integrated simulation example

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, approaching new external resources, 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 in 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 and 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 Fig. 7. These forms of changes demand combinations of various flexibilities such as “operating flexibility, resource flexibility, coordination flexibility and two forms of (managerial) cognitive flexibility” [40]. 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 [75]. Therefore, such change focuses on continuous improvements in the efficiency and performance of existing operations.

The DT-based VF concept, which is built upon a 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 [76, 77]. 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 [17]. Therefore, organisations can simulate various firm-specific operating flexibility scenarios, which are critical for improving and maintaining robustness to respond to the competitive pressures of their environment.

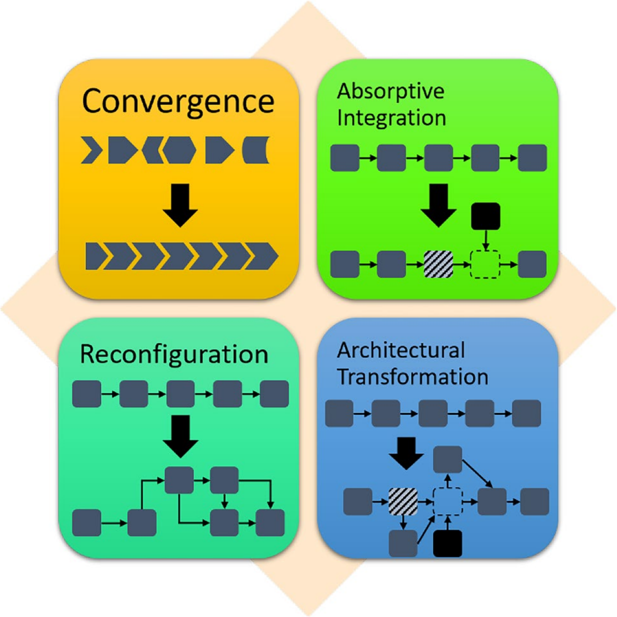

Fig. 7 Types of changes in an enterprise’s architecture [40]

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 [40]. 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 at various resolution levels such as production line, factory, or enterprise levels. Due to DT capabilities, entities in the 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, 40]. Thus, this type of change involves integrating a new type of external resources and functions into an existing organisation to support the organisations' co-evolution.

DT-based VF demonstrations (Fig. 6) performed in the Vestas manufacturing cases cover 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, 19]. 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 [40]. 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 and goals for maintaining strategic effectiveness is considered the reason for "upheaval" in traditional organisation designs [75].

Since the DT-based VF concept is shown to be capable of supporting reconfiguration and absorptive integration, it 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 the DT-based VF concept.

7 Discussion

The 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 and 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 each industry's value promising or criticality. 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 the DT-based VF concept [11, 16–18], which is conducted in various industrial cases, provided shreds of evidence and a 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) [33]. 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 outside of the 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, studies dedicated to extending the knowledge with inbound and outbound supply chain simulations (multi-resolution simulations) as well as their design, development and demonstration in industrial cases are ongoing as part of furthering the VF research.

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 promise 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 the 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 provide managerial guidelines for utilising the DT-based VF concept to handle the concurrent evolution of the 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 case studies as well as conceptualising the prescriptive knowledge discovered during the previous industrial demonstrations.

Funding The research presented in this article was funded by the Manufacturing Academy of Denmark (MADE) and Vestas Wind Systems A/S, including equipment support (Grant: 6151-00006B).

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.

Declarations

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

Conflict of interest The authors declare no competing interests.

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.

