1st World Congress on Industrial Engineering and Operations Management
October 9-11, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/WC01.20240085
Published: October 09, 2024

Scenario-Based Design and Validation of Shop Floor Configurations Using an Enhanced Digital Value Stream Twin

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Abstract

In the competitive landscape of modern manufacturing, validating shop floor configurations before implementation is crucial for minimizing risks and ensuring operational efficiency. Value Stream Management (VSM) is defined as a holistic management approach for mapping, analyzing, designing, and implementing waste-minimized value streams. This paper explores the application of a Digital Value Stream Twin (DVST), mainly focusing on the data-driven design and validation of shop floor configurations. Within this framework, a value stream model expanded to include the dimensions of costs and sustainability is used. The related key figures are considered as part of the scenario assessment to account for various company objectives. By leveraging a Fischer Technik® Training Factory Industrie 4.0 environment and utilizing Arena® for simulation, the potential of DVST in creating optimal shop floor configurations is investigated. The results demonstrate the benefits of using DVST to enhance accuracy, flexibility, and decision-making in manufacturing environments.

Keywords

Digital Value Stream Twin (DVST), Value Stream Management 4.0 (VSM), scenario-based design, Arena® simulation software, Fischer Technik® Training Factory Industrie 4.0

1. Introduction

Value Stream Management (VSM) is a management approach focused on maximizing the value delivered to customers by improving the flow of information, materials, and work through an organization. Based on an end-to-end consideration from supplier to customer, it involves mapping out all the steps involved in delivering a product or service, identifying areas of waste or inefficiency, and making continuous improvements to streamline operations. The goal is to enhance productivity, reduce waste, and improve quality, thereby delivering better value to customers. Within this framework, production lead time is a critical metric as it directly impacts overall efficiency, customer satisfaction, and inventory levels. By analyzing and reducing production lead time, organizations can improve their efficiency and responsiveness to customer demands, as well as reduce costs and capital tied up in production, such as work-in-progress (WIP) stocks, following the principles of Lean Management.

Although Lean Management in general, and VSM in particular, date back to the 1990s (Womack et al. 1990, Womack and Jones 1996, Rother and Shook 2018), it is still widely used in production and logistics environments due to its clear visualization, simplicity, and valid, practically proven principles. However, recent studies have highlighted several limitations, mainly addressing the lack of up-to-date information and accuracy of the Value Stream Map as a core element of VSM, as well as the effort required to adapt the methodology to changes (Balaji et al. 2020). Additionally, modern technologies and applications offer new possibilities in methodology, the potential of which is not fully utilized.

Conventional VSM provides a static snapshot of the process, capturing the state of the value stream at a single point in time (Thulasi et al. 2022). This can quickly become outdated as conditions and variables change, making it difficult to maintain an accurate and relevant map. The mapping of the value stream is typically done during an on-site production walk (Erlach 2013). Creating and updating value stream maps manually is labor-intensive and can be prone to human error. The manual nature of this process also makes it challenging to keep the maps current, especially in volatile environments where processes frequently change. An up-to-date view of the entire value stream is an essential prerequisite for effective decision-making, continuous improvement, and implementation.

Addressing these limitations involves transitioning to more dynamic, real-time, and integrated approaches to VSM. By leveraging advanced technologies, organizations can create more flexible, accurate, and responsive Value Stream Maps. These modern approaches are introduced under keywords such as VSM 4.0, Smart VSM, Dynamic VSM, and similar terms in the context of VSM. One of the discussed approaches is based on the Digital Twin concept and is referred to as DVST (Frick and Metternich 2022). The focus of the DVST investigation is primarily on the development of a framework for the implementation of the technical solution. This is where the present work comes in, with the aim of examining and discussing the application of a DVST in the context of designing and validating shop floor configurations using specific case studies and simulation scenarios.

1.1 Objectives

The approach of the DVST is conceptually considered within the reviewed publications, as described in the following section. Layered architectures provide a general overview of interfaces, data, and functions of the various layers as frameworks. However, the concrete implementation using an example and the verification of the application remain open. The objective of the present study is to transform the available concepts into a concrete use case and to demonstrate applications. As highlighted by Frick, the goal of a DVST is not to directly influence the value stream and adjust value stream elements, such as resources. Instead, the benefit of a DVST lies in supporting decision-makers in structured decision-making (Frick and Metternich 2022). Against this background, the scenario-based design and key performance indicator-supported validation of shop floor configurations within the framework of Value Stream Design are examined.

For this purpose, the classic value stream model is expanded to include the dimensions of sustainability (Hartini et al. 2021, Verma and Sharma 2016) and costs (Gunduz and Fahmi Naser 2017, Ramadan et al. 2017), which are represented by selected key performance indicators. The investigation is based on a learning factory environment and a simulation model of the value stream. In the context of the simulation, a weighted objective function with the functional elements of lead time, costs, and sustainability is used. The core of the investigation is the application of a simulation model of the DVST. Through structured variation and fixation of individual simulation parameters, different scenarios, such as events (e.g., machine failures) and resource configurations (e.g., capacity increase), are examined in terms of the value stream's capability. The results are used for the design and validation of different shop floor configurations under given conditions. All applications are based on a holistic view of the value stream, including the input and output factors as well as individual parameters. The overall configuration is defined as a scenario.

