Article

The Digital Value Stream Twin

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Abstract: The Value Stream Method (VSM) is widely used in manufacturing to analyze and redesign value streams. The aim is to improve processes, reduce waste and create a thorough product flow. Despite having many benefits, VSM also comes with disadvantages regarding modern dynamic production environments. It fails to meet the requirement of providing reliable information for a realistic Value Stream Design (VSD) followed by targeted improvement activities. As a result, the VSM is usually subject to uncertainty and relies on expert knowledge. Digitalization, on the other hand, is leading to an increasing availability of production data. The use of data has the potential to support the VSM with targeted data preparation. In this regard, the concept of Digital Twin (DT) offers the capability of providing the required database to systematically collect and condense this data. This paper provides a framework for the Digital Value Stream Twin (DVST). In addition, requirements for the implementation of a DVST in practice will be elaborated.

**Keywords:** digital twin; value stream method; manufacturing; data analytics

1. Introduction and State of the Art

Challenges like short product life cycles, new disruptive technologies and volatile markets place stress on today's production systems [1,2]. To adapt quickly to changing market demands and customer requirements, there is an increasing need for flexibility and transformability of production on the one hand. On the other hand, productivity and delivery performance targets have to be met. Both conflicting target areas are only insufficiently addressed by the static nature of classical production systems [3]. This leads to increasing inefficiencies. Value stream management (VSMM) [4] has the goal to systematically transform a current state value stream to a desired target state. Its major tool for creating transparency and planning change is the value stream method (VSM) [5]. The VSM aims to identify the causes of waste throughout the value stream and eliminate them by implementing a target state [6]. The target state is designed with the aid of design principles and guidelines. [7] For instance, the design guidelines support the calculation of the customer cycle, the lead time, the design of the process connections and the required number of employees [7,8]. Finally, the developed target state is gradually realized by means of individual projects as part of an implementation plan [6].

However, the VSM is reaching its limits regarding the current challenges mentioned. Due to singular data recording on site, the VSM only provides a snapshot of value streams and thus does not take into account the dynamic development of production systems [9,10]. For this reason, there is a need for further development of the VSM to meet the current dynamics of production systems. According to one study, around 66% of lean experts believe that further development of the VSM using Industry 4.0 technologies is beneficial [2]. By merging the two approaches, the restrictions can be eliminated.

One promising Industry 4.0 technology related to the optimization of production processes is the Digital Twin (DT) [11,12]. DTs received specific attention in the context of digitalization and increased implementation of cyber-physical production systems

(CPPS) where all entities can collect, generate or process data/information [13]. A DT is considered as an efficient way to accomplish the interconnection between physical and virtual spaces [14]. Within this understanding, the terms Digital Model (DM), Digital Shadow (DS) and DT are often used synonymously. However, the definitions differ in the level of data integration between the physical and digital object (see Figure 1) [11].
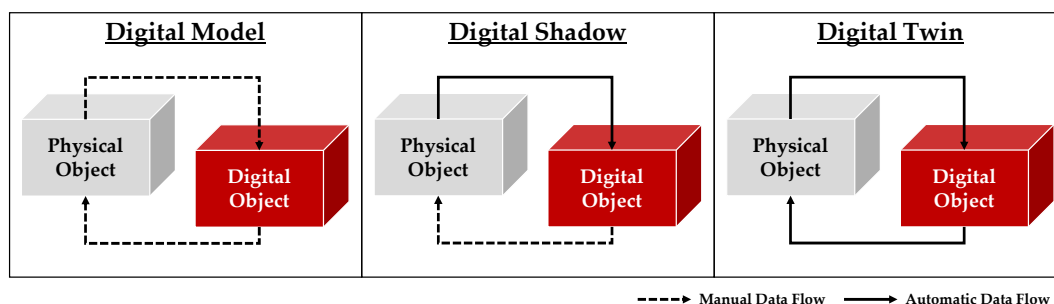
Figure 1. Interlinkage between the concepts of DM, DS and DT (based on [11]).

