Exploring Economic, Environmental, and Social Sustainability Impact of Digital Twin-Based Services for Smart Production Logistics

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Abstract. Digital Twins are increasingly perceived as critical enablers for improving operational performance and sustainability of Smart Production Logistics. Addressing the lack of empirical research on this topic, this study explores the economic, environmental, and social sustainability impact of Digital Twin-based services for Smart Production Logistics. The study presents findings from a Smart Production Logistics demonstrator in an academic environment and underscores the contributions and limitations of current understanding about Digital Twin-based services in relation to their impact on economic, environmental, and social sustainability. The study presents valuable implications for managers responsible for material handling.

Keywords: Digital twin-based services · Sustainability · Smart Production Logistics

1 Introduction

Digital technologies are considered an enabler for achieving superior operational performance and contributing to impact in economic, environmental, and social sustainability [1]. In particular, the literature suggests that Digital Twins (DTs) may contribute to achieving this dual-purpose [2]. DTs refer to a set of linked operations, data artifacts, and simulation models representing and predicting behaviors, and involve a bi-directional relation between a physical production system and its virtual counterpart [3]. For example, recent findings contend that DTs may enhance sustainable development, and predict and material handling in Smart Production Logistics (SPL) [4, 5]. Current research about DTs focuses on developing DT-based services. Yet, current understanding about DT-based services focuses on the performance of SPL, and efforts about the economic, environmental, and social impact of DT-based services remain insufficient. Consequently, the purpose of this paper is to explore the impact of economic, environmental, and social sustainability of DT-based services for SPL in material handling. Empirical data is drawn from an SPL demonstrator.

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The results of this study suggest that the current understanding of DT-based services in SPL may contribute to achieving all impacts in economic, environmental, and social sustainability, but is insufficient.

2 Related Works

Recent research shows that DTs are a way to implement smart manufacturing, and DT-based services improve current circumstances and hurdles. Grieves proposed the concept of DTs in 2003 including three parts, physical space, virtual counterpart, and data connection between two spaces [6]. The physical and virtual models and data in DTs describe the characteristics of the physical object and its digital replica. These are used in diagnosis, analysis, prediction, and optimization of the manufacturing system to support decision-making. DT-based services refer to the components of DT providing intuitive understanding of target objects through multiple data, resources, and distributed computing [7]. In other words, DT-based services offer value-adding services to non-professional users with limited technical expertise. Accordingly, DT-based services assist non-professional users to manage cost, capacity, and real-time status issues [8]. For example, DT-based services include predicting, diagnosing, or reducing the cost and downtime of transport operations in SPL to help staff in charge of operational, tactical, and strategic decisions [9, 10]. To implement DT, the literature provides not only guidelines regarding how to use the Internet of Things (IoT) devices such as networks and sensors [11], but also identifies that the production logistics simulation model needs networking devices and synchronization to develop into DT [12]. Additionally, the recent research discusses the use of DT to support the decision-making process in the field of production and logistics through testbeds containing the IoT infrastructure and simulation software [13]. In relation to sustainability, the literature posits that DTs enhance sustainable development by reducing energy consumption and predict material handling by optimizing transportation equipment in SPL [5].

Sustainability is divided into three interrelated aspects: Economic, Environmental, and Social. Figure 1 based on [15] shows the impact of Industry 4.0 on three sustainability areas. Importantly, impact on one aspect of sustainability affects another. For example, increasing resource efficiency has the effect of reducing the amount of energy used by resources on the environmental aspect, and brings other effects of increasing productivity through the efficient use of resources on the economic aspect.

The literature offers several examples evidencing how DTs and DT services enhance sustainability. For example, prior studies propose applying DTs in data flow systems and develop a sustainability indicator for improving the performance of the sustainable design of products [16]. Additionally, the literature highlights the use of DT services for improving efficiency and productivity of existing processes, and reducing energy consumption and associated costs in small and medium sized companies [17]. Finally, recent efforts propose a DT-driven sustainable manufacturing framework analyzing the impact of DTs in economic, environmental, and social sustainability for equipment systems, and services [18].