2. Literature Review

Recent research addresses the limitations of the conventional methodology mentioned in the preceding section and provides concepts and solutions for optimization and expansion to overcome these limitations, e.g. (Drees 2018, Frick et al. 2024, Meudt et al. 2016, Meudt et al. 2017). The aim is to ensure the future viability of VSM by aligning it with today's challenges in value creation. Erlach distinguishes between two primary research directions concerning the adaptation of VSM (Erlach et al. 2021). One direction enriches the content of the Value Stream Map with specific key figures, particularly in digitalization (Meudt 2020), sustainability (Hartini et al. 2021, Horsthofer-Rauch et al. 2021), and costs (Ramadan et al. 2017), to obtain a more holistic overview and address emerging requirements such as the increasing digitalization and its impact on information management (Behrendt et al. 2023, Metternich et al. 2022, Meudt 2020). The other direction focuses on optimizing the methodology itself through greater integration of data-based technologies and data processing techniques. The utilization primarily involves automating the mapping (documenting the current state) of the value stream by continuously gathering and processing available business data

((Arey et al. 2021, Haschemi and Roessler 2017, Horsthofer-Rauch et al. 2022). This business data is drawn from various business application systems like enterprise resource planning (ERP) and manufacturing execution systems (MES), implicitly considering machine and sensor data (Wollert and Behrendt 2022). Additionally, the application of individual technologies in terms of tracking and tracing the material flow such as Internet of Things (IoT) (Balaji et al. 2020), radio-frequency identification (RFID) (Bartholmai et al. 2017, Ramadan et al. 2016), and positioning systems (Tran et al. 2021) is discussed, providing a fundamental database for enabling data-based decision-making.

The DVST according to (Frick and Metternich 2022, Karmaoui et al. 2023) is based on the approaches previously mentioned and integrates them into a more comprehensive concept that encompasses not only the phase of mapping but also analyzing (Value Stream Analysis) and designing (Value Stream Design). A DVST is a concept combining the principles of Digital Twins (DT) with VSM in the context of managing manufacturing operations. In essence, it creates a digital representation of the entire value stream, including processes, resources, information and material flows, and interactions between various components. This DT is synchronized with the physical value stream in real-time providing a dynamic and comprehensive view of operations. By leveraging data from sensors, IoT devices, and other sources, a DVST enables organizations to monitor, analyze, and optimize their value streams more effectively, based on the actual setup and conditions. It allows for scenario planning, predictive analytics, and continuous improvement initiatives, leading to enhanced efficiency, reduced waste, and improved decision-making.

3. Methods

The applied methodology follows five steps, which are reflected in the structure of the present paper. The procedural model is visualized in Figure 1. First, a conceptual delimitation of the term 'Digital Twin' (DT) is provided (see section 3.1), based on the understanding underlying this study. Next, the use case physically represented within the framework of the fischertechnik® Training Factory Industrie 4.0, along with the derived Value Stream Map, is presented (see section 3.2). Following this, the design of the DVST is explained (see section 3.3). The core of the study is the investigation of the DVST, focusing on scenario-based simulations executed in Arena® simulation software. The database used for each simulation study is described in section 4. In section 5, the use case-oriented investigation of the DVST is discussed. Finally, in the last step the study concludes with a discussion and an outlook on further research steps.