A DM is the digital representation of an existing physical object with no automated data exchange between the physical and digital object. It includes a comprehensive description of the physical object based on mathematical models or any other models of a physical object, which do not need an automatic data integration. The DS is an extension of the DM. For this, an automated one-way data flow between physical and digital object must exist. A change in the physical object determines a change in the digital object but not vice versa. If further, both data flow directions are fully automated, one might refer to it as a DT. In this case, the digital object represents the controlling instance of the physical object. A change in the physical object directly leads to a change in the digital object and vice versa. [11] Technical realization of the DT focuses on implementation for individual production processes, both in research and practice [11,14]. According to [15,16], an integration of the DT to represent an entire production system in digital space is promising as it links the existing production system with real-time data to a digital reflection. This allows us to eliminate the static character of a once created value stream map as dynamic changes of production systems are considered [15,16]. To the authors knowledge, the transfer and adaption of the DT concept to the complex interrelationships within a value stream to support the continuous improvement of it within VSMM has not been taken place yet. Therefore, this paper proposes a framework for the implementation of a DT at the value stream level, the so-called Digital Value Stream Twin (DVST). The DVST is defined as a comprehensive digital representation of a value stream. It includes the properties, conditions, and behaviors of a value stream through mathematical models and data. The virtual, dynamic model helps optimize the performance of a value stream. In VSMM, the DVST is used to model and present a holistic view of interrelationships and dependencies of individual production processes. The optimization of a value stream as a unit is the priority rather than the optimization of an individual production process. Thus, the following three research questions are answered to develop the framework of the DVST:

1. "What are the objectives of the DVST?"
2. "What requirements must the DVST fulfill to be used in practice?"
3. "What does the framework of the DVST consist of to be implemented in practice?"

Based on a systematic literature review, this paper will answer those questions. The remainder of the paper is structured as follows. Within Section 2, the methodology of the systematic literature review is presented. The outcome of the literature review regarding goals (Section 2) and requirements for the DVST (Section 3) are discussed afterwards. Building on the identified requirements, a framework for the DVST is presented in Section 5. Finally, a summary and outlook of the next steps is given in Section 6.

2. Systematic Literature Review

This section outlines the methodology used in the systematic literature review and presents the main findings. The procedure is based on the methodology proposed by FINK [17]. A total of seven databases (Science Direct, EBSCO Host, Springerlink, WISO, Taylor & Francis, Web of Science, IEEE Explore) have been identified. Thus, a vast spectrum of both business- and engineering-based publications are included. To conduct as accurate a literature review as possible, no time limit was set, and the research referred to English- and German-language publications. Since in literature there is no clear definition of the term Digital Twin, several alternatives had to be included, resulting in the following search term:

("*wertstrom*" OR "Wertströme*" OR "value stream" OR "Prozesskette" OR "process chain") AND ("digital shadow" OR "digital twin" OR "digital model" OR "digitaler Schatten" OR "digitaler Zwilling" OR "digitales Abbild")

The research took place in March 2022. A total of 577 publications resulted from this search step. After eliminating redundancies due to papers found in multiple databases, 530 papers remained. For the remaining papers, the titles, keywords and abstracts were analyzed in the following search step. Therefore, two exclusion criteria were used. First, those papers were excluded in which DTs were not discussed in the context of VSMM but, for example, regarding single production processes. Second, papers in which DTs were mentioned solely as an application example were excluded. 67 papers resulted from this step. Hereafter, ten publications had to be excluded for lack of access. Afterwards, 40 further publications were removed in course of the full text analysis based on the exclusion criteria. Using a forward and backward search, five additional publications were identified, resulting in a total of 22 publications for further analysis regarding the aforementioned research questions. Figure 2 provides a summary of the approach used in the systematic literature review.
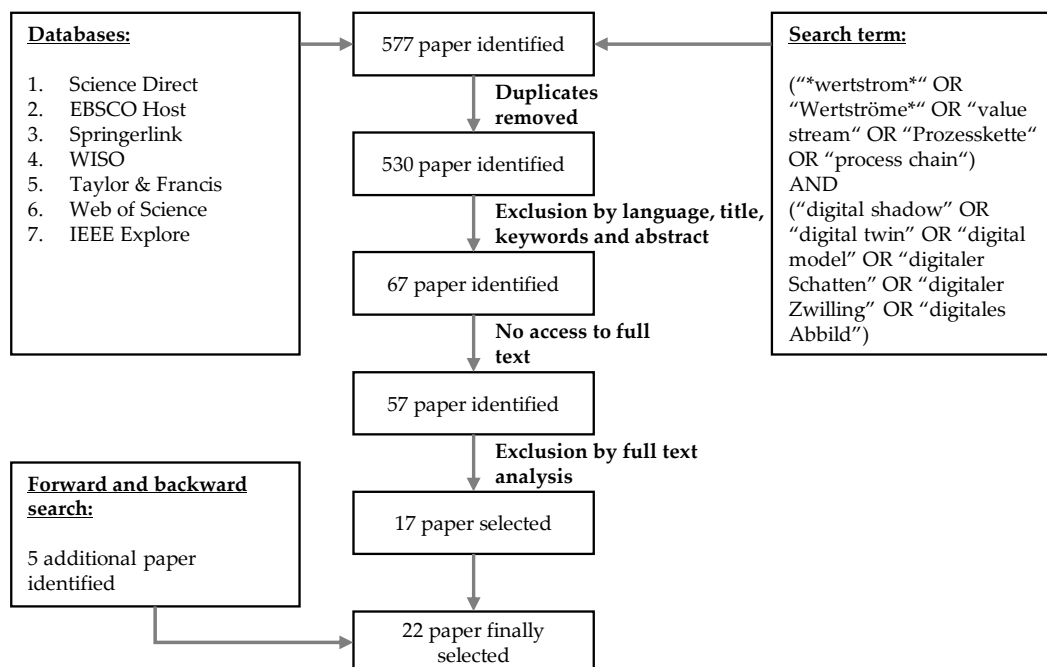
**Figure 2.** Overview of the systematic literature review.

