Aalto University
School of Business

USAGE OF DIGITAL TWINS IN SUPPLY CHAIN RISK MANAGEMENT

A LITERATURE REVIEW AND FOUR CASE STUDIES

Bachelor’s Thesis
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Abstract

With industrial internet revolutionizing many ways we use data, companies and public sector alike are seeking ways to adapt this. One of the adaptions is called a Digital Twin (DT). Digital Twin is a digital replica of any physical object from which data may be collected, and which processes and exchanges data with its physical counterpart, allowing for automatic modifications in the physical part based on the data collected by the twin. The usage of DTs varies depending on the industry and the target, with numerous possibilities in the usage.

One of the ways of using DTs in business is adapting its usage to supply chains. When observing the supply chains (SC), managers often want to make sure the risks in the chain are as small as possible. The Digital Twin of a supply chain has a potential to answer that need. In this thesis, the current literature on the usage of DTs in supply chain's risk management will be reviewed. The goal for the thesis is to answer whether the usage of digital supply chain twin can be feasible for companies seeking to optimize their SC risk management and to have a more efficient deployment of back-up scenarios in case of SC disruption. For the thesis, both conceptual literature and case studies focusing on specific fields of SC are reviewed.

The literature reviewed in the thesis indicates that adapting digital supply chain twins to company's supply chain risk management function is a feasible solution for the company, as it makes the supply chain more visible, resilient, and provides effective recovery policies in case of supply chain disruption. It is also notable, that while the amount of literature on DTs in general is ample, its SC implementation-orientated research is still very limited. Furthermore, the case studies and conceptual literature reviewed for the thesis did not address the cost of digital supply chain twin, thus the discussion on its economical profitability as an investment is also quite narrow, and more research is needed.

Keywords Digital Twin, Supply Chain, Supply Chain Risk Management

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List of Abbreviations

DT	Digital Twin
SC	Supply Chain
IoT	Internet of Things
SCRM	Supply Chain Risk Management
DSCT	Digital Supply Chain Twin
WSN	Wireless Sensor Network
ML	Machine Learning
AI	Artificial Intelligence
ERP	Enterprise Resource Planning (System)
T&T	Track and Trace
RFID	Radio frequency identification technology
BIM	Building Information Modeling
GIS	Geographic Information System
MiC	Modular Integrated Construction

1 Introduction

Information technology is surrounding us more and more every day, and respectively, its applications are spreading into business bringing new opportunities and challenges. The variety of data sources that appear on a regular basis have resulted in an information explosion in today's tech-centred world (Ghadge, Dani and Kalawsky, 2011). Following the increase in the amount of data surrounding us, the implementations using that data are multiplying. One of such implementations is the Digital Twin (DT), which is a digital counterpart of anything physical that data can be gathered from. DT processes and exchanges data with its physical counterpart allowing automatic changes in the physical part based on the data that the twin gathers. (Kritzinger *et al.*, 2018)

DTs are a rising topic in the Internet of Things (IoT) industry with numerous applications created to answer the needs of companies. DT implementations vary from digital shopfloor twins and production lines to industrial machinery twins and digital supply chain twins (DSCT). Among these topics the DSCTs and their usage in risk management are a topic that is still in its infancy when observing the existing literature. SC disruptions have been a risk that companies have been facing for a long time, and international outsourcing and wider and more complex SCs possess greater risks than a more local SC (Christopher and Peck, 2004).

There has been increasing discussion if the usage of DTs could benefit risk management. Theoretically, the DSCT could represent SC network states for any given moment in real time (Ivanov and Dolgui, 2021). The research on DTs is plentiful, however as mentioned earlier, there are only a few studies focused directly on DSCTs. This leaves room for future research and a need for case studies for observing business opportunities of DSCTs.

This thesis will be carried out as a review of current literature and existing case studies on the usage of DTs in supply chain risk management (SCRM). This subject is very topical due to DTs being a rising trend in business and in technology. Because of this, it is important to find out how DTs will influence business in the future, and what kind of opportunities and challenges they will provide and will their usage in supply chain risk management be a feasible solution for companies. Also, Covid-19 pandemic has raised discussion on resilience of SCs and on the effects of possible SC disruptions, making the subject even more current. With globalization making SCs broader and more complex, a need to address their growing risks is urgent. Being able to manage those risks could give a huge business advantage to companies. Possible challenges in implementations of DTs in SC management could be the cost of implementation, availability of usable data and finding a right simulation model to process the data gathered.

