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A DESIGN OF DIGITAL TWINS FOR SUPPORTING DECISION-MAKING IN PRODUCTION LOGISTICS

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ABSTRACT

Recent studies suggest that data-driven decision-making facilitated by Digital Twins (DTs) may be essential for optimizing resources and diversifying value creation in production logistics. However, there exists limited understanding about the design of DTs in production logistics. Addressing this issue, this study proposes a process for the design of DTs in production logistics. This study extends related works describing the dimensions of DTs in manufacturing, and adopts a process perspective based on production development literature. The results present a process for the design of DTs including activities in pre-study, conceptual, and detailed design phases corresponding to five DT dimensions. The proposed process is validated during the development of a DT in a production logistics lab at an academic environment. The findings of this study may be essential for avoiding misplaced resources and lost opportunities in the design of DTs in production logistics, and facilitating the planning and resource allocation.

1 INTRODUCTION

Recent studies suggest that Digital Twins (DTs) are critical for supporting data-driven decision-making in production logistics (Wang et al. 2020). Data-driven decision-making facilitated by DTs may be essential for increasing visibility and resilience, optimizing resources, and diversifying value creation in production logistics leading to increased performance (Ivanov and Dolgui 2019). The importance of DTs in production logistics is underscored by the absence of decision support tools providing managers, engineers, and operators a holistic understanding of decisions and their consequences (Gallego-García et al. 2019). DTs include a set of linked operations, data artefacts, and simulation models representing and predicting behaviors, and involve a bi-directional relation between a production system and its virtual counterpart (Cimino et al. 2019).

The study of DTs is characterized by the increasing number of publications focused on supporting the decision-making in manufacturing companies (Ding et al. 2019). However, research efforts focused on DTs remain predominantly conceptual (Haag and Anderl 2018; Barricelli et al. 2019; Tao, Zhang, et al. 2019), and only a limited number of DT studies address production logistic concerns in manufacturing practice (Kritzinger et al. 2018; Bányai et al. 2019; Wang et al. 2020). For example, Wang et al. (2020) proposed the use of DTs for proactively supporting material handling decisions in production systems. In addition, Bányai et al. (2019) adopted a DT approach for optimizing logistic resources. Studies posits that the restricted adoption of DTs in production logistics originates from the limited guidance offered by research for designing DTs at manufacturing companies (Nikolakis et al. 2019). The literature contends that increasing understanding about the design of DTs is critical for two reasons. Firstly, manufacturing companies may decide against adopting DTs because of the absence of clear guidelines for their design (Lu et al. 2020). Thus manufacturing companies may overlook increased competitiveness facilitated by data-driven decision-making originating from DTs. Secondly, manufacturing companies adopting DTs without clear design guidelines may reach unsatisfactory outcomes including misplaced resources, increased costs, or missed opportunities threatening their competitive advantage (Gallego-García et al. 2019).

Therefore, the purpose of this paper is to propose a process for the design of DTs in production logistics. This study adopts current understanding about the design of DTs in manufacturing (Tao and Zhang 2017; Stark et al. 2019), and production development (Johansson et al. 2019) for proposing a process to design of DTs in production logistics. The proposed process is validated during development of a DT in a production logistics lab for an academic environment. The findings of this study presents two salient contributions advancing the process for the design of DTs in production logistics. Firstly, the study proposes adopting a process perspective for the design of DTs. Accordingly, this study proposes three phases including a pre-study, conceptual and detailed design phases for facilitating the planning and allocation of resources in the process of designing DTs for production logistics. Secondly, this study identifies the activities and design phases corresponding to five dimensions of DTs including a real life production system, virtual production system, services supporting production systems, DT data, and connections for data exchange. Taken together, the findings of this study extend current understanding of DT design, and may be essential for avoiding misplaced resources and lost opportunities in the design of DTs. The remainder of this study includes the following sections. Section 2 presents an overview of related works. Section 3 proposes a process for the design of DTs in production logistics. Section 4 discusses the implication of this study, and Section 5 concludes.