3. Objectives and Definition of the Digital Value Stream Twin

In the following, the objectives and a definition of the DVST are derived based on the results of the systematic literature review. Additionally, the basic literature of VSMM will be considered as well. It appears, that two directions are sought within the framework of VSMM: [6–8,18]

- maintaining the current value stream design (reactive improvement)
- continuous improvement towards the target state (proactive improvement)

The first direction is based on the comparison of the current behaviour of the value stream against its expected performance based on target values and conditions [3]. This includes particularly the *continuous monitoring of the value stream,* e.g., inventories, lead times and overall equipment effectiveness [15]. Furthermore, especially regarding production planning and control, the short-term *capacity adjustment for changing customer takt* is an essential feature of reactive VSMM [7]. To support this reactive improvement, a value stream Map needs to be continuously and timely updated with the latest data and values from each single process of the Value Stream.

In addition to the reactive tasks, the proactive part of VSMM aims at the *initiation of activities for continuous improvement* towards the defined target state [6, 8, 19] which is typically driven by project work. A key element of the proactive part is the lead time reduction. To achieve this, inventory monitoring through *adjustment of Kanban and ConWIP quantities* is essential for VSMM [8]. An overview of the four use cases is provided in Figure 3. Further tasks are found in the corresponding literature [6,8,15,19].
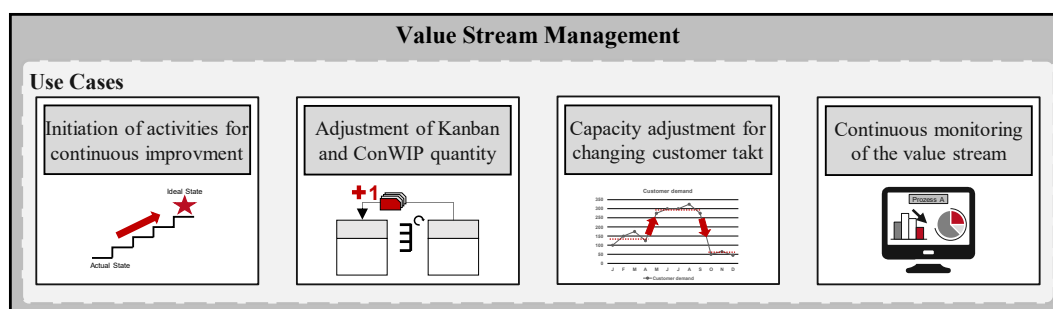
Figure 3. Use Cases for Value Stream Management.

To support this dynamic development of a value stream, the classical value stream method—which is usually based on a static value stream map—needs to be technologically enhanced. Physical changes of the value stream must be immediately reflected within the big picture map in each relevant aspect of VSMM. This includes the processes properties and logistical interconnections, but also the information flows. For this reason, the following definition of the DVST can be derived:

The Digital Value Stream Twin is the digital representation of a value stream, including individual process steps and their properties as well as their logistical interconnections. Its holistic focus lies on the timely display of key Value Stream Indicators to support the daily operational management in reaction to abnormal conditions. Additionally, it represents the actual state of material and information flows to display the effects of project work on lead times and inventories to the value stream manager.

