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Developing a lean digital twin framework for improving supply chain quality

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Abstract

The depth of value creation is decreasing, global value networks are expanding and becoming more complex. Since companies are dependent on the quality capability of their supplier base, ensuring and improving product and process quality is more and more difficult. In this context, the use of digital twins in the value network offers an opportunity to meet these challenges. With the help of digital twins, collaboration between original equipment manufacturers and suppliers can be strengthened, processes can be optimized and new value creation potentials can be tapped. Therefore, this article aims to develop a basic framework for the use of digital twins in value networks. In particular, key elements and essential requirements are highlighted. In addition, the concept is evaluated with respect to the guiding principles of lean management in its role as an enabler of digital transformation. As a result, the use of digital twins in value networks in accordance with the guidelines of lean management enables companies to overcome the complexity barrier of today's production systems and continuously increase supply chain quality.

Keywords: Digital Twin; Lean Management; Quality Management; Supply Chain Quality, Value Network

1. Introduction

The era in which customers, as claimed by Henry Ford, were only supposed to buy black cars in order to operate the production system economically came to an end a long time ago. While automotive production at Ford started with just one single version, the "Model T", at the beginning of the 20th century, today there are a multitude of variants that make billions of individual vehicles possible [1]. This trend towards complexity and variant diversity is reinforced by globalization and has significant effects on manufacturing companies and, in particular, on their value networks. These networks are geographically expanding and becoming more complex. On top of that, digitalization and networking further increase the competitive and innovation pressure on companies [2].

In order to meet these challenges, companies are required to continuously adapt their (quality) management systems and recognize the benefits of new technologies [3, 4]. Effective supply chain quality management is essential in order to minimize dependencies, reduce costs and improve quality [5]. In view of the volume and diversity of information that companies face in networked value systems, they must be able to gain direct insights into markets, customers, suppliers and internal processes from the available data [2].

At this point, the management of global value creation networks can be supported using modern information and communication technologies such as the digital twin. A digital twin is essentially a dynamic, digital image of a real, physical system [6, 7]. Applications can be found in many areas of a company, from development, production and logistics to quality management and supply chain management [4]. There is great potential for increasing productivity, automated processing of information and the efficient networking of globally distributed companies [3]. The overarching vision is

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to create dynamic, real-time optimized and self-organizing, cross-company value networks and to realize transparent control and organization of this network over the entire life cycle of goods and products [8].

In this context, the aim of the present article is to develop a basic framework for the use of digital twins in value networks. In particular, fundamental requirements and key elements will be highlighted. Furthermore, the concept is evaluated with regard to the guiding principles of lean management in its role as an enabler of the digital transformation. The result will reveal to what extent the use of digital twins in value networks complies with the known lean principles and whether digital twins can lead to a reduction of waste in the supply chain.

2. Background

The increasing outsourcing of value creating activities and the external procurement of critical goods underline the need for robust quality management throughout the supply chain and the entire value network. Coordination of such networks requires special attention due to power relationships, information sovereignty and missing trust [5]. However, the lean approach alongside modern digital technologies can support supply chain quality management.

2.1. Interdependence of lean and digitalization

Lean is a holistic management approach and a corporate philosophy that aims to align all processes in the company with customer requirements, minimize waste and maximize efficiency [9].

The core of lean management can be characterized by the following five lean principles: Specification of value from the customer's point of view, identification of the value stream, flow, pull and perfection. Accordingly, the customer requirements must first be specified to determine which characteristics of the product constitute its value. It is then necessary to identify all internal and external activities of the value creation process, whether they add value or not. This implies examining the entire value network, including suppliers. As part of the flow principle, the previously identified value creation process should be prevented from being interrupted by the intermediate storage of semi-finished or finished products. Pulling the value ensures that just the amount is produced that is actually required by the downstream process step or the customer. The production process is therefore triggered in a decentralized, consumption-oriented manner by the (internal) customer instead of by the company's central planning process. Ultimately, lean incorporates the continuous pursuit of improvement, culminating in perfection and zero defects [9, 10].