References

1. Tolio T, Ceglarek D, Elmaraghy HA et al (2010) SPECIES-Co-evolution of products, processes and production systems. CIRP Ann Manuf Technol 59:672–693. https://doi.org/10.1016/j.cirp.2010.05.008
2. O'Grady PJ (1999) The age of modularity: using the new world of modular products to revolutionize your corporation. Adams & Steele
3. Baldwin CY, Clark KB (2000) Design rules: the power of modularity. MIT press
4. Sanchez R (1995) Strategic flexibility in product competition. Strateg Manag J 16:135–159
5. Sanchez R, Heene A (1996) Managing articulated knowledge in competence-based competition. In: Strategic learning and knowledge management. John Wiley & Sons, pp 163–187
6. Brunoe TD, Andersen A, Sorensen DGH, Bejlegaard M (2019) Integrated product-process modelling for platform-based co-development. Int J Prod Res. https://doi.org/10.1080/00207543.2019.1671628
7. Lumsakul P, Sheldrick L, Rahimifard S (2018) The sustainable co-design of products and production systems. Procedia Manuf 21:854–861. https://doi.org/10.1016/j.promfg.2018.02.193
8. Zhang HC, Zhang D (1995) Concurrent engineering: an overview from manufacturing engineering perspectives. Concurr Eng Res Appl. https://doi.org/10.1177/1063293X9500300308
9. Azevedo A, Almeida A (2011) Factory templates for digital factories framework. Robot Comput Integr Manuf 27:755–771. https://doi.org/10.1016/j.rcim.2011.02.004
10. Vernadat F (2020) Enterprise modelling: research review and outlook. Comput Ind. https://doi.org/10.1016/j.compind.2020.103265
11. Yildiz E, Møller C, Melo M, Bessa M (2019) Designing collaborative and coordinated virtual reality training integrated with virtual and physical factories. In: International Conference on Graphics and Interaction 2019. IEEE Press, pp 48–55
12. Yildiz E, Møller C, Bilberg A (2020) Virtual factory : competence-based adaptive modelling and simulation approach for manufacturing enterprise. In: 13th IFIP WG 8.1 working conference on the Practice of Enterprise Modelling. Springer International Publishing, Riga, Latvia, pp 197–207
13. Onosato M, Iwata K (1993) Development of a virtual manufacturing system by integrating product models and factory models. CIRP Ann Manuf Technol 42:475–478. https://doi.org/10.1016/S0007-8506(07)62489-5
14. Jain S, Choong NF, Aye KM, Luo M (2001) Virtual factory: an integrated approach to manufacturing systems modeling. Int J Oper Prod Manag 21:594–608. https://doi.org/10.1108/MRR-09-2015-0216