To make this possible, relevant data is collected and transferred automatically from the physical value stream to the digital representation, then processed and provided. The final decision regarding an adjustment in the value stream remains with the operational production management and the value stream manager, the DVST merely supports the decision-making process.

Once the objectives as well as the definition of the DVST have been derived, the requirements for technical implementation are deducted from the identified literature as follows.

4. Requirements Digital Value Stream Twin

In the following, the requirements for the DVST are extracted from the identified literature. The results are summarized in Table 1. Following ONAJI ET AL. and ZHANG ET

AL., the requirements are categorized into three groups: **physical layer, virtual layer** and **connection layer** [20,21]. **Further requirements** are documented as well. The findings show that the existing approaches in literature all cover similar requirements. The four categories are discussed in detail below.

Table 1. Requirements for the Digital Value Stream Twin.

Author (year)	Source	Type	Physical Layer — Data integration	Open and standardized communication gateways	Visualization of the actual state	Virtual Layer — Storage of historical data	Access to different data sources	Modeling of the value stream	Central data model	Specific sub models for each application	Connection Layer — Continuous data acquisition (real time data)	Unique identification / standardization of data	Information feedback into the VS (closed loop)	Further Req. — Data storage in a central cloud	Definition of employee roles for the application	DT architecture compliant with AAS
Coronado et al., (2018)	[22]	A	•	•	•	•	•							•		
D'Amico et al., (2019)	[23]	C		•	•	•			•	•	•			•		
Deuter et al., (2019)	[24]	C		•					•	•		•				•
Göckel und Müller (2020)	[25]	A	•	•	•	•		•			•	•		•		
Guo et al., (2021)	[26]	A	•	•	•	•	•	•		•	•	•	•			
International Organization for Standardization (2021)	[27]	N	•	•		•	•			•	•	•			•	•
Jagusch et al., (2019)	[28]	C			•		•		•		•	•				
Kunath und Winkler (2018)	[29]	C	•	•	•	•	•	•	•	•	•	•	•			
Lugert (2019)	[19]	C	•	•	•	•	•	•	•		•	•	•		•	
Lugert et al., (2018)	[3]	C	•	•	•	•	•	•	•		•		•			
Magnanini et al., (2021)	[30]	A				•		•				•	•			
Malakuti (2021)	[31]	C		•		•			•	•		•		•	•	•
Onaji et al., (2022)	[20]	A	•	•	•	•	•	•		•	•		•			
Pause und Blum (2018)	[32]	C	•		•				•	•	•	•				
Ricondo et al., (2021)	[33]	A	•	•	•	•	•	•		•	•					
Ruppert und Abonyi (2020)	[34]	C	•	•				•		•	•					
Schleich et al., (2019)	[35]	L	•			•	•			•	•		•			
Schmitt et al., (2021)	[36]	C		•				•	•							
Tao et al., (2019)	[14]	L		•	•			•		•	•	•				
Uhlemann et al., (2017)	[37]	C	•	•							•				•	
Uhlemann et al., (2017)	[38]	C	•			•			•		•		•		•	
Winkler et al., (2020)	[39]	C		•	•	•					•	•	•			•

A = Application Example; C = Concept; N = Norm; L = Literature Review. • Requirement contained in source

The **physical layer** refers to the integration of physical entities of the shopfloor. With the help of *data integration*, relevant information is collected on the shop floor. This includes data from existing IT systems, e.g., Enterprise-Resource-Planning (ERP) systems or Manufacturing Execution (MES) systems, but partially automated input by employees can also be included. [20,27,29] Other examples of data acquisition directly related to value

stream mapping based on sensor integration deal with the use of indoor localization systems or real-time locating systems, which can be used to acquire time-related data [40–43].The information collected must be made available with the help of *open and standardized communication gateways*. The most used communication protocols in this context are MQTT and OPC UA. [20,39] The third requirement is especially crucial for the DVST. Academia agrees that a visualization of the observation object represents the greatest benefit of the DT0 [3,19,21,39]. For this reason, a *visualization of the actual state* of a value stream is one of the key tasks of the DVST. To achieve transparency of a value stream, the visualization must be aligned with the representation and symbolism of the VSM. This allows us to display complex interdependencies between individual manufacturing steps. [4,7]