2 RELATED WORKS

2.1 Dimensions and Activities for Designing Digital Twins

DTs comprise a high-fidelity representation of the operational dynamics of production systems along its lifecycle and a key enabler of Industry 4.0 (Schleich et al. 2017). This study adopts the work of Tao and Zhang (2017) who proposed five dimensions defining the characteristics and functionalities DTs. The five dimensions of DTs comprehend real life production systems (D1), virtual production systems (D2), services supporting production systems (D3), DT data (D4), and connections for data exchange (D5). This choice is explained by the number of studies in manufacturing adopting a five dimensional approach for DTs (Cimino et al. 2019; Ding et al. 2019; Guo et al. 2019; Park et al. 2019; Qi et al. 2019; Tao, Zhang, et al. 2019; Lu et al. 2020).

A first dimension comprehends real life production systems. From this perspective a real life production system includes all sets of elements (e.g. human, material, processes, environment) from which data will be conveyed into a virtual domain (Tao and Zhang 2017). While the vision of a DT includes the holistic representation of a complete production system current examples of DTs are limited to particular products, processes, or activities in manufacturing (Zhang et al. 2017; Barricelli et al. 2019; Cimino et al. 2019; Park et al. 2019).

A second dimension includes virtual production systems. This dimension refers to models representing physical entities including physical properties, behaviors and responses, rules of operation, structures of assets, parameters, and simulation models optimizing parameters (Tao and Zhang 2017; Damjanovic-Behrendt and Behrendt 2019; Stark et al. 2019).

A third dimension involves services supporting production systems and provides accurate shop-floor management, reliable operations, and feedback to decision-makers (Qi et al. 2018). Examples of real-time monitoring, energy consumption, management and behavior analysis, operation guide, optimization and update, failure analysis, maintenance strategy, or virtual operation exemplify services supporting production systems (Tao and Zhang 2017).

A fourth dimension contains DT data. DT data comprehends databases, data structures and data flows, which integrates multi-source heterogeneous real-time data (Zhang et al. 2019). Specifying DT data is crucial for successfully collecting, transmitting, storing, processing, fusing, and visualizing information leading to decision-support (Qi et al. 2019). Examples of DT data relate to real life production systems (e.g. capacity, quantity, real-time states of resources), virtual production systems (e.g. history records, simulation data, forecast data of resources), services supporting production systems (e.g. enterprise plan data, product data), and fusion of data through data association, mining, combination (Tao et al. 2018).

A fifth dimension comprises connections for data exchange. This dimension specifies the communication processes between production systems, environment, domain experts and DTs for interaction and operation (Tao and Zhang 2017). Connection for data exchange contain three kinds of interaction and collaboration: physical–physical, virtual–virtual, and virtual–physical (Qi et al. 2019). Examples of elements comprised in this dimension include sensors, and communication interfaces, protocols, standards ensuring a smooth data interaction (Lu et al. 2020). Table 1 presents a description of the five dimensions of a DT according to Tao and Zhang (2017).

Table 1: Description of the five dimensions of a DT according to Tao and Zhang (2017).

Dimension	**Description**
Real life production systems (D1)	Transformation system including human, equipment, and materials conveying and receiving data from a virtual production system
Virtual production systems (D2)	Faithful replicas of production systems including properties, behaviors, and rules
Services supporting production systems (D3)	Services supporting the management, control, operation and evolution of a virtual production system
DT data (D4)	Data originating from production systems, virtual production systems, services, and modeling and processing methods
Connections for data exchange (D5)	Connections between physical entities, virtual models, services, and data enabling real-time information and data exchange

Studies show that achieving the five dimensions of DTs involves a progression of activities. According to Qi et al. (2019), these activities begin with the definition of real life problem in a production system and the objective of a DT towards solving this problem. Activities for the virtual production systems dimension includes specifying rules and behavior of production system in virtual world, specifying the type of software and simulation environment to address the real life problem in a production system (Cimino et al. 2019). Activities for the services supporting production system development dimension comprehend identifying, characterizing, and developing full integration of DT services (Stark et al. 2019; Tao, Qi, et al. 2019). Activities related to DT data comprise identifying useful data throughout the lifecycle of a production system, including readily available one, useful for solving a problem (Damjanovic-Behrendt and Behrendt 2019; Stark et al. 2019). In relation to the dimension involving connections for data exchange the literature suggests activities focused on the planning, developing and securing data exchange across virtual models, data, and real life production systems (Redelinghuys et al. 2019). The studies above increase understanding about the dimensions and activities for designing DTs. Yet research highlights the need for specifying the activities for designing DTs throughout the life cycle of production development (Lu et al. 2020).