On the way to this perfection and in order to identify and eliminate non-value-added activities, all waste in the form of transportation, inventory, motion, waiting, overproducing, over-processing and defects must be eliminated [1].

With regard to the relationship between the lean approach and modern technologies such as the digital twin, lean and the digitalization of production systems are mutually interdependent and complement each other in many respects. For instance, a positive correlation between the lean maturity level of companies and the degree of implementation of digital technologies has been proven [11, 12].

On the one hand, lean organizations and lean processes are considered a prerequisite and enabler of digitalization. For example, alignment with lean principles can be identified as the basis for the successful introduction of modern technologies. Before processes are digitalized, they should be optimized using lean methods [1, 12]. On the other hand, traditional lean methods need to be supplemented by modern technologies, as their potential for increasing efficiency is almost exhausted. As illustrated in Fig. 1, lean reaches its complexity barrier beyond which additional optimization efforts are of little use. In this context, information and communication technologies support lean management in further improving processes and productivity [13].

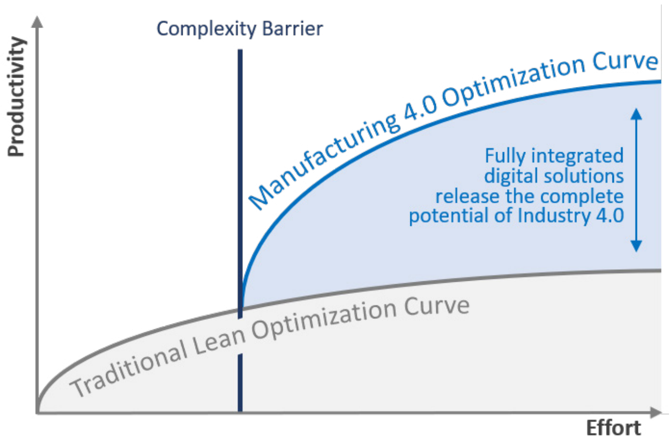

Fig. 1. Overcoming the complexity barrier by combining lean management and Industry 4.0 (adapted from [13]).

2.2. Concept of digital twins

The origin of the digital twin can essentially be found in the US space agency NASA as well as in Dr. Michael Grieves. As early as 1970, NASA used a physical twin of the Apollo 13 space capsule, which helped to rescue the astronauts when the spacecraft's oxygen tank exploded. This physical twin remained on Earth throughout the space mission and served to simulate the conditions in the actual space capsule. This early approach can be considered a predecessor of today's digital twins [14]. Meanwhile, Grieves presented an approach in the field of product lifecycle management in 2003. Although he initially labeled it differently, his concept already fulfilled the characteristics of a digital twin [15].

Today, a digital twin is defined as a dynamic, digital image of a real, physical object, process or system, including its properties, behaviors and state changes. This virtual image enables the monitoring, simulation, control and optimization of its real counterpart through long-term, bidirectional data exchange. This merging of the virtual and real worlds will continue in the future, occasionally resulting in cross-organizational digital twin ecosystems [6, 7, 16].

