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 lifecycle 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 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: Section 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; Section 3 introduces the vocabulary and VF concept; Section 4 evaluates the VF based on four dimensions of competence theory; Section 5 discusses the implementation of basic forms of change in organisation architectures using VF tools, before concluding in Section 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.

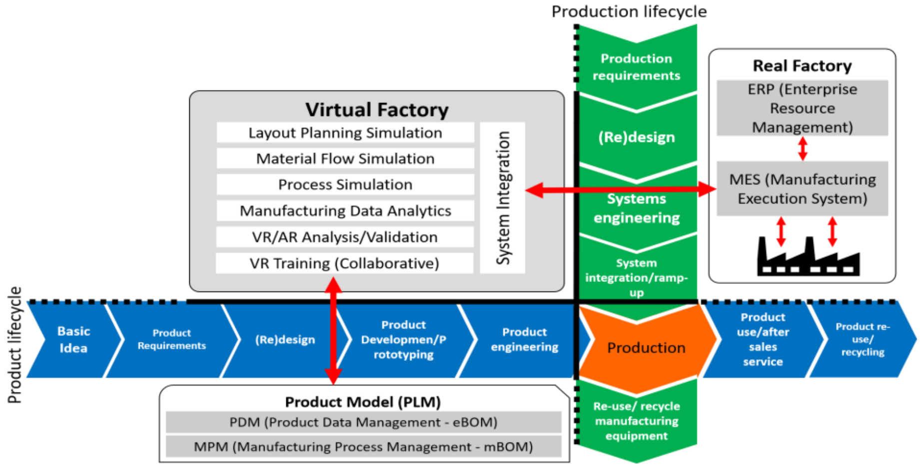

Fig. 1 Virtual Factory Concept

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.

Modular VF Architecture for Manufacturing Enterprise. Fig. 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.

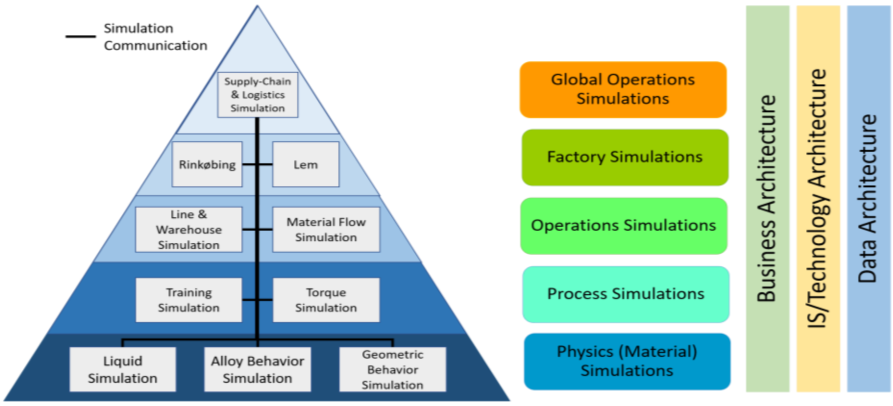

Fig. 2 Virtual Factory Architecture

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.

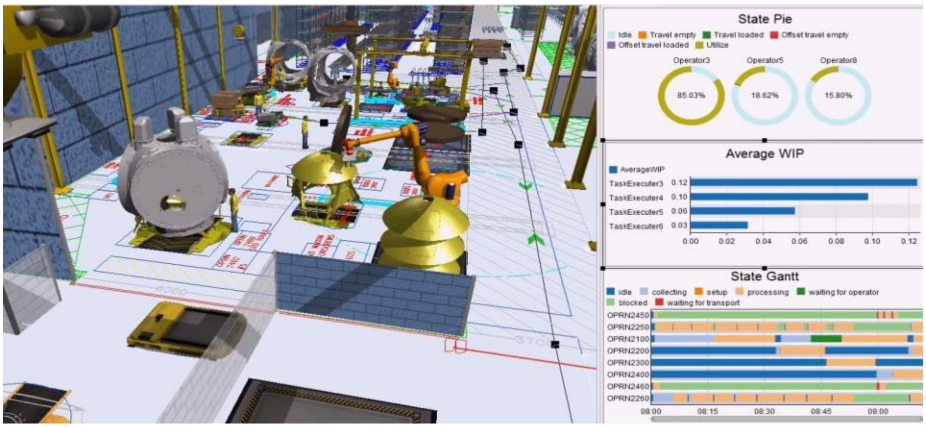

Fig. 3 3D Discrete Event Virtual Factory Simulation

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.

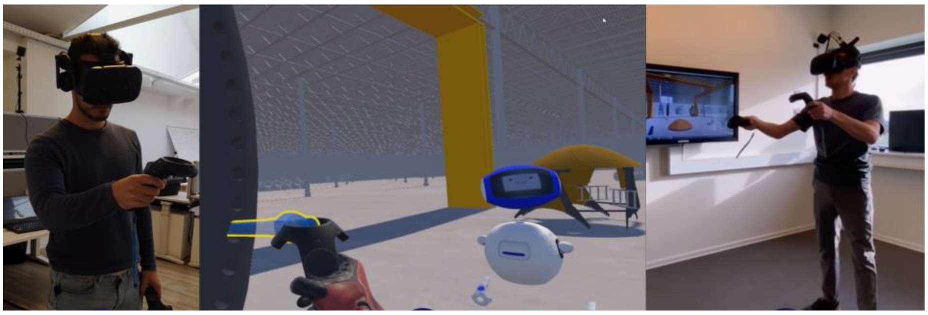

Fig. 4 Collaborative VR Assembly Simulation [27, 28]

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 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.

Fig. 5 Scan QR code for VF demo.

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.

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