2.2 Production Development in the Design of Production Logistics

Production logistics refer to the activities and processes connected with managing the flow of materials (and adherent information) within the physical limits of an isolated facility (Cao et al. 2019). For example, production logistics tasks include warehousing, material handling, storage and material picking within a warehouse or factory (Negri et al. 2017). Accordingly, the primary goal of production logistics is to provide greater capability and reliability to machines and workstations at a minimum cost and maximum efficiency (Closs and Savitskie 2003; Huang et al. 2019).

Prior publications recognize production logistics as a sub-system of production (Rösiö and Bruch 2018). Consequently, literature on production development underpins the design of production logistics (Granlund and Wiktorsson 2014). Production development is often described in terms of a project management stage-gate process with close integration to the product development process. Figure 1 illustrates the phases of a generic production development process according to Johansson et al. (2019). The production development process includes seven phases. A first phase involves project resulting in a project directives and resource plan. A second phase includes a pre-study resulting in a requirement specification and refined plan. The third phase comprehends the conceptual design resulting in a solution in accordance with the requirements. The four phase relates to the detailed design for refining and planning the solution and providers. A fifth phase includes adaption and purchasing of the planned solution. The sixth phase involves implementation resulting in acceptance tests. Finally, a launch phase includes implementing the developed solution and handing over to operations.

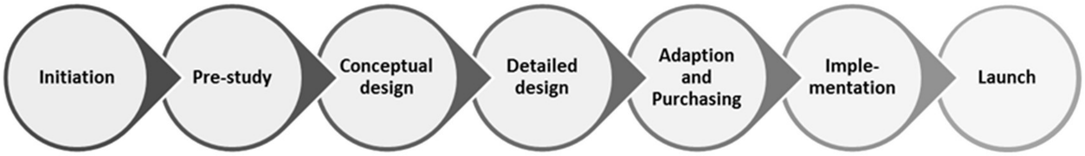

Figure 1. Phases of a generic production system development process according to Johansson et al. (2019).

Relating this generic production system development process containing production logistics is especially relevant for the design of DTs in the pre-study, conceptual and detailed design phases. Firstly, the purpose of the pre-study phase is to capture the requirements of the production system. During the pre-study questions about the company's goals and strategies are raised. The problem of interest is clarified, and changes to an existing production system are anticipated. Secondly, the conceptual design phase includes dealing with overall questions, such as process choice, layout, technological level, material supply, work place design, and work environmental considerations. Formulated alternatives are evaluated in order to determine which alternative best fulfils stated demands. Thereafter, the work continues with the detailed design. The final result is a detailed description of the chosen systems solution. Thirdly, the detailed design phase involves the selection of the most suitable production system concepts based on the quotes or the equipment suppliers. Equipment suppliers are selected, and the production system is specified. A risk analysis is performed, and planning for the implementation of the production system occurs.

3 PROPOSING A PROCESS FOR THE DESIGN OF DIGITAL TWINS IN PRODUCTION LOGISTICS

3.1 Phases, Dimensions, and Activities for the Design of Digital Twins in Production Logistics

This section proposes a process for the design of DTs in production logistics. To formulate this process, the study adopts current understanding about dimensions and activities for designing DTs. The proposed process includes a process perspective originating from production development literature for the design of production logistics. The process for the design of DTs in production logistics is based on the five dimensions defining the characteristics and functionalities DTs reviewed in section 2. The components in the dimensions represented by the physical environment (D1), virtual environment (D2), data (D4), and connections for data exchange (D5). In this process the dimension of services (D3) constitute the applications used by staff in production logistics for operating the DT. The service dimension is included in the process of designing DTs for production logistics because identifying and working concurrently with the considered application benefits the DT outcome.

The process for the design of DTs involves pre-study, conceptual, and detailed design phases. First, the pre-study phase clearly defines the requirements for building DTs in production logistics. In this phase, the components are defined based on the real life production system (D1), and the components of the virtual environment (D2) are defined to sufficiently express the physical environment. Also, for the communication between the virtual environment and the physical environment, requirements for data platform, data service, and database specifications to exchange data must be specifically defined.