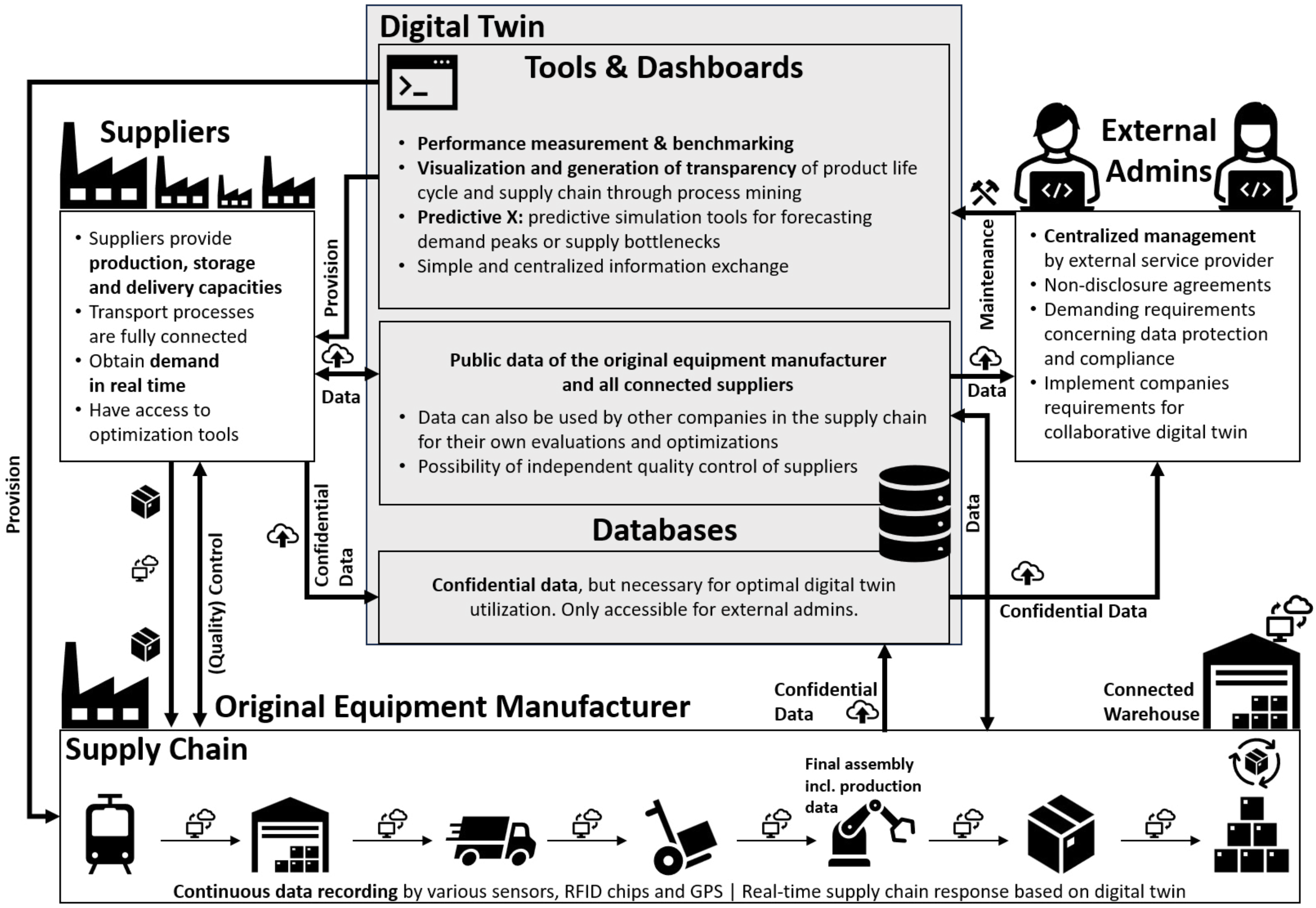

Fig. 2. Framework for the use of digital twins in value networks.

3. Application framework for digital twins in supply chain quality management

Applications of digital twins in the field of supply chain quality management currently include for instance preventive maintenance and repair [17], quality control and monitoring [18], predictive fault detection and correction [19] as well as process optimization [20]. Other examples comprise the coordination and synchronization of multimodal transport chains [21], the optimization of sourcing strategies and supplier selection [22], decision support in terms of warehouse and inventory strategies [23] as well as supply chain risk management [24].

The framework, shown in Fig. 2, is built based on this state of the art. The concept aims to clarify the different layers of the digital twin and their interactions within the value network. It illustrates the embedding of a digital twin in the value chain, particularly with regard to quality and process optimization. The focus is specifically on cross-company collaboration as well as the identification of key elements and requirements.