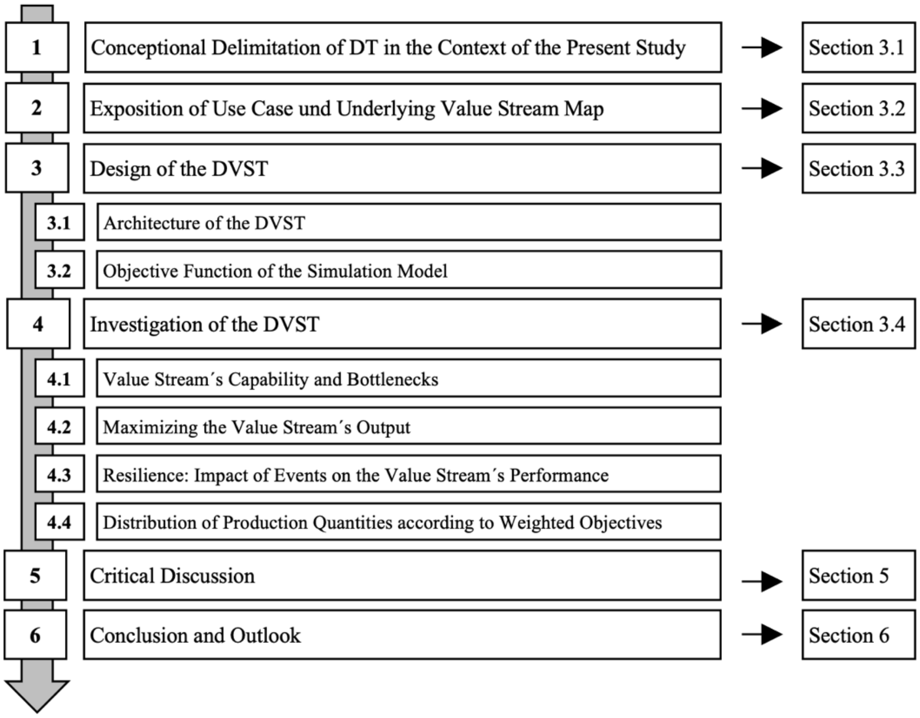

Figure 1. Applied methodology

3.1 Conceptual delimitation of DT in the context of the present study

The concept of the DT has evolved over time, as evidenced by several research studies (Barricelli et al. 2019, Liu et al. 2020). In the present study, the DT is distinguished from Digital Models and Digital Shadows (DS) based on the flow of data between physical and digital objects as shown in Figure 2 (Kritzinger et al. 2018). A Digital Model is a static representation of a physical object. Changes to the object must be manually transferred to the other. The physical and digital objects are thus decoupled in terms of automated data flow. A DS involves automated one-way data flow from the physical object to the digital one. In contrast, a DT involves a bilateral connection with automatic data flows, where changes to the physical object directly impact the Digital Model, and vice versa.

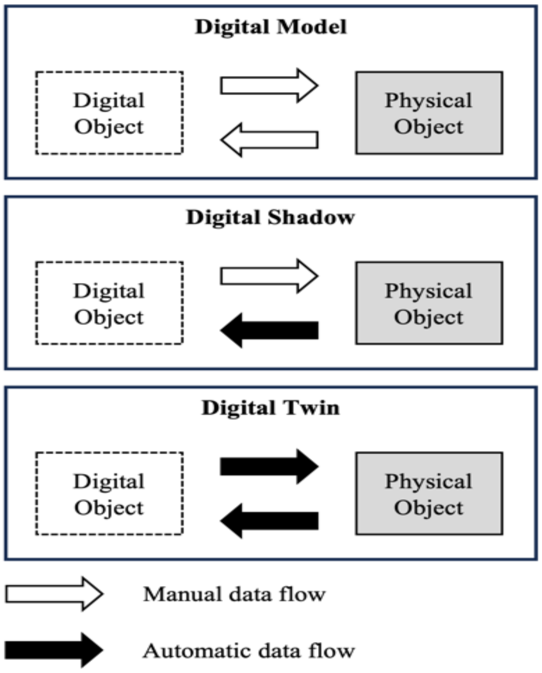

Figure 2. Delimitation of DT (Kritzinger et al. 2018)

As previously explained, the digital object - the value stream model - is automatically enriched and updated with real-time data. In the underlying concept, the feedback serves as decision support for a decision-maker who intervenes in the value stream (Frick and Metternich 2022). Frick and Metternich distinguish between reactive and proactive improvements in this context. The reactive perspective involves online monitoring of the value stream and keeping the Value Stream Map up to date, while the proactive perspective focuses on identifying and implementing improvement measures. Depending on the use case, such as adjusting capacities, rescheduling orders, or releasing improvement measures, different stakeholders, e.g., production planners, lean managers, foremen, and others, are involved in taking action based on the prepared information.

Since the data flow is not fully automated and aims to support decision-makers who take specific actions, strictly following the delimitations and characteristics above, the approach can be characterized as DS, where the data flow from the digital object to the physical one is manual. If the approach is used in such a way that operation times, availabilities, and similar metrics are recorded, analyzed, and averaged to automatically feed this data back from the model into operational application systems, such as ERP or MES - thereby improving master data quality, planning quality, or impacting production planning and control by rescheduling production orders based on changed conditions - these application cases align with the previous definition of a DT. The delimitation of the concept is not sharp and clear, but rather gradual. Therefore, in the context of the present study, the term DVST is used, encompassing all mentioned uses cases without specific distinction.

3.2 Exposition of the use case and underlying Value Stream Map

The validation of the Digital Value Stream Twin concept in terms of scenario-based design and validation of shop floor configurations underlies a use case, which is described in the following section.The manufacturing process in the learning factory environment comprises 7 workstations, which are referred to as stations and are consecutively numbered (stations 1 - 7), and represent the production of a fictional finished good. At station 1, the logistical goods issue takes place (operation 10). At this point in the process, the material flow branches into two lines: on the one side into sequential machining via universal machines for turning (operation 20) at station 2 and milling (operation 30) at station 3, and on the other side into automated machining via a complete machining center, where turning and milling are performed in one step at Station 4 (operation 35). After machining, the material flows converge, and a visual inspection is carried out at station 5 (operation 40). Following this, the RFID chip of the finished good is programmed with product data at station 6 (operation 50) and handed over for delivery at station 7 (operation 60). All stations are connected by conveyor belts, which facilitate the material transport between the stations. The control of the manufacturing process is managed using the Fischertechnik Cloud application, which covers essential MES functions including order data.