In the next step, the conceptual and detailed design phases constitute a continuation of the pre-study phase. The results from the conceptual design phase must take a sufficient evaluation process, and detailed design should be performed using the verified results. Compatibility between various types of physical facilities constituting the production system is important, and interoperability between physical and virtual environments is critical when designing DTs for production logistics. A middleware platform is also required for data exchange between the system components. In the next step, a DT is implemented based on the detailed design results and operated according to a predetermined scenario. It is important to improve all dimensions constituting the DT through the feedback process, and it is possible to perform the practical operation through a sufficient verification process.

The data for the DT is gradually revised as the design phase progresses. The data requirements defined in the pre-study phase are specified in the design phase and verified in the realization and planning phase. In the actual operation stage, not only real-time data, but also historical data is used, and better decision-making can be supported based on various analysis results. Figure 2 describes the process for the design of DTs in production logistics, and compares this process to that of production system development. The process includes activities corresponding to the dimensions and phases for the design of DTs in production logistics. These activities constitute a progression from the definition of real life problem involving production logistics tasks to a fully developed DT including its five dimensions. Additionally, the activities included in the proposed process for the design of DTs align to the objectives of the pre-study, conceptual, and design phases. Activities target capturing the requirements, formulating alternatives, and selecting the most suitable concept in the pre-study, conceptual, and detailed design phases respectively. Table 2 presents the activities, dimensions, and phases in the process for the design of DTs in production logistics.

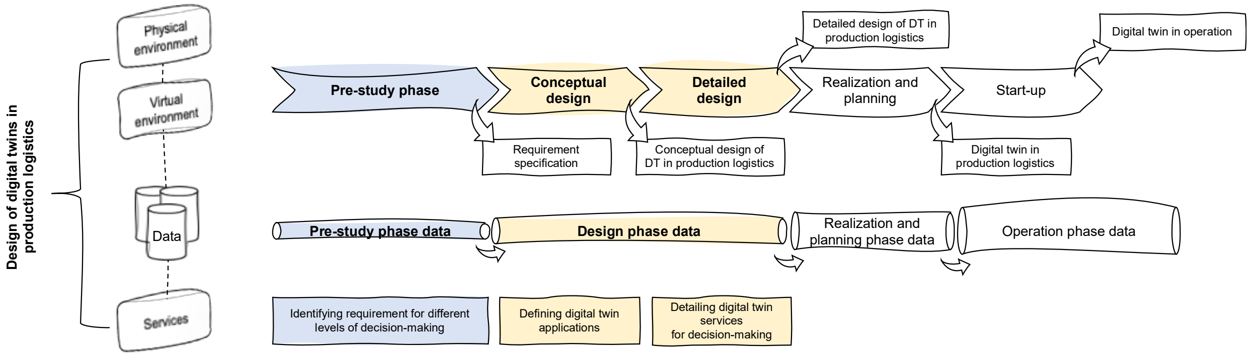

Figure 2: Process for the design of DTs in production logistics.

Table 2: Activities, dimensions, and phases in the process for the design DTs in production logistics.

	Pre-study phase	Conceptual design phase	Detailed design phase
D1	• Formal project initiation • Clarification of problem definition • Anticipation of changes to production logistics • Developing requirements	• Preliminary production logistics concept • Virtual analysis • Refinement of production logistics concept • Risk analysis	• Selection of production logistics concept • Specification of production logistics solution • Risk analysis • Planning for realization
D2	• DT architecture and layers • Specifying rules and behavior of production system in virtual world	• Specifying the software and type of simulation environment • Providing semantic elements representing the design and operation of a production line, and facilitates the exchange of information	• Locating the malfunction reason, rule out the design mistakes, inspect the system • Interface, model, module, engine, rule, and algorithm components according to their respective roles, while each layer is classified by its main role
D3	• Identifying required management and control for different levels of decision making	• Defining status analysis application, DT application, and process design planning application	• Detailing services for decision-making including visualizations, automatic response, prediction of behavior
D4	• Identifying various kinds of data such as customer satisfaction, product sales, product competitiveness, investment plans, etc. • Describing data repositories	• Formulating dataset and acquisition protocols	• Synchronization information stored and managed in the database according to the time of need • Interaction and convergence between historical data and real-time data
D5	• Specify various physical devices, such as actuators and sensors, which can provide or consume signals • Represents the data source of real life production logistics system	• Establish communication interfaces from DT to virtual production logistics system • Contextualize data, and process data for use • Develop communication services facilitating storage of historical information • Investigate threats to data security	• Achieve linkage between information systems, physical equipment, and simulation models • Provide functionality to user interfaces connecting to real-time and historical information • Remote test of system performance