1.1 Research objectives and research questions

Globalization has made SC networks even more complex and large, creating a need to answer to that complexity with more efficient risk management methods. While there is lot of research on DTs, SCs, and SCRM separately, the research addressing the usage of DTs in SCRM is still in its infancy with only a few studies published. In this thesis the focus in on the current literature and existing cases in the mentioned field. The research objective is to create a thorough review on the current literature on DT implementations in companies' SCs, and to analyse what kind of role DTs play in SCRM. The goal is to answer the following research questions through existing literature:

i. Can Digital Twins be used to develop company's supply chain risk management?
ii. Can the implementation of a Digital Twin increase profit through supply chain risk management?
iii. What kind of challenges does the implementation of a Digital Twin pose to a company?

1.2 Scope of research

This thesis will review and discuss scientific literature concerning DTs and their role in managing companies SC risks. The theoretical background in this thesis will cover DTs as a concept and different aspects of companies' SCRM with the focus on SC disruptions and how DTs can influence them. The literature reviewed in this research will aim to provide answers to the research questions mentioned and give an overall look on current literature on DTs and their usage in SCRM.

This study does not provide empirical research on the usage of DTs in SCRM, thus mathematical models and implementations are not presented. Also, any kind of interviews on the matter will not be conducted. The articles and case studies presented will provide insight on the existing empirical studies on the topic concerning, for example, the usage of DTs in a module construction site and in the pharmaceutical industry. The thesis will not restrict to any specific industry, but the overall usage of DTs according to current literature.

1.3 Methodology

The thesis will be a carried out as a literature review of the current topics regarding DTs as a factor in SCRM. Material for the thesis is acquired from scientific article database Scopus, and Google Scholar is also used. Search of literature has been executed by combining keywords Digital Twins, risk assessment, risk management, revenue, profit, Internet of Things, IoT and Industrial Internet, supply chain, and supply chain disruption. The time frame for the articles concerning DTs was limited to 9 years as the concept of Industry 4.0 has been formalized in 2013 (Bevilacqua *et al.*, 2020). However, most of the articles fit in the time frame of 5 years as DTs are a quickly evolving topic and a rather new concept in business. Any older articles were used to define the background theory concerning risk management in supply chains as a concept. The number of citations and publication forum's citation ranking was used to provide critical overview for the source material.

1.4 Structure of the research

From now on, the thesis will be structured as follows. Chapter 2 will be defining the theoretical background and the key concepts for the thesis. First, the concept of DT will be defined and the difference between Digital Twin, Digital Model and Digital Shadow will be defined. After that, the background theory about SCRM will defined and introduced.

In chapter 3 the literature on usage of DTs in SCRM will be reviewed. First, the amount of research about the topic will be discussed. Next, the topic will be observed through conceptual literature. Then, total of 4 case studies will be introduced and discussed. Last, the challenges in the DTs supply chain implementations will be discussed.

Chapter 4 will conclude the thesis with discussion and conclusions. Implementations to practice will be discussed. Also, possible limitations and future research will be addressed.

2 Theoretical background

In today's tech-centred world companies continuously seek better ways to predict and optimize their business. Adapting digital solutions to existing business models enables companies to increase quality of products, decrease waste, reduce costs and improve efficiency and market share (Atalay *et al.*, 2022). With SCs becoming more complex and broader, a need for better risk management is necessary. Implementation of DTs are a major application of digitalization in companies. This chapter will define the background concepts of DTs and SCRM according to the current literature on the topics. The focus for the SCRM will be on disruption risks due to availability of research, and on how they can be managed and observed through DTs.

2.1 Digital Twin, Digital Shadow, and Digital Model

One of the new technologies in the digitalization has been the Internet of Things, where objects surrounding us are implemented with different kind of wireless sensors to create a Wireless Sensor Network (WSN). The network of these wirelessly communicating devices offers us ability to measure, infer and understand them, creating the Internet of Things, also known as IoT. (Gubbi *et al.*, 2013)

Internet of Things has many adaptions within. One of these a Digital Twin (DT). The definition of DT has some variation depending on the source. The term appeared first time in 2002 by Michael Grieves in the context of product lifecycle management, but the definition has had some changes throughout the years. One definition is that it is a digital counterpart of something physical that can be nearly anything from which real-time data can be gathered. In 1970, NASA's Apollo 13 mission suffered an unanticipated explosion in its oxygen tank, which destroyed the spacecraft's primary engine and pushed it 400 miles per minute off course. The mission team, on the other hand, swiftly modified multiple high-fidelity simulators to match the real-world conditions of the damaged spacecraft and used this information to assist the astronauts in making the best decisions for a safe return to Earth. One of the first real-world applications of a digital twin was possibly this. (Neethirajan and Kemp, 2021)