The learning factory is modular in design, allowing for various shop floor configurations to be implemented. It is noted that the same factory element is assumed for stations 2, 3, and 4, represented by a multi-processing station. The configuration is done by individually adjusting the set time. With a focus on the manufacturing process, supplier processes and customer processes constitute input and output factors of the learning environment. The integration of an ERP system is excluded at this point. The transport and processing times are derived from the system's data. Assumptions are made for the cost rates and energy consumption, as this information is currently not available or cannot be derived from the available data of the learning factory environment.According to (Erlach 2013, Erlach 2020), separating material flows are indicated by quantity-related distribution percentages. In the underlying use case, the fixed allocation of the percentage distribution is open, as the allocation is made based on the objective function of the simulation model.

Based on the elucidated use case, a Value Stream Map of the current value stream is created, visualized in Figure 3.

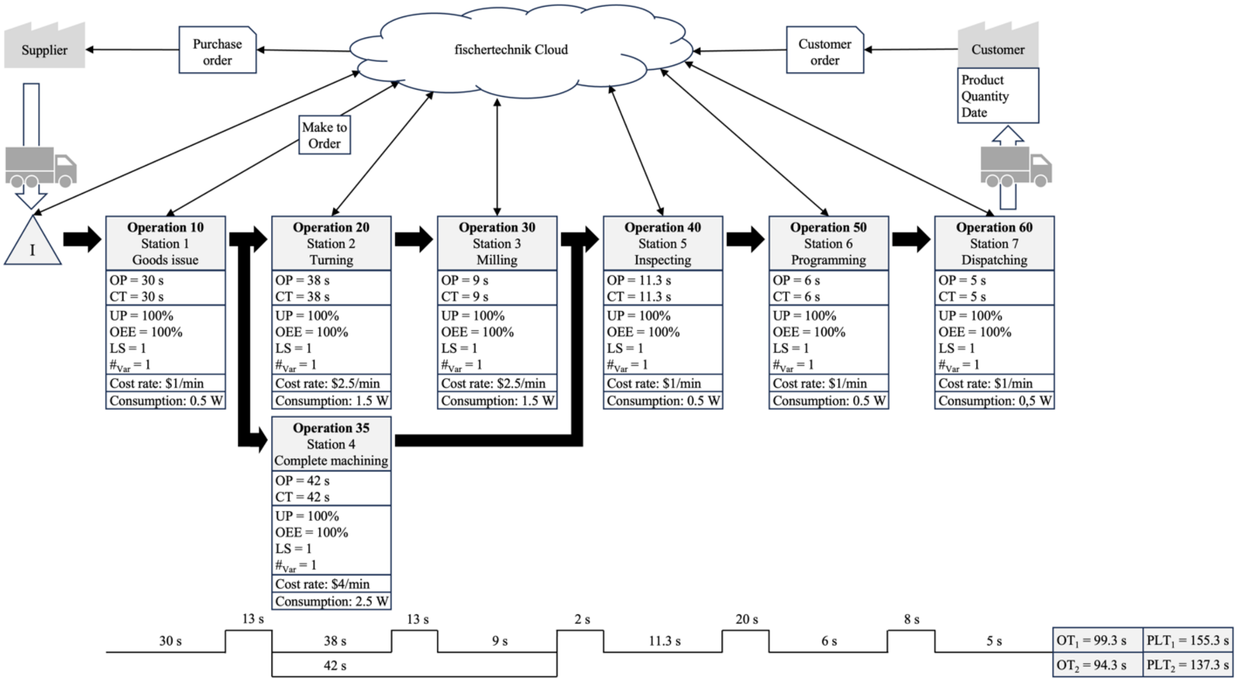

Figure 3. Value Stream Map of the Underlying Use Case

3.3 Design of the DVST

The architecture of the DVST is schematically visualized in Figure 4. The hardware setup of the fischertechnik Training Factory Industry 4.0 represents the physical model of the production process, which is highlighted in the previous section in the context of the underlying use case. It corresponds to the physical object of the DT concept. TXT controllers are used to control and monitor the actuators and sensors installed in the learning environment. Process control based on orders is carried out within the fischertechnik Cloud application, providing traditional MES functions. A bilateral communication between the cloud application and the hardware elements of the learning factory environment takes place via MQTT (Message Queuing Telemetry Transport). For data import and export Node-RED (software) is applied. In addition, an export from and import into Node-RED via .csv files is supported.

The virtual model of the value stream is depicted in Arena simulation software. The design of the simulation model builds on the work of (Al-Aomar et al. 2020). In addition to the classic key figures in VSM, the model was expanded, as previously described, to include the areas of cost and sustainability. For the purpose of reducing complexity, average values are assumed to examine the fundamental feasibility and focus on the investigation of scenario-based design and validation of shop floor configurations. The objective function of the simulation model plays a central role in this, which is described in more detail in the following section. It corresponds to the virtual object of the DT concept. Whereas the production process of the value stream is based on the physical model, the areas of customer and supplier are input and output factors, represented by assumed parameters, relevant for the scenario-based simulation. As shown by the dotted arrows in Figure 4, synchronization between the physical model of the learning factory environment and the virtual model as representation of the value stream is carried out manually at the current implementation status.

