Design Model for Digital Shadow of Value Stream

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The value stream method, a key tool in industry to analyze and visualize value streams in production, aims to holistically optimize process steps, reduce waste, and achieve continuous material flow. However, this method primarily relies on data from a single on-site inspection, which is subjective and represents just a snapshot of the process. This limitation can lead to uncertainty and potentially incorrect decisions, especially in industries producing customer-specific products. The increasing digitization in production offers a solution to this limitation by supporting the method through data provision. The concept of the digital shadow emerges as a key tool that systematically captures, processes, and integrates necessary data into a model to enhance traditional value stream mapping.

value stream management digitalization digital shadow design model

1. Introduction

Global competition, short product life cycles, disruptive technologies and volatile markets regularly confront manufacturing companies with new challenges. Increased requirements for flexibility, efficiency and resilience of production and thus its value streams are indispensable [1]. Traditionally, production systems are usually designed for a specific combination of product mix and production volume. Neglecting this optimal operating point typically leads to efficiency losses [2]. To reduce these efficiency losses, it is necessary to have short-term updated information about the status of a production system or the associated value streams [3]. A method widely used in industry for the transparent representation of value streams is the value stream method [4][5]. Both material and information flows can be visualized with its use, and wastage in the process can be revealed [6]. However, with the need to adjust a value stream quickly and objectively to new challenges, the value stream method reaches its limits. The usually paper-based, single data collection on-site only enables a subjective snapshot of a value stream and does not consider the dynamic development of production [7]. Since the information to describe a value stream is typically collected through on-site inspection, the effort to update value stream parameters on a situational basis is too costly [8]. Although the proportion of available transaction data is increasing through the use of production data acquisition systems or technologies for automatic identification, these are usually not sufficient to describe the value stream completely [9]. Essential data, such as set-up times, technical availabilities or batch sizes, are not continuously recorded [10]. For this reason, a further development of the value stream method is necessary to be able to capture the dynamics in production systems. A study from 2017 [8] indicates that around two thirds of the lean experts questioned consider a further development of the value stream method with the help of Industry 4.0

technologies to be promising. The combination of both approaches has the potential to eliminate the aforementioned restrictions of the conventional value stream method without neglecting the actual goal—a reduction in waste in the value stream [8]. In recent years, multiple scientific papers examined which Industry 4.0 technology is most suitable for this application [11][12][13][14][15][16][17][18][19][20]. This showed that the concept of the digital shadow is considered the most likely to address the disadvantages mentioned and to further develop the value stream method towards a digital management approach.

The concept of the digital shadow has the potential to systematically capture the necessary data, condense it and make it available in a data model [21]. There are already approaches in the literature that deal with the implementation of digital twins in production [22][23]. A universally valid design model of the digital shadow for a value stream, however, does not exist. A design model can be understood as a so-called target model. It enables a system-oriented planning and design of complex systems [24]. In this way, large systems can be subdivided into individual parts and become manageable. The target model provides alternative solutions and decision recommendations for users [25]. Due to the heterogeneous IT landscapes and complexity of the value streams, though, there is a need for a generally valid model for the implementation of a digital shadow for a value stream [21].

2. Design Model for Digital Shadow of Value Stream

2.1. Value Stream Management

Value stream management is not consistently defined in the literature. Often, the term is used synonymously with the value stream method [21][26]. A more detailed understanding can be found in the work of Erlach, who understands value stream management as the "continuous adaptation and improvement of the value stream during production operations" [6]. This includes, among other things, the planning and control of parameters, such as monitoring the number of kanban cards, as well as activities of conventional production planning. Following this understanding, there are three planning levels into which value stream management can be divided [6]:

- Long-term planning to design a value stream;
- Medium-term planning for balancing the production;
- Short-term planning for production control.

Long-term planning aims to design a value stream. This includes, for example, the re-dimensioning of production resources in case of changes in customer demand or the redesign of material flow connections. In *medium-term planning*, the value stream is planned by balancing the production. Besides the formation of release quantities, an adjustment of Kanban and ConWIP quantities (constant work in progress) takes place, if necessary. Furthermore, it must be ensured that the installed capacities provided by personnel and labor planning can execute the production program. During *short-term planning*, the release units are sequenced for production and the bottleneck process is controlled at the operational level. The customer demand is transferred into a production program under constraints which must consider the available capacity and delivery deadlines [6]. In summary, it can be stated that value stream management means the planning, management, and control of the value stream along the material flow, with the aim of continuously enabling the best possible design of the value stream based on a holistic perspective [14]. Accordingly, an improvement of the value stream ideally does not take place selectively, but continuously. In consequence, continuous application of the value stream method is necessary to analyze the current state and design the future target state.

This is a major challenge for value stream managers, as the conventional value stream method has a static project character and, due to the intensive personnel effort required to implement the value stream method in companies, it is usually only applied occasionally and not regularly [8]. Only if companies manage to reduce the implementation and, above all, update effort of the value stream method, a continuous application and thus a holistic value stream management will be feasible in practice. To realize this, it is advisable to use digital support that reduces the effort required to update the value stream maps [8]. An analysis of existing approaches in the literature for enhancing the value stream method shows that the concept of the digital twin is seen as offering the greatest potential.