3.2 Designing a Digital Twins for Production Logistics in a Lab Environment

Various situations in production logistics can be verified and tested through a virtual environment such as a simulation model. However, it is not easy to fully reflect the physical environments and constraints because there may be parts that are omitted or abstracted in the process of building a model. DTs can help solve these problems since their domain includes virtual and physical environments. Scenarios that are difficult to apply directly to the physical environment can be tested indefinitely in the virtual one. Correspondingly, physical constraints that are difficult to model in the virtual environment can be verified in the physical environment. Therefore, the virtual and the physical environments in DTs are complementary. Yet, exclusive work on physical and virtual environments for developing DTs is insufficient. Instead, data, communication, and services in addition to virtual and physical environments must be robustly designed and clearly defined in order to construct the DT-based system. This study validated the process proposed in the previous section based on the development of a DT for production logistics in an academic lab environment.

The purpose of developing a DT for production logistics in an academic lab environment includes testing scenarios involving tasks such as material handling, transportation, warehousing, or order picking, and the applicability of automation and intelligent technologies for supporting these tasks. Two research project exemplify the purpose of a DT for production logistics. A first project includes Digital and Physical Testbed for Logistic Operations in Production (DigiLog; https://www.kth.se/sv/hpu/research/projects/digilog-1.889090). DigiLog involves a combination of a physical and a virtual test bed facilitating the export and import of collected data from actuators and sensors in both environments. The project utilizes a DT for identifying possible improvements at process (information and material flow), and organizational (layouts and operational issues) levels. The results provided by the DT may help understand how digitalization technologies can support the human in executing the daily production logistics task. A second project involves Cyber Physical Assembly and Logistics Systems (C-PALS; https://www.kth.se/sv/hpu/research/projects/c-pals-1.906829). C-PALS involves a DT and real time location services for planning and controlling the delivery of materials in production logistics. The project utilizes a DT for optimizing transportation and guiding logistics staff in material handling tasks in a factory. The results provided by the DT may help monitor functioning of assets, identify the cause of anomalies, and reduce costs of human-based tasks in production logistics.

Currently, the DT for the production logistics lab includes a collaborative robot, automated guided vehicle (AGV), real-time location system (RTLS) sensors, individual network, vision system (2D, 3D camera), three-dimensional visualization model, discrete event system (DES) simulator, and data streaming bus for the DT. The production logistics lab is developed based on the DT concept and includes virtual environments, data, and connections for data exchange and services. Figure 3 presents the DT in the production logistics lab. In this lab the physical environment can be monitored in real-time through the virtual environment. Also, the DT provides remote control of the physical components from the virtual environment. To realize this, all components of the physical environment are connected to the data streaming bus, and the collected data is stored without overlapping in the storage space. AGV usage patterns can be analyzed by analyzing stored historical data, and collaborative work between different components can be performed using real-time data.

Developing a DT in an academic lab environment reveals the importance of improving ad hoc procedures in the design of DTs for production logistics. The proposed process for the design of DTs in production logistics offers guidelines for mitigating ad hoc practices. Two examples are presented. First, introducing new devices or systems increasing the capabilities of the academic lab environment. Frequently, new device or systems involve unique operating systems or data exchange protocols. For example, RTLS and AGV provide web applications and APIs from their manufacturers which differ from those of the collaborative robot using a unique operating system and socket connection for data exchange. The absence of clear guidelines including the interrelation of RTLS, AGV, and collaborative robot including services, data, and connections for data exchange require additional development work to integrate the components. Second, providing additional DT-based services supporting production logistics tasks. The development of a DT may extend beyond its original scope, and include additional tasks, users, or phases of production logistics lifecycle. DT-based services must adapt accordingly. Second, providing additional DT-based services supporting production logistics tasks. The development of a DT may extend beyond its original scope, and include additional tasks, users, or phases in a production logistics lifecycle. DT-based services must adapt accordingly. The proposed process for the design of DTs in production logistics offers a pathway to introducing additional DT-based services. Importantly, this includes the relation of DT-based services to the real life production system, its virtual counterpart, data, and data exchange. Accordingly, ad hoc work in designing and implementing additional DT-based services can be avoided, and resources scheduled during the design of a DT.