The digital twin at the center is connected to both the suppliers and the original equipment manufacturer and consists of three different layers. This division into three layers has already proven to be best practice in this context [25, 26]. The top layer is the optimization layer. This is actively used by companies, both suppliers and original equipment manufacturers. The optimization layer provides all required optimization and overview tools. These include dashboards with important KPIs and benchmarking, process visualizations, simulation and quality tools as well as access to appropriate communication channels. The lower and middle layers of the digital twin consist of the underlying databases in the form of two communication layers. It should be noted in advance that the digital twin is managed centrally in this case and not by the companies using it. The external service providers are also responsible for maintaining and setting up the digital twin. This form of administration can be particularly advantageous in terms of scalability and generating trust between the value creating partners.

The split communication layer intends to ensure data security and data sovereignty within the concept. The upper communication layer is also accessible and can be viewed by the participating companies. Data from here can be used for individual company evaluations and applications. This can, for example, simplify supplier analyses, the selection of inventory and procurement strategies as well as quality control. The lower communication layer, contrariwise, is not publicly accessible and is only managed by the administrators of the digital twin. This is where data is stored that should not be made publicly available for the value creating partners, but which is nevertheless relevant for cross-company optimization.

Overall, the use of digital twins in value networks is characterized by a number of key elements and related requirements:

3.1. Digital infrastructure

The supply chain depicted in the framework is fully networked. An important prerequisite for this connectivity is the corresponding digitalization of the value network and the implementation of essential basic technologies. The use of sensor technology plays an integral role in this concept. For example, goods and products can be tracked using RFID to create the necessary transparency within the supply chain. The fact that time stamps are recorded at all necessary process points in the supply chain is highly relevant for data processing within the optimization layer with regard to process mining and time series analyses. Besides, transport vehicles can be equipped with GPS so that their location can be transferred to the cloud and thus to the digital twin as required and used to optimize route and transport planning. Overall, the efficient and reliable collection of all supply chain data is an essential prerequisite for an optimal mapping of the value network using the digital twin.

3.2. Real-time data transmission

Real-time capability is a frequently discussed aspect of digital twins. While a rapid update frequency is regularly required for processes at the shop floor level, real-time tracking of containers on long sea journeys, for example, does not create any added value. Therefore, the implementation of digital technologies must always consider the specific circumstances and business goals of the individual use case.

Moreover, the complete networking of the supply chain permits continuous data transmission, which strengthens the controllability and manageability of the value network for companies. Capacity peaks, capacity utilization and demand are continuously monitored by the value-added partners. Continuous data transmission also enables effective risk management, for example by reporting system failures in real time within the network and simulating their effects. Suppliers can react to critical stock levels and prevent supply bottlenecks. Ultimately, the real-time transmission of data within the supply chain serves to enhance the resilience and efficiency of the entire system.

3.3. Scalability

The scalability of the concept is primarily ensured by outsourcing the digital twin to an external service provider. As part of the framework, the service provider provides both the platform and the cloud and is also responsible for maintenance. Partner companies that decide to implement a joint digital twin can consolidate their requirements and forward them to the service provider who will then set up the platform. On the one hand, this principle of software-as-a-service has some disadvantages, such as dependence on the solution provider. On the other hand, the advantages of this solution often outweigh the disadvantages, resulting in long-term profitability. For example, the use of a cloud platform does not require any major investment in proprietary hardware or infrastructure, which is often a hurdle especially for smaller companies at the end of the supply chain. Moreover, the establishment of trust between value-added partners can be facilitated by the involvement of an independent third-party provider in the administration of the digital twin.

3.4. Collaboration

Another crucial aspect of the utilization of digital twins in value networks is collaboration. Thus, suppliers and original equipment manufacturers work together and establish a joint data ecosystem. While data security and data sovereignty regulations are essential, the willingness to work together and mutual trust are fundamental prerequisites for the shared use of digital twins. The collaborative digital twin therefore creates comprehensive transparency across the entire product life cycle and the entire value chain, assuming a critical mass of collaborating partner companies is reached. Quality issues, errors, and delivery bottlenecks can be identified and resolved together at an early stage, thereby ensuring high product and product quality within the value network. In addition, new business ideas and strategies can be developed collectively on the basis of close cooperation, which can generate a competitive advantage over non-networked companies.