According to the definition of the DVST by (Frick and Metternich 2022), the lack of automized synchronization between the physical object and the virtual object does not represent a limitation in this context, as the aim of the concept is to support decision-makers (as reasoned in section 3.1). This also applies to the use case underlying the present work, as it relates to the design and validation of shopfloor configurations before implementation. Nevertheless, there remains the option to feedback operation times and similar master data and transactional data into the MES in order to improve planning accuracy. The second use case then follows the narrower definition of the DT, but is not the main focus in the study at hand.

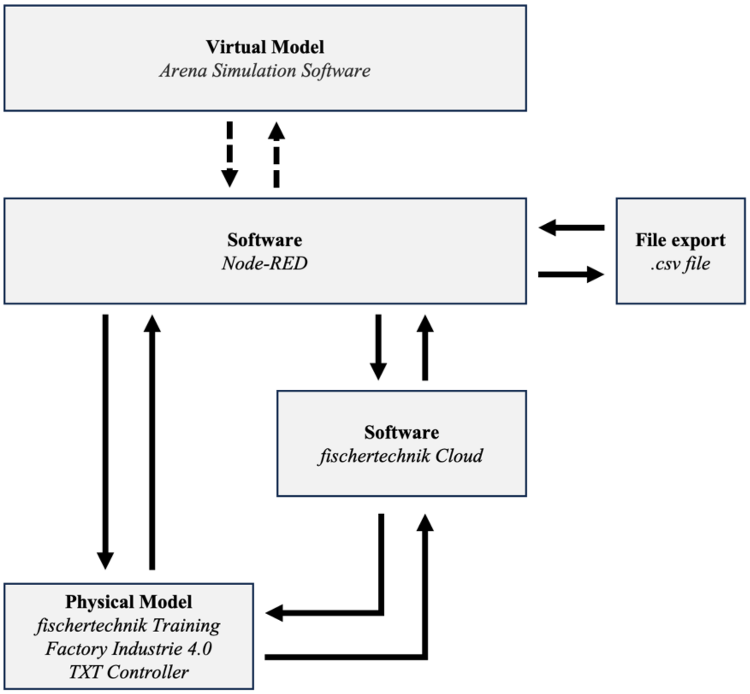

Figure 4. Schematic Representation of the DVST Architecture

According to Erlach (2013) the value stream method, in contrast to the often technologically oriented optimization of individual production processes, aims at a holistic consideration of all individual processes in interaction. The focus here is on customer orientation by aligning customer takt time and cycle time as well as the reduction of waste or non-value-adding activities, in general. In addition to considering easily recognizable weaknesses, the degree of flow and the degrees of capacity utilization represent significant improvement potentials in the classical sense. The degree of flow corresponds to the ratio of the sum of operation and processing times to the production lead time (also mentioned as throughput time) and represents an indicator for the dynamics in production. The optimum is a value of 1. In this case, the material to be produced is fully in flow, and no waiting times occur. At this point, it is emphasized that the classical calculation logic of lead time refers to the sum of all ranges of coverage, which is calculated as the division of WIP inventory in front of a station by daily demand, and the daily available time. In the setup of the learning factory, there are no permanent inventories forcing a first-in, first-out (FIFO) processing, so the intermediate time between two processing steps is used as the basis. Based on this definition, the first element of the objective function arises from the lead time, defined as sum of all waiting times and transportation, defined as the end of one operation and the start of the following operation, taking into account the planned availability (shift schedule) (Wollert and Behrendt 2022), and production-related times. In an ideal test environment, no waiting times occur because the low utilization and absence of disturbances make the times reproducible. This is a theoretical perspective that does not reflect practical reality. For this reason, a dynamization of the time-related indicators, such as operation time, processing time, and transportation time, is implemented by utilizing probability models in ARENA® (TRIA, UNIF, EXPO, NORM, etc.). This dynamization leads to the formation of temporary queues and fluctuations in the lead time.

The second element of the objective function arises from the costs. Machines, equipment, manual workstations, and similar resources have defined cost rates used for product calculations, order costings, controlling evaluations, and similar applications. Cost rates are typically maintained in ERP systems. In general, setup costs, machine costs, personnel costs and similar ones can be differentiated. The total costs of the value stream are the sum of the individual process costs per workstation. The individual costs are calculated as multiplication of the cost rate per unit of time and the unit of time. In the context of the use case, the cost analysis is simplified to a simple average per station. Multi-machine operation and comparable scenarios are not considered in the current implementation stage. Furthermore, material costs are not taken into account.The third element of the objective function represents sustainability, reflected by the energy consumption of the value stream. Based on the electrical power values of the individual stations and the related operating time, the energy consumption is calculated. In the context of sustainability, water consumption, greenhouse gas emissions, and waste generation form additional factors besides energy consumption (Chopra 2019) but are not taken into account at the current state of implementation. Similar to the cost calculation, the use case is simplified, assuming average values. Depending on the type of material processing, the energy consumption of systems and machines fluctuates. This variance is not considered. Thus, the calculation is carried out on the basis of assumed average values and the operating time.