Data and information system integration is achieved in the data level within the **virtual layer**. Different requirements are attached to this. One is to ensure that *historical data* is stored and made available for further data analysis [22,27,33]. Due to the heterogeneous IT landscape in manufacturing companies, it is likewise important that the DVST has *access to all relevant data sources*, such as ERP or MES systems [22,27,35]. The central element of the DVST is the model level, for which the following requirements must be fulfilled. To be able to describe the value stream sufficiently precise with the help of the DVST, a *model of the value stream* is required [19,25,36]. This model can be created by mathematically modeling the impact relation between the elements of the physical layer of the value stream, which forms the basis for the DVST. This model is stored in a *central data model*. The task of this data model is to ensure the correct flow of data and information. It provides the linkage between the virtual layer and respective use cases of the VSMM. [23,32,37] The use cases arising from VSMM are configured in *specific sub models* and use the central data model. Due to this modular structure, the DVST can be continuously extended by new sub models and individual modules can be adapted individually. [20,23,29] However, it is in the nature of the resulting activities of redesigning the value stream, that they are carried out by employees [8]. Therefore, the requirement of realizing a *closed loop* cannot be automized but is accomplished through the employees on the shop floor.

In the **connection layer,** two information flow directions are differentiated. Information flows from the physical to the virtual layer and vice versa. In the first direction, the DVST must be able to capture, store and provide *real-time or near-real-time data* [14,27,28]. Furthermore, to be able to make targeted decisions, it is important that the data is *uniquely identifiable and stored in a standardized form* [24,27,29]. Ultimately, it is crucial that information flows back into the value stream after the data processing and analysis have been completed [3,35,37]. This is the major characteristic of the DVST compared to classic DT concepts. Although an automated information return flow can be realized with the DT of a machine, for example, this is not possible for the DVST. The goal of the optimization by the DVST is the continuous improvement of the value stream performance in the context of VSMM.

In addition, **further requirements**, which are mentioned occasionally in literature, are listed in Table 1. Some authors propose centralized data storage in a cloud [23,25,37,38]. However, since cloud solutions are rather a configuration preference and not necessary, this is not a fixed requirement for the DVST. Beyond this, various authors suggest defining employee roles to prevent unauthorized access to data [19,31,39]. These roles are associated with specific tasks and therefore require specific rights. The value stream manager, for example, has full rights, as he or she is responsible for the value stream, whereas a shop floor employee only has rights for certain applications. [19]Finally, three authors suggest that the technical architecture of the DVST should be compatible with the concept of the Asset Administration Shell (AAS) [24,27,31]. Since the concept of AAS is a new concept in academia and is closely related to the concept of DT, it is expected that this requirement will become more of a focus in the future.

Based on the identified requirements, the framework for the DT in the context of VSMM is conceptualized as outlined in the following. In addition to the technical

requirements, explicit use cases from the VSMM are included (see Section 3), which determine the structure of the framework.

5. Framework Digital Value Stream Twin

The DVST is understood as a comprehensive digital representation of an individual value stream. It includes the properties, conditions, and behaviors of the value stream through mathematical models and data. The virtual, dynamic model helps to optimize the performance of the value stream. In VSMM, the DVST is used to model and present a holistic view of the interrelationships and dependencies of individual production processes. The optimization of the value stream as a unit is the priority rather than the optimization of an individual production process.