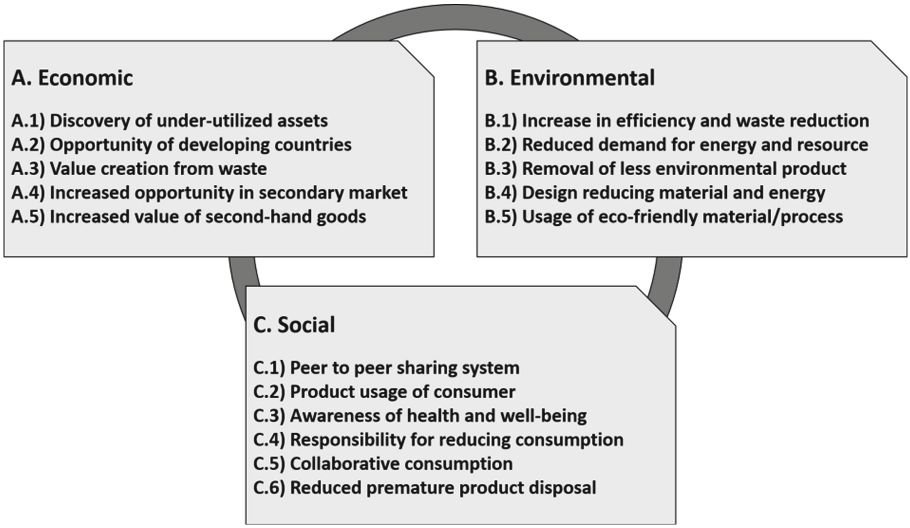

Fig. 1. Economic, environmental, and social sustainability

3 Digital Twin-Based Services and Sustainability

This section describes a DT for material handling in production logistics and its services addressing economic, environmental, and social sustainability. The DT includes five dimensions according to [19, 20] involving a physical world, digital world, data storage, networking, and DT-based services. The proposed DT-based services comprehend monitoring, prescription and prediction of material handling tasks. Finally, we describe the relation of the proposed DT-based services to sustainability.

The DT comprehends a physical world, digital world, data storage, networking, and DT-based services for material handling. The physical world includes three warehouses, up to three forklifts, and three production processes composed of six stations. Ultra-Wideband (UWB) radio tags and Radio Frequency Identification (RFID) sense points collect data in real-time from the forklifts. The virtual world provides a digital representation of the physical world. The virtual world encapsulates, processes, and synchronizes information including resource (forklift name, distance travelled, location, speed, time stamp), and order (product, order, confinement and delivery location, pickup and delivery time). Databases in a server store real-time data and information processed in the virtual world. Additionally, the DT utilizes a Node-Red application for transferring data from the factory floor, and communicating across DT-based services.

This study proposes DT-based services including monitoring, prescription and prediction for material handling. These services target distinct functions in logistics organizations. Monitoring services involve a web-based application displaying the real-time movement and plotting of spaghetti diagrams and heat maps of forklifts. Additionally, the monitoring service presents the utilization, distance travelled, and collisions incurred by forklifts. The monitoring services benefit managers responsible for supervising and assigning resources in material handling. Prescriptive service applies a task scheduling optimization algorithm that arranges material handling tasks according to position of a forklift, its distance to a station, and the time for picking and delivering material. The algorithm minimizes the delivery time, makespan, and distance travelled by a forklift when delivering material handling tasks. The prescriptive services support forklift drivers responsible for picking and delivering material in the factory. Finally, the predictive service utilize historical information including number of forklifts and material handling tasks as an input to a discrete event simulation model. The model tests scenarios including changes to number of tasks, forklifts and their availability providing a prognosis delivery, makespan, and distance for material handling. Figure 2 present the monitoring, prescriptive, and predictive DT-based services for material handling.