Figure 3: DT in the production logistics lab.

4 DISCUSSION

The purpose of this study is to propose a process for the design of DTs in production logistics. In particular, this study adopts current understanding about the dimensions and activities for designing DTs and production development. In this section we present the theoretical and practical implications of this study. Extant literature is compared to findings from a proposed process for the design of DTs in production logistics and its development in a production logistics lab at an academic environment. The findings of this study are particularly relevant in light of the interest from manufacturing managers and academics for understanding the dimensions, process, and activities for designing DTs in production logistics.

4.1 Theoretical Implications

Recent studies recommend the adoption of five dimensions defining the characteristics and functionalities for the design of DTs in manufacturing (Tao and Zhang 2017). However, understanding about the dimensions of DTs has not resulted in an increased use of DTs in production logistics, as opposed to the fields of manufacturing or maintenance (Barricelli et al. 2019). The findings of this study reveal that the dimensions of real life, virtual, and services supporting production systems, DT data, and connections for data exchange are indispensable for designing DTs in a production logistics. In particular, this study suggests that understanding of DT dimensions may lead to avoiding misplaced resources and lost opportunities when designing DTs in production logistics. For example specifying the dimensions of a DT in production logistics help define the purpose, and scope the extent of a DT against a background of limited time and resource available during its design. This knowledge may be essential for linking production logistic tasks, data, and simulation models producing a bi-directional relation between a production system and its virtual counterpart. Importantly, the findings of this study suggest that addressing the five dimensions of DTs may not be achieved by a single department at a manufacturing company. Instead, this study suggests the need for cross disciplinary understanding including simulation, data, communication, and production logistics competences. Extending current understanding, this study proposes that the dimensions of DTs are critical but insufficient for the design of DTs in production logistics. Additionally, this study underscores the need for equal comprehension about the process and activities for designing DTs in production logistics. This study suggests that adopting a process including activities for designing DTs may transform isolated DT dimensions into fully functional DTs solving PL tasks including material handling, warehousing, transportation, order picking or packaging.

Current understanding about the design of DTs follow a model-based systems-engineering approach that emphasizes data and models (Tao, Qi, et al. 2019). Our findings show that consistent with the literature the importance of data and models are central in the design of DTs for production logistics. Contributing to current understanding, the findings of this study highlight the relevance of adopting a process perspective for the design of DTs, which is achieved by drawing from literature in the field of production development. In this study the importance of a process perspective for designing DTs in production logistics is exemplified by proposing a correspondence between the dimensions of DTs, and the process of developing a production system including a pre-study, conceptual, and detailed design phases. In doing so, this study extends current understanding for designing DTs in production logistics and proposes a process that is time dependent, sequential, and involves specifying requirements (pre-study phase), formulating and evaluating alternatives (conceptual design), and selecting a suitable concept (detailed design phase). Proposing a process for the design of DTs in production logistics is critical because existing models describing the design of DTs give precedence to specifying the characteristics and functionalities of DTs. By presenting a process for the design of DTs in production logistics an important step is taken for addressing the need for pathways describing how to build viable DTs (Tao, Zhang, et al. 2019).

A final contribution of this study relates to the activities for designing DTs. Prior studies delve into the activities specifying the design of DTs as exemplified by the work of Park et al. (2019). However, understanding about the correspondence of DT dimensions and activities is scattered in various works. We advance current understanding by offering a synthesis of activities and dimensions for designing DTs in production logistics. This constitutes an important finding that may contribute to moving research a step closer in achieving the benefits of DTs throughout the lifecycle of production logistics.

4.2 Implications to Practice

The results of this study provide valuable contributions for managers and simulation specialists responsible for designing DTs in production logistics, and consequently, for supporting data-driven decision-making leading to increased performance. At the outset, the findings reveal the process, dimensions, and activities essential for structuring and managing the design of DTs in production logistics. In short, this study provides a pathway describing how to design DTs for production logistics.