This understanding as well as the requirements identified in Section 4 serve as the basis for the development of the framework (see Figure 4).
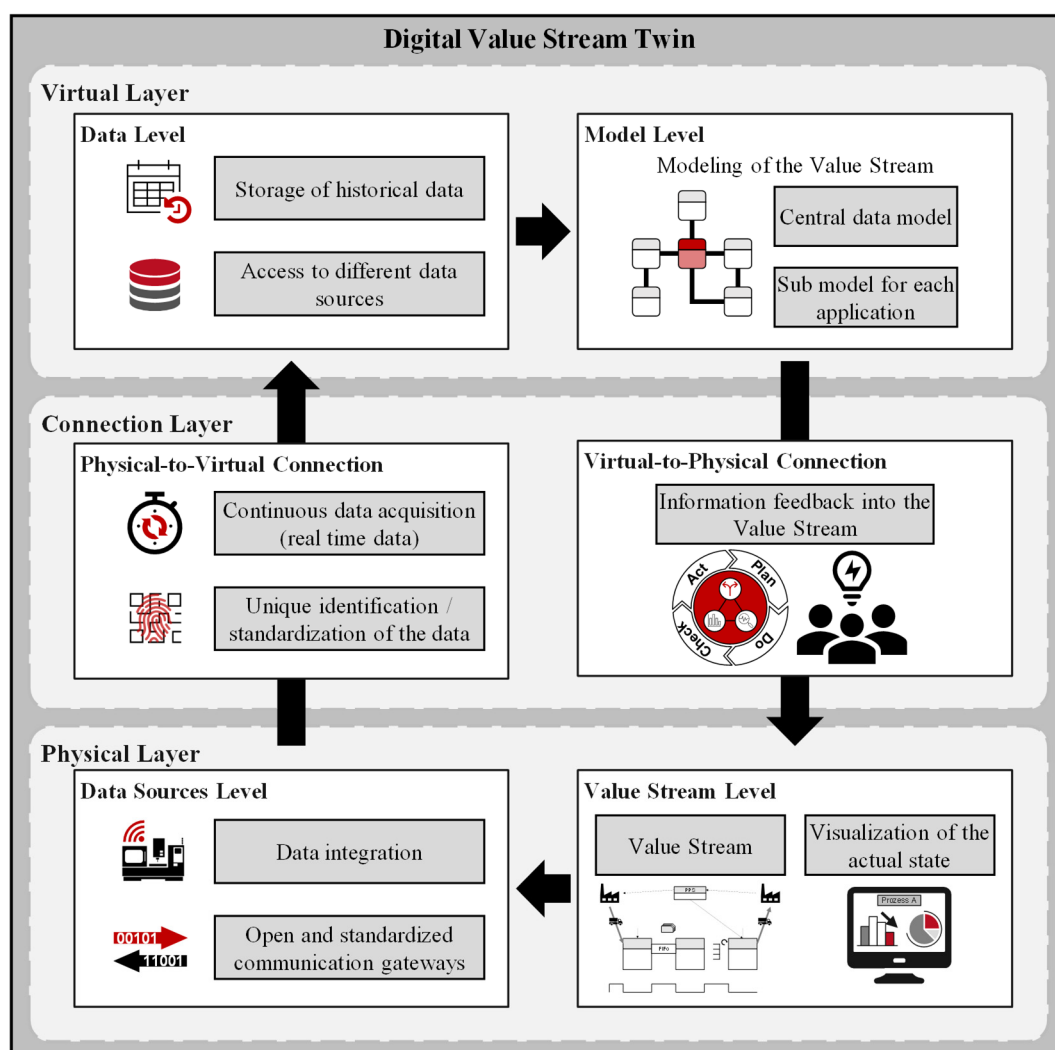

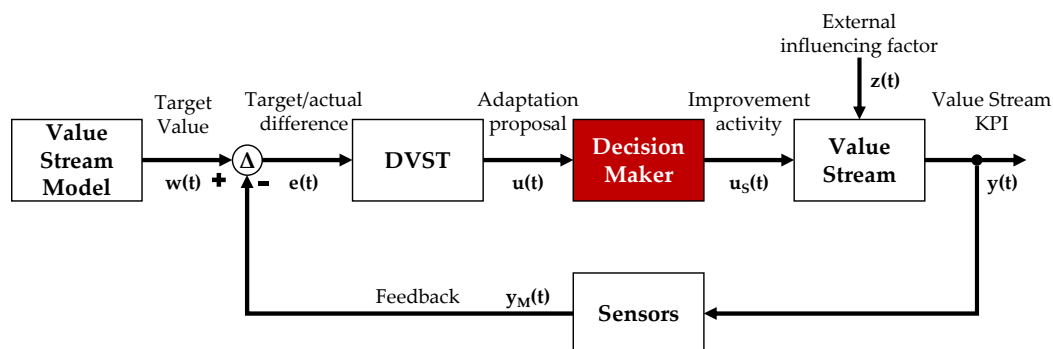**Figure 4.** Framework Digital Value Stream Twin.