15. Hegel GWF (1816) The encyclopaedia logic. 1991, Hackett Publishing Company, Inc., Indianapolis / Cambridge
16. Yildiz E, Møller C (2021) Building a virtual factory: an integrated design approach to building smart factories. J Glob Oper Strateg Sourc 14(4):608–635. https://doi.org/10.1108/JGOSS-11-2019-0061
17. Yildiz E, Møller C, Bilberg A (2021) Demonstration and evaluation of a digital twin-based virtual factory. Int J Adv Manuf Technol 114:185–203. https://doi.org/10.1007/s00170-021-06825-w
18. Yildiz E, Møller C, Bilberg A, Rask JK (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
19. Yildiz E, Møller C, Bilberg A (2020) Virtual factory: digital twin based integrated factory simulations. In: Procedia CIRP (53rd CIRP Conference on Manufacturing Systems). Elsevier B.V., pp 216–221
20. Yildiz E, Møller C, Bilberg A (2021) Demonstrating and evaluating the digital twin based virtual factory for virtual prototyping. 8th Changeable, Agile, Reconfigurable, and Virtual Production Conference (CARV2021). Springer, Aalborg, pp 297–304
21. Yildiz E (2020) Virtual factory: a systemic approach to building smart factories - YouTube. In: Youtube. https://www.youtube.com/watch?v=aPUfbGQc-FQ. Accessed 6 Feb 2021
22. Yildiz E (2020) Multi-user VR simulation for collaborative and coordinated learning/training scenarios - YouTube. In: Youtube. https://www.youtube.com/watch?v=meyiSqN95HU. Accessed 1 Feb 2022
23. Yildiz E (2022) Outbound supply chain simulation for wind turbine generators - YouTube. In: Youtube. https://www.youtube.com/watch?v=7vOU24rOrOE. Accessed 1 Feb 2022
24. Hribernik K, Cabri G, Mandreoli F, Mentzas G (2021) Autonomous, context-aware, adaptive digital twins-state of the art and roadmap. Comput Ind. https://doi.org/10.1016/j.compind.2021.103508
25. Leng J, Wang D, Shen W et al (2021) Digital twins-based smart manufacturing system design in Industry 4.0: a review. J Manuf Syst 60:119–137
26. Gregor S (2006) The nature of theory in information systems. MIS Q 30:611–642
27. Hevner A, March S, Park J et al (2004) Design science in information systems research. MIS Q 28:75–105. https://doi.org/10.2307/25148625
28. Simon HA (1996) The sciences of the artificial, 3rd edn. MIT Press, London, England
29. Peffers K, Tuunanen T, Rothenberger MA, Chatterjee S (2007) A design science research methodology for information systems research. J Manag Inf Syst 24:45–77. https://doi.org/10.2753/MIS0742-1222240302
30. Holmström J, Ketokivi M, Hameri A-P (2009) Bridging practice and theory: a design science approach. Decis Sci 40:65–87. https://doi.org/10.1111/j.1540-5915.2008.00221.x
31. Drechsler A, Hevner A (2016) A four-cycle model of IS design science research: capturing the dynamic nature of IS artifact design. In: 11th International Conference on Design Science in Information Systems and Technology (DESRIST). pp 1–8
32. van Aken J, Chandrasekaran A, Halman J (2016) Conducting and publishing design science research: inaugural essay of the design science department of the Journal of Operations Management. J Oper Manag 47–48:1–8. https://doi.org/10.1016/j.jom.2016.06.004
33. Ketokivi M, Choi T (2014) Renaissance of case research as a scientific method. J Oper Manag 32:232–240. https://doi.org/10.1016/j.jom.2014.03.004
34. Sanchez R, Heene A, Thomas H (1996) Introduction: Towards the theory and practice of competence-based competition. In: Dynamics of competence-based competition theory and practice in the new strategic management. Pergamon, pp 1–35
35. Glaessgen EH, Stargel DS (2012) The digital twin paradigm for future NASA and U. S. Air force vehicles. In: 53rd Structures, Structural Dynamics, and Materials Conference. pp 1–14
36. Kritzinger W, Karner M, Traar G et al (2018) Digital twin in manufacturing: a categorical literature review and classification. IFAC-PapersOnLine 51:1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474
37. Marx K (1845) Theses on Feuerbach. Foreign Languages Press 104:61–65.https://doi.org/10.1525/rep.2008.104.1.4
38. Heidegger M (1969) Martin Heidegger from a 1969 interview with Richard Wisser on Marx and World Change. YouTube
39. Fine CH (2000) Clockspeed-based strategies for supply chain design. Prod Oper Manag 9:210. https://doi.org/10.1111/j.1937-5956.2000.tb00134.x
40. Sanchez R (2012) Architecting organizations: a dynamic strategic contingency perspective. Research in Competence-Based Management 6:7–48. https://doi.org/10.1108/S1744-2117(2012)0000006004
41. von Bertalanffy L (1968) The meaning of general system theory. In: General System Theory. Foundations, Development, Applications. pp 30–53
42. von Bertalanffy L (1956) General system theory
43. Frodeman R (2013) Sustainable knowledge: a theory of interdisciplinarity
44. Guberman S (2004) Reflections on Ludwig Bertalanffy's "general system theory: foundations, development, applications." In: General system theory. Foundations, Development, Applications. pp 44–57
45. Ackoff RL (1994) Systems thinking and thinking systems. Syst Dyn Rev 10:175–188. https://doi.org/10.1002/sdr.4260100206
46. Ackoff RL (2005) Creating the corporate future. In: Lucas M (ed) Understanding business environments, 1st edn. Routledge, pp 224–234
47. Simon HA (1962) The architecture of complexity. Proc Am Philos Soc 106:467–482. https://doi.org/10.1080/14759550302804
48. Simon HA (1976) How complex are complex systems. In: Proceedings of the Biennial Meeting of the Philosophy of Science Association. pp 507–522
49. Snowden DJ, Boone ME (2007) A leader's framework for decision making. Harv Bus Rev. https://doi.org/10.1109/MCDM.2007.369449
50. Sanchez R (1997) Strategic management at the point of inflection: systems, complexity and competence theory. Long Range Plan 30:939–946. https://doi.org/10.1016/S0024-6301(97)00083-6
51. Hegel GWF (1932) The phenomenology of mind. Nature. https://doi.org/10.1038/130420c0
52. Mourtzis D (2020) Simulation in the design and operation of manufacturing systems: state of the art and new trends. Int J Prod Res 58:1927–1949. https://doi.org/10.1080/00207543.2019.1636321
53. Turner CJ, Hutabarat W, Oyekan J, Tiwari A (2016) Discrete event simulation and virtual reality use in industry: new opportunities and future trends. IEEE Transactions on Human-Machine Systems 46:882–894. https://doi.org/10.1109/THMS.2016.2596099
54. Jain S, Shao G, Shin SJ (2017) Manufacturing data analytics using a virtual factory representation. Int J Prod Res 55:5450–5464. https://doi.org/10.1080/00207543.2017.1321799
55. Fine CH (1998) Clockspeed: winning industry control in the age of temporary advantage. MIT Sloan School of Management, Perseus Books, Reading, MA
56. Fine CH (1996) Industry clockspeed and competency chain design: an introductory essay. In: Proceedings of the 1996 Manufacturing and Service Operations Management Conference. MIT Sloan School of Management, pp 1–9
57. Lepercq P (2008) The fruit fly and the jumbo jet: from genetics to the theory of industrial cycles applied to the aircraft industry. Supply Chain Mag (online)
58. Leitner K-H (2015) Pathways for the co-evolution of new product development and strategy formation processes: empirical evidence from major Austrian innovations. Eur J Innov Manag 18:172–194. https://doi.org/10.1108/EJIM-01-2014-0002
59. Fine CH, Vardan R, Pethick R, El-Hout J (2002) Rapid-response capability in value-chain design. MIT Sloan Manag Rev 43:68–76