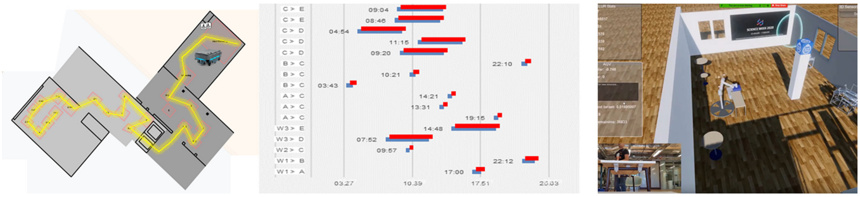

Fig. 2. Monitoring, prescriptive, and predictive DT-based services for material handling

DT meets the requirement of personalized manufacturing and has the environmental sustainability benefits of not only increasing resource efficiency but also reducing the waste of energy, and the social sustainability benefits of focusing on user use. DT services make it easier for members of the shop-floor and factory to share information, discover underutilized resources, and remove products or processes damaging the environmental aspect. The use of real-time location information enables operators to grasp in advance the collision that may occur during logistics movement and material handling at the production site and creates a safe environment for operators and manufacturing resources.

4 Case Study

This section presents a case from an automotive company in Sweden. Forklifts operators perform material handling tasks manually including delivery of part from warehouse to production stage and transfer of part from previous to next production stage. However, forklifts operators are in trouble when locating the point of confinement and delivery of parts and determining the sequence of scheduled tasks. Moreover, managers struggle with understanding the reasons for deviations of scheduled tasks, and improving delivery, makespan, and distance of material handling. The case applies the proposed SPL demonstrator (Fig. 3) including the DT-based services for material handling.

The forklift executes a schedule including 25 material handling tasks specifying the order number, pick and delivery time, and pick and delivery locations. We planned two scenarios before (As-Is) and after (To-Be) using the DT-based services. In the before scenario, operators execute the schedule ad hoc. Forklift operators arrange and deliver chronologically material handling tasks according to the earliest consumption time.

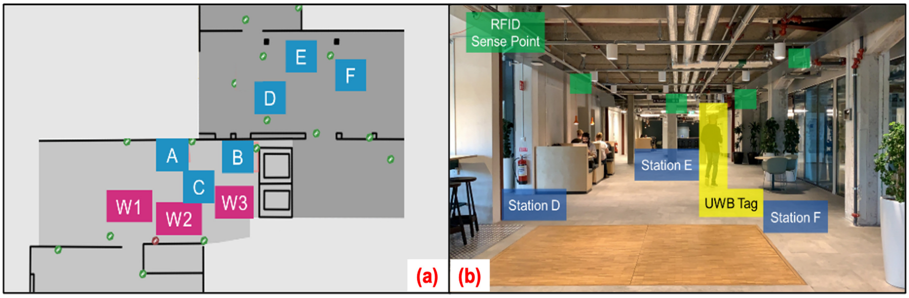

Fig. 3. (a) Layout and (b) IoT environment of production shop floor in SPL demonstrator

In the after scenario, forklift operators utilize DT-based services obtaining an optimal schedule for material handling. The results show improvement on key performance indicators involving on time deliveries, distance, and makespan when applying the DT-based services. The late deliveries decrease from two late deliveries to zero late deliveries. The total distance travelled by forklifts also decreases from 850 m to 670 m. Finally, the makespan decreases from 23:48 min to 23:42 min. Table 1 presents the results of the DT-based services demonstrator.

Table 1. Results of DT-based services system demonstrator

Scenario	Late deliveries (# of tasks)	Distance (meters)	Makespan (minutes)
As-Is	2	850	23:48
To-Be	0	670	23:42

5 Discussions

The findings of this study suggest that current understanding about DT-based services in SPL may contribute to, but is insufficient for, achieving all impacts of sustainability. The results indicate that current understanding about DT-based services may contribute to, one out of five type of impact on economic sustainability, two out of five types of impact in environmental sustainability, and two out of five types of impact in social sustainability. Table 2 presents the sustainability impact and empirical results of this study. A description each DT-based services contributing to impact in economic, environmental, and social sustainability follows.