The physical layer is divided into the **value stream level** and the **data source level**. Here, the *value stream* to be represented by the DVST is first defined at the value stream level. To *visualize the current state*, a suitable *sensor integration* for data acquisition is crucial on the shop floor and *open and standardized communication gateways* are configured to establish a connection to the virtual layer.

For this purpose, the **physical-to-virtual connection** is implemented in the connection layer. The DVST must be capable of *continuous data acquisition* in real time or near real time. Additionally, a *unique identification and standardization of the data* must be provided for the recorded data to be uniquely identifiable and assignable to individual products and processes. In this context, a *storage of historical data* is essential in the **data**

level. Due to heterogeneous IT landscapes in companies, *access to different data sources* is indispensable. If the relevant data is available, the value stream under consideration is represented in the *central data model* at the **model level** by mathematically modeling the relationships of processes and their connections. In addition, depending on the respective use cases of VSMM, further *sub models for each application* are developed. Depending on the use case, both the data requirements and type of information may differ at this point and require a different design of the previous components.

After *modeling of the value stream,* the information is provided via the **virtual-to-physical connection**. Here, the special feature of the DVST in comparison to the classic understanding of the DT occurs. Although the DT provides an automated information return flow and the adaption of a physical asset, this is not possible in the DVST due to the special purpose of VSMM. The DVST relies on the target/actual comparison between the current state and the defined target state of the value stream design. Based on optimization algorithms, the system proposes specific adaptation proposals for improvement, which are then presented to the decision maker. The final decision, the *information feedback into the value stream*, is taken by the value stream manager or the operational manager, depending on the type of decision. If it is a short-term improvement in daily operations, the operational manager is responsible. If, instead, it is a long-term improvement that effects the value stream, the value stream manager is responsible. Hence, the resulting adjustment of a physical asset in the value stream requires an active change by an employee. This special characteristic of the DVST can be described using the model of the technical control loop as illustrated in Figure 5 [44,45].

Figure 5. Closed loop of the Digital Value Stream Twin (based on [44,45]).

An external influencing factor affects one parameter, e. g., a production process, of the value stream which is represented with the help of explicit value stream KPIs. Corresponding sensors record the current value of the value stream KPI and transfer it to the virtual layer. Here a comparison is conducted between the currently measured value and a previously defined target value, which originates from the value stream model. If a deviation in the value stream KPIs requires action, the value stream manager is informed. The latter defines an adaptation proposal regarding a specific value stream parameter, corresponding to the external, affected parameter. Based on the value stream parameter to be adjusted, the improvement activity is initiated and realized in the value stream. Once this is done, one loop of the continuous improvement process (closed loop) is completed, and the adaptation cycle starts again. The value stream manager has the central role in this control loop, since without his decision no adaptation of the value stream is possible.

The presented framework will be used to structure the technical implementation of a DT for a value stream "from door-to-door". The special focus is on the use case-specific extensibility of the central data model by developing additional sub data models. By considering all aspects mentioned in the framework, the user will be able to implement a DT in his own company and use it in the context of VSMM. A short-cycle adaptation of

the value stream according to the challenges of today's production systems will be feasible and will support companies in the continuous improvement process.

6. Conclusions and Outlook

This paper introduces a framework for the Digital Value Stream Twin based on a structured extension of necessary requirements from the literature. The DVST is the virtual representation of a value stream from "door-to-door" with its internal and external dependencies. The special characteristic of the DVST in comparison to the classical understanding of the DT lies in the backflow of information from the virtual to the physical world. Whereas the concept of the DT foresees an automated backflow of information and adaptation, in the DVST the final decision whether to realize an adaptation of the value stream stays with the manager responsible for the value stream. Consequently, the DVST represents a recommendation system; the practical implementation, as part of VSMM, is subsequently carried out by the employees. The conceptual framework proposed is open and general and hence can be applied in various industrial sectors.

The requirements for the DVST identified in the paper provide a generally applicable basis based on articles written on the use of DTs in production environments. In order to verify these requirements, experts from industrial practice will be consulted as part of future research to create a holistic requirements profile for the DVST. After the framework has been finalized by industrial experts, the DVST will be implemented in industrial practice and thus continuously improved and its functionality validated. In this way, a universally applicable framework for the DVST is developed. To support this, the focus of further research is on the development and standardization of a consistent method that guides and supports industrial companies in the implementation of the DVST in practice.

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