DTs can be thus used for observing the present system as well as predicting and assessing future states of it, enabling more efficient operations (Atalay *et al.*, 2022). They integrate artificial intelligence (AI), machine learning (ML) and software analytics with the data that is collected from the physical counterpart through sensors, and create a digital simulation model that is updated when something in the physical counterpart changes (Bevilacqua *et al.*, 2020). DTs have been created for example from industrial valves (Schroeder *et al.*, 2016), supply chains (Ivanov, 2020), farm's water management systems (Alves *et al.*, 2019) or even from an entire city (Schrotter and Hürzeler, 2020).

One might establish a common understanding of DTs as the digital counterparts of physical items based on the above definitions. However, the terms Digital Model, Digital Shadow, and Digital Twin are frequently used as synonyms in these descriptions. However, the extent of data integration between the physical and digital counterparts differs between the offered descriptions. Some digital representations are created manually and have no physical connection to the real world, while others are fully linked with real-time data exchange. (Kritzinger *et al.*, 2018) The following will explain and visualize the difference between Digital Model, Digital Shadow, and Digital Twin. Different visual frameworks and representation of DT in SC will be introduced later in this thesis.

Digital Models are digital depictions of existing or projected physical objects that do not include any automated data transfer between the physical and digital objects (see Figure 1). Existing physical systems' digital data may still be used in the development of such models, but all data transmission is done manually. (Kritzinger *et al.*, 2018)

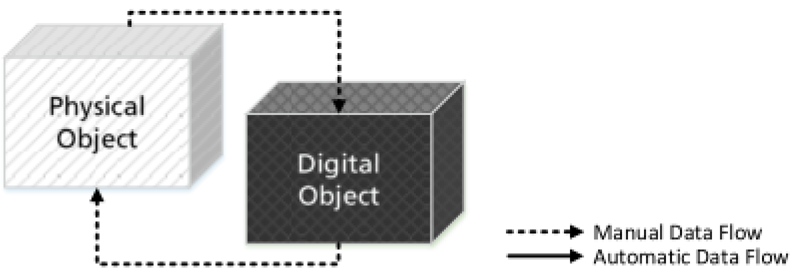

Figure 1: Representation of Digital Model's data flow (Kritzinger *et al.*, 2018)

Digital Shadows on the other hand consist of a one-way automated data flow in the process of transferring data from physical object to its digital counterpart (see Figure 2). A change in the physical object creates a change in the digital shadow, however a change in digital shadow does not lead to a change in its physical counterpart. (Kritzinger *et al.*, 2018)

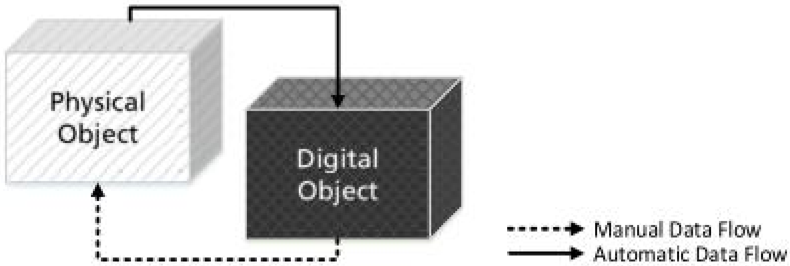

Figure 2: : Representation of Digital Shadow's data flow (Kritzinger *et al.*, 2018)

Digital Twin is the third category concerning the digital counterpart classification according to the automated data flow. In the case of a Digital Twin, changes in physical counterpart leads to changes in the Digital Twin and vice versa (see Figure 3). DT can also be said to control the physical counterpart. (Kritzinger *et al.*, 2018; Atalay *et al.*, 2022)

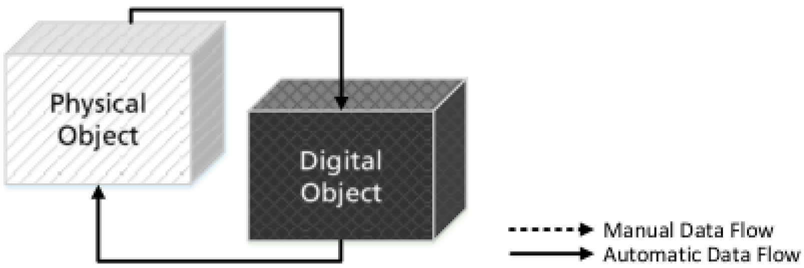

Figure 3: Representation of Digital Twins data flow (Kritzinger *et al.*, 2018)

Kritzinger (2018) states that due to the usage of mentioned terms as synonyms, establishment of a common definition is necessary. This thesis will be using the level of data integration as a defining factor, aligned with published research.