Ciano et al. use a multiple use case study to identify one-to-one relationships between Industry 4.0 technologies and lean production techniques. The value stream method is assigned to the concept of vertical integration. Linking them has the potential to identify production weaknesses and eliminate them with the help of end-to-end data integration [11]. Dillinger et al., in turn, use a Delphi study and a domain mapping matrix to assign direct relationships between lean production techniques and Industry 4.0 technologies. This study identifies the majority of linkages. The linking of the value stream method with vertical integration, fundamental analytics, the area of big data, the digital twin, horizontal integration, support through Auto-ID, integration in cyber-physical systems, the use of real-time data, the use of cloud computing or support through simulation are named as promising further development potentials [12]. Erlach et al. use a literature analysis to determine the current directions for further development of the value stream method in context of digitalization. The main development potential is seen in supporting the application of the method through analytics or the implementation of a digital twin [13]. Langlotz and Aurich proceed in their analysis of existing links between Industry 4.0 technologies and lean production methods based on Industry 4.0 clusters. The value stream method is assigned to the automatic condition monitoring cluster with the concept of the digital twin [14]. Mayr et al. identify correlations between lean methods and Industry 4.0 technologies based on a use case. The biggest value for the value stream method is seen in increasing transparency through a real-time image using real-time data of the value stream. Supporting Industry 4.0 technologies are Auto-ID, the digital twin, the use of analytics and big data, the integration of cloud computing and the simulation of future target states [15]. Dillinger et al. assign Industry 4.0 technologies to the methods of lean production with the help of expert interviews. The technologies of big data, digital twin, Auto-ID and real-time data are assigned to the value stream method [16]. Florescu and Barabas use a systematic literature analysis to identify correlations between lean production methods and Industry 4.0 technologies. Regarding the value stream method, vertical and horizontal integration, big data, digital twin, cyber-physical systems and simulation correlate with the value stream method [17]. Liu and Zhang also use a systematic literature analysis to determine the current development directions of the value stream method. Within the context of Industry 4.0, the digital twin, the use of real-time data and the expansion using simulation are identified [18]. Ortega et al. conduct a case study analysis to identify the influence of lean production methods in combination with Industry 4.0 technologies on company performance. The technologies of big data, digital twin and cloud computing are identified for the value stream method, but without specifying the influence on company performance [19]. Pereira et al. use a systematic literature analysis to determine the influence of lean methods on companies with the aid of Industry 4.0 technologies. The use of analytics, big data and simulation in the context of the value stream method is mentioned [20].

Accordingly, the virtual image of reality—known as the digital shadow in the literature—has the capability to push the dynamization and further development of the method into a management approach. Therefore, the basics of the digital shadow concept are presented below.

2.2. Digital Shadow

The concept of the digital shadow is not uniquely defined in the literature [27][28]. Nevertheless, three standard components can be identified that form the core elements of the digital twin:

- the object of observation is a physical object in real space;
- the above is represented by a virtual object in virtual space;
- both objects are connected directly by a bidirectional data and information flow [29].

Depending on the design of the bidirectional data and information flow, the literature refers to the concepts of digital model or digital twin. The concepts differ in the level of data integration between the physical and the virtual object [28][29]. A visualization of the differences can be found in **Figure 1**.

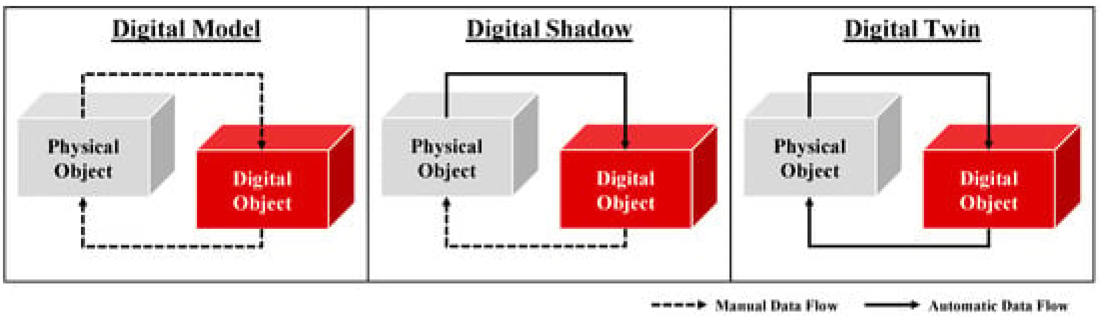

Figure 1. Interlinkage between the concepts of DM, DS and DT (based on [29]).

The **digital model** (DM) is the digital representation of a physical object without an automated data flow between the physical and the digital object. The digital object represents a sufficiently accurate image of the physical object for the specific application. Simulation models of planned factories, mathematical models of new products or virtual representations of physical objects are typical examples. Although the data of the physical object can be used to develop a DM, all data exchange is manual. A change to the physical object's state has no immediate effect on the digital object and vice versa [29]. Based on the DM, the **digital shadow** (DS) has a unidirectional automated data flow—from the physical to the digital object. This means that a change of state in the real world is reflected in the virtual world, but not vice versa [29]. Often, the DS is used exclusively for the provision of information and has no further functionalities [30]. Schuh et al. specify that the DS is always related to a specific question or task and therefore only comprises a subset of the available data. Thus, it does not completely represent a production system. The data can originate from different data sources and do not have to be homogeneous, structured or centrally available. The DS thus serves to filter, link, abstract and aggregate the data with reference to the specific problem [31]. The **digital twin** (DT), in turn, relies on the DS by automating the data flow bidirectionally. A status change of the physical object leads to an immediate status change of the digital object and vice versa. Thus, the digital object is the controlling instance of the physical object [29]. In summary, it can be said that digital twins are virtual representations of immaterial or material objects (machines, processes, services, etc.) that represent the object as realistically as possible in the digital space. In contrast, the digital shadow is merely a sufficiently accurate virtual image of the object. Only by creating a metamodel based on the DS a DT can be created.

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