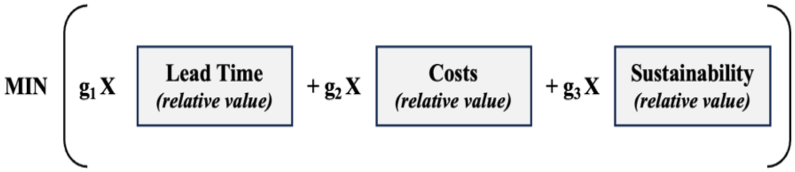

Figure 5. General Representation of the Objective Function

Taking into account various priorities in the objectives of businesses, a weighting of the three elements lead time, costs, and sustainability is performed. The three weighting factors together add up to a value of 1, allowing the simulation model to support flexible alignment. The three elements of the objective function have different units - lead time in a time unit [s], costs in a monetary unit [$], and energy consumption in an energy quantity [Ws], which cannot be combined. Therefore, in addition to weighting, normalization is performed. In this process, the original value stream with its specific metrics is used as a basis. Values of 1 indicate no improvement, values less than 1 indicate optimization compared to the original value stream, and values greater than 1 indicate deterioration. The objective function is a weighted sum of the individual factors. The sum formulation is used because the factors contribute additively to the goal, making it necessary to consider the individual significance of each factor independently of the others. Additionally, with a product formulation, if one weight factor is set to zero (e.g., due to weighting), the overall result would be zero. Since an efficient value stream is characterized by low lead time and costs with minimal resource usage, the goal is to minimize all factors. From this, the following objective function is derived, as illustrated in Figure 5.

The underlying use case is based separating material flows, representing alternative sequences. As illustrated in Figure 3, this results in various lead times. The allocation of production quantities to production resources or lines is dynamically determined by the application of the simulation model and is not predetermined. Within the objective function, a corresponding weighting is applied according to the percentage distribution of production quantities to account for this circumstance.

3.4 Investigation of the DVST

In the context of investigating the DVST based on the simulation model, a simulation methodology that is built on 6 phases is used. The procedure model is illustrated in Figure 6 according to (Rossetti 2016).

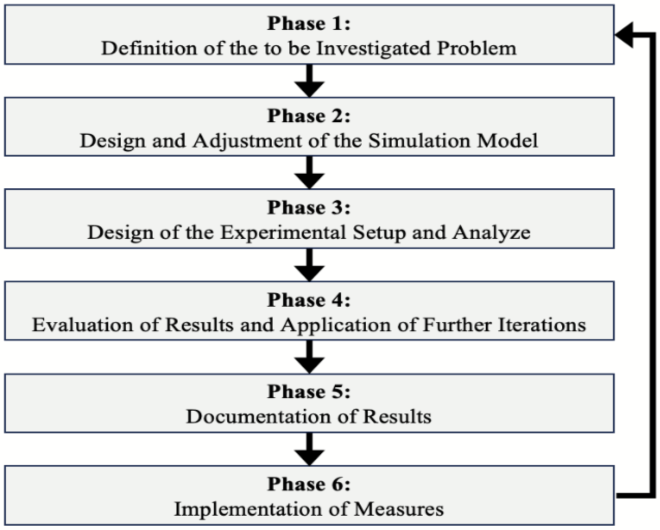

Figure 6. Procedure Model of the Simulation Methodology (Rossetti 2016)

In the first phase, the problem to be investigated is defined. In the context of the investigation, the problem definition correlates with the scenario definition, elucidated in the following section. Based on the objectives, the simulation model is designed and adjusted in the second phase. In this context, various design options of the simulation model are developed, e.g. the usage of probability models. In the third phase the experimental setup is applied and the first simulation result is analyzed with respect to the objectives, defined in the first phase. In the context of the fourth phase, the actual simulation is carried out based on the use case, the results are evaluated, and further iterations are optionally conducted. Within the scope of the use case, various scenarios are simulated to support decision-makers in the design and validation of various shop floor configurations. The representation of these scenarios is achieved by selectively fixing and varying simulation parameters. During the process of variation, ranges of values are defined for parameters, while fixed parameters are considered as given constraints. Phase 5 refers to the documentation of the simulation results. In the sixth phase, measures are implemented. Following the concept of DVST, the procedure forms a control loop, leading back to phase 1.

In all scenarios, an available capacity of 8 hours per day is assumed for each resource. The customer demand is 900 units per day. A presentation of the parameterization of the simulation model is provided in the context of data collection (see section 4). Four scenarios are investigated in the context of the DVST, elucidated below. The results are presented in section 5.In the first scenario “Value Stream´s Capability”, the technological capability of the value stream is examined. The goal is to determine the maximum possible output, considering the available resources and capacities. The output of the value stream, represented as customer demand is increased until the first resource reaches

100% utilization. This resource represents the bottleneck of the value stream and limits production performance. Additionally, the utilization of each resource is determined.