2.2 Risk management in SCs

Risks can be found nearly everywhere in business from service industry to heavier productions. Risk management in supply chains as defined by Tang by combining the definition by Deloitte and Touche: "'The management of supply chain risks through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity." (Tang, 2006).

Risks concerning SCs are one of the major risks companies face in their daily business, and the spreading of COVID-19 has made the topic even more current with broad disruptions in the global SCs (Ivanov, 2020). Risk managers observing SCs and logistics are interested in factors that support decision making to identify disruption scenarios, understand the vulnerability of certain areas of the network to disruptions and reinforce them, observe, and recognize disruptions in real time, and determine measures for the time of interruption and recovery (Ivanov and Dolgui, 2021; Oehmen *et al.*, 2009; Wang, Tiwari and Chen, 2017).

There are many ways of categorizing SC risks. One way is to split SC risks into two categories: 1) operational risks, referring to risks that originate from the problems of coordinating company's supply and demand, and 2) disruption risks, referring to risks that are born from disruptions to normal activities, such as natural disasters, economical disorders and terrorism (Kleindorfer and Saad, 2005; Tang, 2006). SC risks can also be divided to external and internal SC risks (Wu, Blackhurst and Chidambaram, 2006). Also the division between physical, financial, informational, relational, and innovational risks has been proposed (Cavinato, 2004). Due to the availability of literature and earlier case studies, the focus of this thesis will be on disruption risks. Also, the cases presented in this thesis about DTs and SC management focuses on disruption risks and their observation.

As stated earlier, disruption risks are something companies take account on when assessing the risks of their SCs. Equipment failures, unplanned SC disruptions, and human-centered issues such as strikes and frauds are all part of disruption risk management, as are risks posed by political issues, acts of terrorism or natural disasters (Kleindorfer and Saad, 2005). Being able to manage the firm's SC's disruption risks is essential for the company's success. In the case of a disruption risk, the resulting material shortages and delivery delays spread downstream the chain, leading in a ripple effect and performance degradation in terms of productivity, revenue or service level (Garvey, Carnovale and Yeniyurt, 2015). Also, among the publicly traded firms, disruptions are proven to weaken the firm's abnormal returns and raise equity risk due to increase in financial leverage (Hendricks and Singhal, 2005).

3 Digital Twins in SCRM

This section will review and discuss the literature concerning usage of DTs in SCRM accordingly to the background literature. First, the amount of literature will be discussed. Next, the conceptual literature on the subject will be reviewed and discussed. After that, four case studies on the topic will be reviewed and discussed. After that, the challenges on DTs will be discussed on general level. Last, the overall findings on the topic will be addressed.

3.1 About the research on usage of DTs in SCRM

The research focused on DTs and their usage in SCs is very recent, with the first article containing the keywords "Digital Twin" and "Supply Chain" published in 2015. As we can see from Figure 4, there has been a spike in the articles published containing the said keywords with 153 articles published in the years 2019 – 2021. In total, Elsevier's Scopus database offers 183 articles when searching articles with the mentioned keywords. One notable factor is how new the articles are and how much the number of publications is focused on years 2020 and 2021.