60. Tolio T, Sacco M, Terkaj W, Urgo M (2013) Virtual factory: an integrated framework for manufacturing systems design and analysis. Procedia CIRP 7:25–30. https://doi.org/10.1016/j.procir.2013.05.005
61. Sanchez R, Heene A (1997) Reinventing strategic management: new theory and practice for competence-based competition. Eur Manag J 15:303–317. https://doi.org/10.1016/S0263-2373(97)00010-8
62. Sanchez R (2004) Creating modular platforms for strategic flexibility. Design Management Review 15:58–67. https://doi.org/10.1111/j.1948-7169.2004.tb00151.x
63. Souza MCF, Sacco M, Porto AJV (2006) Virtual manufacturing as a way for the factory of the future. J Intell Manuf 17:725–735. https://doi.org/10.1007/s10845-006-0041-1
64. Yang X, Malak RC, Lauer C et al (2015) Manufacturing system design with virtual factory tools. Int J Comput Integr Manuf 28:25–40. https://doi.org/10.1080/0951192X.2013.800948
65. Bal M, Hashemipour M (2009) Virtual factory approach for implementation of holonic control in industrial applications: a case study in die-casting industry. Robot Comput Integr Manuf 25:570–581. https://doi.org/10.1016/j.rcim.2008.03.020
66. Tolio T, Copani G, Terkaj W (2019) Factories of the future the Italian Flagship Initiative. Springer Open
67. Choi S, Kim B, Noh S (2015) A diagnosis and evaluation method for strategic planning and systematic design of a virtual factory in smart manufacturing systems. Int J Precis Eng Manuf 16:1107. https://doi.org/10.1007/s12541-015-0143-9
68. Mantravadi S, Møller C (2019) An overview of next-generation manufacturing execution systems: how important is MES for Industry 4.0? Procedia Manuf 30:588–595. https://doi.org/10.1016/j.promfg.2019.02.083
69. Mantravadi S, Møller C, Christensen F (2018) Perspectives on real-time information sharing through smart factories: visibility via enterprise integration. In: International Conference on Smart Systems and Technologies (SST). IEEE
70. Lapalme J (2012) Three schools of thought on enterprise architecture. IT Professional 14:37–43. https://doi.org/10.1109/MITP.2011.109
71. Nardello M, Møller C, Gøtze J (2017) Organizational learning supported by reference architecture models : Industry 4.0 laboratory study. Complex Systems Informatics and Modeling Quarterly. IT Prof. https://doi.org/10.7250/csimq.2017-12.02
72. Nardello M, Han S, Møller C, Gøtze J (2019) Automated modeling with abstraction for enterprise architecture (AMA4EA): business process model automation in an Industry 4.0 laboratory. CSIMQ. https://doi.org/10.7250/csimq.2019-19.03
73. Mikel A, Ghassempouri M, Ozturk E, Peysson F (2018) Twin-control a digital twin approach to improve machine tools lifecycle. Springer, Cham, Switzerland
74. Porac JF, Thomas H, Baden-Fuller C (1989) Competitive groups as cognitive communities: the case of Scottish knitwear manufacturers. J Manage Stud 26:397–416
75. Tushman ML, Romanelli E (1985) Organizational evolution: a metamorphosis model of convergence and reorientation. Res Organ Behav 7:171–222
76. Delbrügger T, Meißner M, Wirtz A et al (2019) Multi-level simulation concept for multidisciplinary analysis and optimization of production systems. Int J Adv Manuf Technol 103:3993–4012. https://doi.org/10.1007/s00170-019-03722-1
77. Zhang Z, Guan Z, Gong Y et al (2020) Improved multi-fidelity simulation-based optimisation : application in a digital twin shop floor. Int J Prod Res. https://doi.org/10.1080/00207543.2020.1849846