3.5. Optimization

The optimization layer of the model offers a wide range of applications and insights for original equipment manufacturers and involved suppliers. Cooperative dashboards provide access to important KPIs and foster benchmarking of the supplier base. Indicators such as delivery reliability, delivery punctuality, scrap rate, supplier response time, stock levels and other criteria such as the sustainability performance of suppliers can be evaluated and compared. Continuous updates allow companies to reassess how they want to respond to the current status of the KPIs on a daily basis. In the event that a supplier's rejection rate increases over time, a supplier audit can be initiated in a timely manner.

Furthermore, processes can be transparently displayed from the beginning of the supply chain up to the finished end product by integrating cross-company process mining. This approach supports the discovery and explanation of process weaknesses that could not previously be identified or justified.

The optimization layer of the digital twin can also stimulate other applications related to quality management. Any predictive models, here designated as "predictive-x", can be employed effectively by integrating a digital twin and artificial intelligence. This integration enables both suppliers and original equipment manufacturers to forecast the remaining useful life of machines or predict faults.

All in all, the framework adopts a collaborative approach and aims to strengthen cooperation between original equipment manufacturers and suppliers. The individual key elements are intertwined and complement each other. In terms of ensuring and improving product and process quality in the value network, the use of digital twins promotes, for example, the early detection of errors in combination with appropriate fault and risk management. The extensive data sets available permit the detection of unplanned process behavior within the supply chain through the use of digital twins. More precisely, if a transporter loads the wrong containers, the digital twin immediately identifies the deviation from the target status and the error can be directly rectified. At the same time, this information can also be forwarded to downstream stations or companies, which can then adapt their subsequent processes to the delay that has occurred. Consequently, an adequately developed risk management system offers the potential for the formulation of recommendations for future action based on the error that has occurred and the available data.

4. Framework evaluation based on lean criteria

As outlined above, the combination of lean management with contemporary information and communication technologies such as the digital twin enables a new level of increased efficiency and productivity. Consequently, it is important to examine the extent to which the use of digital twins in value networks aligns with the basic lean principles and to what extent the proposed concept helps to effectively minimize the various types of waste.

4.1. Fulfillment of lean principles

Firstly, the framework emphasizes collaboration between suppliers and original equipment manufacturers. The digital twin facilitates the definition and coordination of intermediate or end customer requirements and expectations. This simplifies the identification of deviations at an early stage, allowing appropriate countermeasures to be implemented before faults affect the end customer. Moreover, the digital twin of the product permits the transfer of user behavior from the application phase of a product back into future development cycles, thereby enhancing customer orientation in accordance with the first lean principle.

In order to fulfill the value stream principle, it is necessary to comprehensively capture the value stream. All components of the value stream must be analyzed and optimized in an appropriate manner and all influences must be considered. This is made possible by equipping the various stations and parts of the supply chain with sensors, chips and computers as well as process mining integrated into the optimization layer. The necessary transparency of the value stream is created and a holistic representation of the supply chain is established.

In addition, the concept also enhances the process flow within the supply chain by identifying bottlenecks, preventing waiting times and supply chain disruptions as well as avoiding downtimes or failures due to errors. This is achieved within the framework through continuous data transmission and monitoring of the value network, which enables the predictive planning of further process steps.

The pull principle, which entails the demand-oriented alignment of production, is also supported by the digital twin of the value network. Production processes, intermediate stocks and inventories are continuously updated and made available. As a result, products can be manufactured immediately as soon as a customer need arises or a potential customer need becomes apparent. Suppliers can react early and automatically. Distributed across the various stages of the value chain, the digital twin approves decentralized control of the network.