Table 2. Sustainability impact and empirical results

Sustainability impact	Empirical result
A.1) Discovery of under-utilized assets	Increase of the number of forklifts required
B.1) Increase in efficiency and waste reduction	Reduction of the number of delayed deliveries
B.2) Reduced demand for energy and resource	Reduction of the travelled distances of forklifts
C.3) Awareness of health and well-being	The traffic and collisions history of forklifts
C.4) Responsibility for reducing consumption	Information of resource utilization for tasks
A. Economic; B. Environmental; C. Social	

The results of this study suggest that DT-based services in SPL may contribute to achieving impact on economic sustainability. In this study, monitoring and prescriptive DT-based services apply real-time location and task scheduling optimization showing the position of individual forklifts with respect to time and their execution of material handling tasks. Furthermore, the results suggest that managers applying real-time location and task scheduling optimization may recapture the value of forklift utilization. For example, DT-based services may be essential for logistics planners responsible for allocating forklifts to specific areas of a factory or sharing forklifts across different processes in material handling.

Additionally, the results of this study suggest that prescriptive DT-based services for SPL contribute to impact on environmental sustainability. In particular, this study argues that scheduling optimization is crucial for reducing the distance travelled by forklifts in material handling, and thereby contribute to increasing resource efficiency and waste reduction. However, the findings of this study suggest that energy spent in material handling may be decreased in relation to the distance travelled by forklifts. This finding may be essential for manufacturing organizations concerned with reaching environmental sustainability goals. DT-based services revealing travelled distance may be essential for identifying and reducing unnecessary delivery routes, minimizing forklifts, and motivating the choice of material handling equipment with improved energy efficiency. Consequently, this study posits that current understanding about DT-based services in SPL may reduce demand for energy.

Furthermore, this study argues that existing understanding about monitoring and predictive DT-based services in SPL may lead to impact in social sustainability. Empirical results suggest that DT-based services may contribute to increased awareness toward health and well-being in two ways. Firstly, DT-based services including path traces register traffic and heat maps reveal the frequency of travel of forklifts. Path traces and heat maps indicate areas of high risk for staff in logistics and operations who may be ex-posed to forklift collisions. Secondly, DT-based services register the location and number of collisions of forklifts during material handling. Collisions are registered in real-time and historic data in a layout of the factory. Consequently, managers may implement corrective actions preventing future incidents threatening the wealth and well-being of staff. Furthermore, DT-based services may facilitate increased accountability towards reduced production and consumption. DT-based services show the number and distance travelled by forklifts in real-time for completing a delivery schedule. This information is critical for analyzing the utilization of resources and revealing waste (e.g. excess distance or forklifts) in material handling. Based on this information, manufacturing companies may increase awareness and implement policies increasing accountability towards the reduction of resources for material handling.

While having the advantage of meeting some of the three aspects of sustainability, we confirmed challenges. A.4) Increased opportunity in secondary market and A.5) Increased value of second-hand goods of Fig. 1 are insufficient to be supported by the DT service presented in this study. These are connected to the product life cycle. In other words, simulation services related to product usage scenarios, not for services for material handling, are necessary to check the life cycle of the product to disposal. B.5) Usage of eco-friendly material/process requires the development of new material for product and process design. This is because the product design is decided and the manufacturing process changes depending on the material. C.5) Collaborative consumption and C.6) Reduced premature product disposal are accomplished by the product design services. Therefore, DT should design products with the requirements of consumers offered from online and produce and execute a production process. Virtual experiment services to determine the durability of the designed product is necessary to reduce premature product disposal.

6 Conclusions

This study developed a demonstrator of SPL in an academic environment based on current understanding about DT-based services. Empirical results indicated that current understanding about DT-based services in SPL may contribute to, but is insufficient for, achieving all impacts in economic, environmental, and social sustainability described in literature. This study presents important contributions to practice including a description of benefits of DT-based services in SPL for operators, and logistics and factory managers, and their implications to economic, environmental, and social sustainability. Future research could focus on verifying results by drawing data from different industrial segments, and different aspects of SPL for example automated guided vehicles, forklift fleets, and different levels of the automation. Furthermore, the findings of this study underscore the need for extending current understanding about and proposing DT-based services leading to impact in economic, environmental, and social sustainability.

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