In the second scenario “Maximizing the Output of a Levelled Value Stream”, the leveling of the value stream is examined with focus on inefficiently utilized resources. The goal here is to optimize the operation time of the resources with the lowest utilization and to determine the capacity requirements of the remaining resources as well as the maximum possible output. The output of the value stream is increased until all resources reach a utilization of at least 100%.In the context of resilience, the third scenario “Impact of Events on the Value Stream´s Performance” examines the value stream's ability to respond to unforeseen events. In this scenario, the parameters of the model are adjusted manually to simulate specific situations. This could include scenarios such as the failure of a resource, limited availability, fluctuating demands, or similar events. Sustainability and costs, alongside lead time, are increasingly important factors that must be considered in design, planning, and control. In the fourth scenario “Allocation of Production Quantities”, the distribution of production quantities is examined based on altered objectives. This involves adjusting the weighting of the objective function. Additionally, scenarios 1 to 3 are reconsidered under the modified conditions.

4. Data Collection

Value Stream Management is based on specific metrics that enable the analysis of the value stream's efficiency. It involves a comprehensive framework of metrics that influence each other and form the basis for leveling the production and eliminating waste. As previously described, the impact on specific value stream metrics is examined in four scenarios. The following tables illustrate the parameterization of the simulation model. The process steps are temporally and logically linked. The considered value stream is based on a learning factory, which provides an ideal environment with low variance. For this reason, variability was defined within the scope of the simulation. Furthermore, value ranges were defined for variable parameters. These were defined as constraints alongside the objective function.

Transport between the stations is continuous via conveyors, with the distance and time being fixed. The following table (see Table 1) provides an overview of the source and destination as well as the transport time. Waiting times occur in front of the stations due to queues, which, however, only appear in the simulation due to the idealized environment.

Table 1. Transport Matrix

Source	Destination	Duration
Station 1	Station 2	13 s
Station 1	Station 4	13 s
Station 2	Station 3	13 s
Station 3	Station 5	2 s
Station 4	Station 5	2 s
Station 5	Station 6	20 s
Station 6	Station 7	8 s

In the table below (see Table 2), the fixed parameters of the simulation model are presented. Variable parameters include production quantities and utilization. Derived from these, the following metrics are calculated:

Throughput/lead time:
The total time required for passing the production line.
Resource utilization: Categorized as underutilization (<100%), normal utilization (100%), or overutilization (>100%). Utilization is defined as the ratio of occupied time to available time. Assuming 100% availability and 100% OEE, the available time corresponds to the planned capacity of 8 hours. The occupied time is calculated as the product of quantities and operation time (OT) or cycle time (CT), which are identical in the example under consideration.

Costs: The total cost, which is the sum of all station-specific cost rates and times.
Energy consumption: The total energy consumption, is calculated as the sum of all power consumption and times.

Table 2. Fixed Parameters of the Simulation Model

Station	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
Operation Time (OP)	30 s	38 s	9 s	42 s	11.3 s	6 s	5 s
Cycle Time (CT)	30 s	38 s	9 s	42 s	11.3 s	6 s	5 s
Up-Time (UP)	100 %	100 %	100 %	100 %	100 %	100 %	100 %
OEE (Overall Equipment Effectiveness)	100 %	100 %	100 %	100 %	100 %	100 %	100 %
Lot Size (LS)	1	1	1	1	1	1	1
No. of Variants ($\#_{var}$)	1	1	1	1	1	1	1
Cost Rate	\$1/min	\$2.5/min	\$2.5/min	\$4/min	\$1/min	\$1/min	\$1/min
Energy Consumption	0.5 W	1.5 W	1.5 W	2.5 W	0.5 W	0.5 W	0.5 W

5. Results and Discussion

As part of the simulation study, numerous scenarios were examined. This included hypothetical technology changes that affect both operation time and cycle time. The following analysis of the results is limited to the four scenarios defined previously.

5.1 Numerical Results

In the scenario “Value Stream´s Capability”, the technological capability of the value stream is examined. Based on the underlying use case, station 1 is identified as the limiting resource. The maximum output increases to 960 units per shift. Furthermore, the greater emphasis on sustainability or costs only affects the allocation of production quantities to stations 2/3 or station 4. The overall output remains the same, as the throughput at station 1 defines the input of the entire value stream. The utilization of the remaining resources ranges between 10% and 80%, indicating inefficiencies in the value stream that offer potential for improvement. However, increasing the input quantity in combination with variable process times leads to longer wait times. This reduces the stability of the throughput time.

In the scenario “Maximizing the Output of a Levelled Value Stream”, the leveling of the value stream is examined with focus on inefficiently utilized resources. In this context, the planned capacity of each resource is considered a variable parameter. In the use case, assuming a single-shift capacity of 8 hours, the capacity can be increased by adding additional shifts. Processing in this manner is sequential. However, this has the drawback of increased wait times, which negatively impact the throughput time. Alternatively, additional resources can be employed. This allows for the parallelization of the value stream, which is particularly beneficial for stations 2 and 4. Emphasizing sustainability and costs more strongly influences the allocation of production quantities to stations 2/3 and 4. As a result, the utilization of stations 2, 3, and 4 increases or decreases accordingly.