To-date, few studies focus on designing DTs in production logistics. Consequently, managers responsible for improving production logistics tasks find themselves with insufficient guidance on the steps for designing DTs. The absence of guidelines is comprehensible because of the recent interest from manufacturing companies in using DTs in production logistics. This study forwards recommendations that may enhance understanding about DT design. In particular, this study promotes the importance of a structured process necessary for avoiding ad hoc practices, ensuring the continuity and completion of DT dimensions, and focusing work on supporting production logistics tasks. In addition, this study underscores the importance of increasing understanding about DT dimensions. This knowledge is essential for achieving functions and avoiding neglect of critical characteristics of DTs. Finally, managers may benefit from the list of activities for designing DTs in production logistics proposed by this study. This knowledge, in combination with production development understanding, may be essential for controlling, planning and coordinating resources associated to the design of DTs.

The findings of this study include three practical contributions for simulation engineers. A first benefit of this study suggests the importance of simulation competence throughout the process of designing DTs, and the need for increased data traceability along production logistics lifecycle. Accordingly, simulation engineers need to pay particular attention to cross-functional activities and the junction of the different phases in the process of designing DTs in production logistics. A second benefit relates to the need for working concurrently with the five dimensions of DTs in the process of designing DTs for production logistics. In particular, this study proposes that the efforts of simulation engineers towards designing DTs may be ineffective if real life and virtual production systems, services, DT data, and connection for data exchange are disregarded. Describing the five dimensions of DTs may help simulation engineers increase their knowledge about DTs, and reveal the distinctness of DTs when compared to traditional simulation models (e.g. discrete event) in production logistics. Finally, simulation engineers may find this study useful for better understanding the need for continuous collaboration with different functions, in addition to stakeholders responsible for production logistics tasks, during the design of DTs. Table 3 presents the practical implications for managers and simulation engineers of the propose process for the design DTs in production logistics.

Table 3: Practical implications for managers and simulation engineers of the propose process for the design of DTs in production logistics.

	Stakeholders	
	Managers	**Simulation engineers**
Process	• Provide structured way of working and avoid ad hoc practices • Completion and continuity of dimensions and activities for DT design • Generic guidance for designing DTs including production logistics tasks	• Simulation competence essential throughout the process of designing DTs • Increased data traceability along production logistics life cycle
Dimensions	• Understand DT dimensions • Achieve DT functions and avoid neglect of critical DT characteristics	• Understanding of difference between simulation and DT • Assessment of current knowledge about DTs
Activities	• Provide practical guideline of what to do (role and responsibility) • Set up milestones and avoid costly mistakes	• Different from one time (or single-use) simulation project. Highlights the need for a sustained effort • Requires continuous collaboration with different functions, not only the activities from physical dimension

5 CONCLUSIONS

The purpose of this study was to propose a process for the design of DTs in production logistics. This study adopted the findings of prior studies identifying the dimensions and characteristics of DTs, and extended current understanding about DTs to the field of production logistics. The proposed process for the design of DTs in production logistics included the phases of pre-study, conceptual design and detailed design. Additionally, the study presented a series of activities corresponding to five dimensions of DTs for each phase of the process for designing a DTs in production logistics. Validation of the proposed process included the development of a DT in a production logistics lab at an academic environment for remote control and real-time monitoring of production logistics tasks. The findings of this study may benefit managers and simulation engineers responsible for the design of DTs in production logistics. Practical implications of this study may be essential for avoiding misplaced resources, lost opportunities, and facilitating the planning and allocation of resources in the design of DTs for production logistics.

Three limitations circumscribe this study. A first limitation includes results drawn from an academic environment. Therefore, an immediate step involves verifying and validating the results of this study in industrial cases involving production logistics tasks such as warehousing, material handling, packaging, and order picking. A second limitation comprehends the need for increased work towards standardization of DT development. Future research could synthesize the findings of this study with parallel efforts involving the standardization of DT development. This is important given the expectations surrounding DTs across supply chains involving for example different factories within an organization or suppliers and end users across organizations. A final limitation includes detailed analysis of DT services. Increasingly, research points towards the need for specifying DT services benefiting production logistics tasks. While DT services constitute one of the dimensions examined in this study, future work involving DT services supporting production logistics is essential for revealing new insights including diagnosis and prognosis of production logistics tasks.

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