Eventually, the implementation of digital twins also contributes to continuous improvement by identifying weaknesses and highlighting opportunities for optimization. This is particularly evident in the reduction of the seven wastes. Continuous improvement is made possible by the constant monitoring of processes and KPIs using dashboards, process mining and analytics tools. At the same time, the concept helps to strengthen cross-company collaboration and thus enables a more holistic approach to process optimization.

4.2. Elimination of wastes

The integration of digital twin technology and real-time data transmission in transport processes has the potential to optimize goods traffic and reduce waste. The use of GPS equipment on transport vehicles offers the precise real-time localization. The monitoring of stock levels and production requirements also allows for the planning of transportation in line with demand. The digital twin indicates the demand and location of products in real time, which features the optimization of route planning in order to minimize transport times and reduce fuel consumption. Using real-time data, the digital twin can coordinate deliveries so that they arrive exactly when the goods are needed. This also reduces unnecessary storage times. The optimization of transport is therefore closely linked to storage and waiting.

With regard to storage, it should be complemented that the digital twin can analyze stock levels in real time and initiate automated ordering processes to avoid overstocking. This minimizes storage costs and promotes just-in-time delivery. Besides, the digital twin can be utilized to ascertain optimal storage and inventory strategies through simulations.

By providing all the relevant information, the amount of physical movement can be reduced. The precise location tracking of products, parts, and vehicles through the digital twin supports the planning of efficient means of transporting goods within the factory and between different locations. By avoiding unnecessary movements and optimizing routes, not only is the physical workload reduced, but energy consumption and environmental impact are also minimized.

As the production process and the supply chain are fully networked in the framework presented and workloads, positions and requirements can be derived, a significant reduction in waiting times within the supply chain can be expected. In addition, machine downtimes can be minimized within the optimization layer. By analyzing historical data, the system is able to determine the remaining useful life of a machine and initiate preventive maintenance measures before a breakdown occurs. This allows for the avoidance of idle and waiting times caused by breakdowns.

The use of digital twins provides an important foundation for the prevention of overproduction in conjunction with demand-driven production. The real-time transmission and continuous availability of data within the digital twin enable precise demand planning. Overproduction, which can be attributed to uncertainties in demand and planning due to fluctuations in supply and demand, is minimized by accessing current stock levels, historical sales data, trends through analytics and holistic process transparency.

With regard to over-processing, waste within existing workflows can be identified in particular through integrated process mining. Overall, however, the digital twin has comparatively less influence in this area.

Finally, the digital twin, when combined with the integration of sensors in the production process, can immediately detect and recognize deviations from the defined quality standards. Early warning systems can react automatically as soon as process parameters exceed the defined process limits. This allows potential quality issues to be identified at an early stage, causes to be rectified and scrap and rework to be minimized.

5. Conclusion

The utilization of digital twins in value networks offers a multitude of opportunities to ensure and improve product and process quality. For instance, digital twins are capable of identifying quality deficiencies in real time. In the context of troubleshooting, digital twins in conjoined with contemporary data analyses assist in determining the root cause of errors and implementing suitable solutions. Process optimizations can also be tested based on simulations without the necessity of intervening in the actual system.

The framework depicted in the present paper offers a basic orientation as well as a functionally expandable approach that can be adapted to the individual company. Certain key elements are relevant in this context, in particular the availability of a basic Industry 4.0 infrastructure including enabling digital technologies, continuous data transmission, scalability, collaboration between the value-added partners and the holistic optimization of the value network. The more holistic and in-depth the digital twin is embedded in the value network, the greater the potential value added.

All in all, it is evident that the basic lean principles are also employed in the planning and control of contemporary value networks. In conjunction with digitalization, the complexity barrier of today's production systems is overcome and performance is further enhanced. For example, numerous potential sources of waste in the value network can be identified and eliminated with the assistance of technology through the digital twin.

The subsequent stage is to further explore the utilization of digital twins at a cross-company level, based on defined use cases, and to continuously increase their maturity and acceptance. In the longer term, this will guarantee that car manufacturers like Ford can continue to produce far more than just black cars profitably and that today's companies can deal with the complex and dynamic market environment.

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