In the scenario “Impact of Events on the Value Stream´s Performance” the value stream's ability to respond to unforeseen events is examined. In the present study, total failures of stations 2, 3, and 4 were examined. For this purpose, the utilization was set to 0 %, which is equal to no capacity. In this scenario, 100 % of the production quantities are routed through either station 2/3 or station 4. Since no alternative material flows are possible, there exists only a sequential value stream, where the higher emphasis on sustainability and costs in the objective function has no influence on the allocation of production quantities. In the event that station 4 fails, the capability of the value stream reduces to 757 units per shift, with Station 2 becoming the limiting factor. If either Station 2 or Station 3 fails, material flow through these resources becomes impossible. Consequently, material flow is rerouted through station 4. Station 4 becomes the bottleneck of the value stream because its cycle time is slightly longer than that of Station 1.

Therefore, the output decreases to 684 units per shift. Measures to meet customer demand include increasing capacity or reducing cycle time.

In the scenario “Allocation of Production Quantities”, objectives are altered to determine the distribution of production quantities. Since stations 1, 5, 6, and 7 do not have alternative sequences, in the underlying use case, the objective function affects the allocation of production quantities primarily to stations 2/3 and alternatively to station 4. When considering individual resources in isolation, more production quantities are allocated to station 4, focusing on lead time. Station 2/3 are more utilized when focusing on costs and sustainability. Taking into account dynamic cycle times and the lack of leveling the entire value streams, effects such as queue formation negatively impact the overall lead time as well as its stability.

5.3 Proposed Improvements

Based on the simulation model, selected scenarios were analyzed with the aim of optimizing the value stream in general and designing and validating shop floor configurations in particular. The investigation focused on the technological capability of the value stream and identifying potential for increasing output, as well as the resilience of the value stream in the face of unforeseen events, such as machine failures or increases in demand (implicitly covered by Scenario 1 and 2). It was observed that the value stream is characterized by various metrics that, in turn, influence each other. In addition to adjusting resources, such as increasing capacity, the allocation of production quantities to individual resources was also examined as part of production planning and control. In this regard, simulation studies prove to be a flexible tool that enhances planning security before implementation. The concrete scenario-based improvements of the shop floor configuration and its impacts of the value stream´s performance is described in the preceding section.

6. Conclusion and Outlook

DVST represents an approach that integrates conventional optimization methods with the concept of the DT, providing targeted support to decision-makers. This approach applies across various levels of decision-making, including design, planning, and monitoring. The aim of the present study is to examine the DVST within the framework of designing and validating shopfloor configurations, with a particular focus on conducting simulation studies.

Based on current research, there are studies available that conceptually examine the DVST and present a framework for its design and application. However, transferring this to a specific use case remains open. Beyond the DVST concept, various value stream approaches expand the classical method into additional areas. In the context of the present study, both research streams are combined into an enhanced DVST approach. A significant focus is placed on designing the objective function of the simulation model, which opens up a new research direction by integrating various dimensions into one cohesive approach.

The present study illustrates the architecture of a DVST through a practical example, based on a fischertechnik Training Factory Industrie 4.0, which is employed for teaching and research purposes at Magdeburg-Stendal University of Applied Sciences. Furthermore, the application of DVST is verified through scenario-based design and validation. Various scenarios are outlined and tested using the underlying simulation model, implemented in Arena software simulation. At this point, it should be noted that the DVST of the learning factory does not fully cover the functionality of a DT. Interfaces to the fischertechnik Cloud, which would enable bilateral automated data exchange, have not been implemented. However, the fundamental feasibility is demonstrated in the preceding sections. Therefore, the current study is subject to limitations that are noted within the scope of the paper.

Learning factories provide ideal environments where operations are reproducible and free from disruptions. Deviations in process times or queues do not occur naturally but need to be manually parameterized in the simulation model. Missing is the integration of field testing to validate these parameters. The current implementation of the DVST relies on synchronizing physical and virtual objects using a .csv file and operates asynchronously. Therefore, synchronization according to the DT concept is currently not implemented, despite being described conceptually.

The use of Value Stream Management enables various applications, including the initiation of improvement measures within the phase of Value Stream Planning (VSP). The validation of measures before their implementation plays a crucial role in operations. The present study is limited to four specific application cases, each exhibiting significant variability in their characteristics. The complexity necessitates a deeper examination of scenario selection. In addition to flow analysis, exploring conflicting value streams utilizing the same resources and conducting operation-specific investigations offer further research potential, not covered within the scope of the present study.

Derived from the limitations of the study at hand, the next step requires the examination of a real-world example. This approach serves two purposes: first, it enables the identification of additional cases that are practically relevant and demonstrate the economic value of a DVST from a business perspective. Second, the data variance in this study was artificially created using simulation operations, whereas a practical application would improve data quality. Furthermore, due to the diverse process and system landscapes, which are always company-specific, there is a need to investigate approaches to solve the challenge of creating a technical platform for data collection, processing, transformation, and provision as the basis for automated data flows.

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