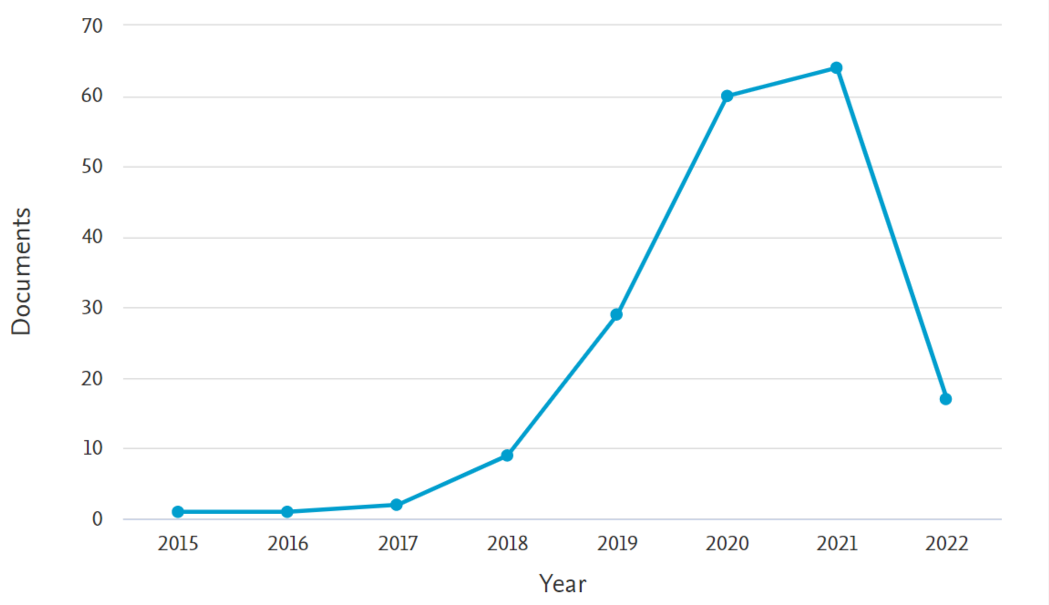

Figure 4: The distribution of articles between years 2015 and 2022, containing the keywords "Digital Twin" and "Supply Chain" (source: Scopus database 3.3.2022)

As can be seen from Figure 4, the research on DTs and SCs is relatively new. Also, a notable factor is the amount of research on DTs and SCRM. The database search with keywords "Digital Twin", "Supply Chain" and "Risk" provides only 31 results, while the search with the keywords "Digital Twin", Supply Chain" and "Risk Management" only provides 7 articles as a result. This indicates that the research on DTs in SCRM is yet very little. Also, after skimming the results with the mentioned keywords, the results indicate that many of the articles are conceptual and only a few case studies can be found.

While the concept and research on SCRM is older and broader, the research on DTs has had a large spike after 2017. This would indicate a rising interest on the matter, and that more research will be made in the coming years.

3.2 DTs a factor in SCRM

Regarding the SC management, organizations must currently adjust to changing conditions on a regular basis. As was stated in the background analysis, SCRM supervisors are interested in supporting factors in choice making to detect disruption scenarios, understand the vulnerability of specific areas of the chain to disruptions and reinforce them, observe, and recognize disruptions in real time, and act accordingly with correct measures for the time of interruption and recovery. In this chapter, we will review the literature and overall situation in the studies concerning DTs in SCRM.

DT of SC represents the physical SC according to literature examples on DTs, and it can be utilized for planning and real-time control decisions based on inventory, transportation, capacity and demand (Ivanov and Dolgui, 2021). One study noted that analytics using big data can help create more sufficient SCRM and disaster recovery (Papadopoulos *et al.*, 2017), possibly indicating that DT using big data could be advantageous in mentioned actions.

The availability of data and the timing when that data may be gathered are critical factors in the effectiveness of modelled decision-making support in resilient SC management and utilization (Ivanov and Dolgui, 2021). Ivanov and Dolgui (ibid.) also stated that using just offline decision-making, and neglecting real-time route disruptions, and ignoring improved supply signal recognition and real-time disruption detection can lead to erroneous disruption scenarios for SC risk analysis and late or inefficient recovery policy deployment. It could thus lead to lower profit through incapability to answer to demand. The same study stated that model-based decision-making support in the DSCT allows simulation of the SC's behavior in case of a disruption. Furthermore, potential consequences on SC performance may be analyzed prior to an interruption, and recovery methods can then be optimized.

Furthermore, Ivanov and Dolgui (ibid.) stated that during the SC design phase, data analytics is employed at the proactive stage to create accurate disruption scenarios built on risk data from previous disruption events and other information, such as supplier reliability data from enterprise resource planning systems (ERP). Data analytics is deployed in the reactive stage to identify disruptions in real time utilizing process feedback data, such as from sensors, T&T (Track and Trace), and RFID (Radio frequency identification technology).

A study from 2019 gave an example concerning the SCRM with DTs that if a strike occurs in an international logistics hub and leads do SC disruption, a risk data monitoring tool can identify the disturbance and transfer it to the DT as a disruptive event. DT can then be used to simulate the interruption propagation and quantify its impact. (Hosseini, Ivanov and Dolgui, 2019) Furthermore, the simulation allows for fast recovery policy testing and adoption of contingency plans based on the event, such as on-the-fly reconsideration of alternate network topologies and backup routes. A case example concerning the usage of backup routes is presented later in the thesis.

Because DT may represent the state of a network at any given point in time, it enables total end-to-end SC visibility, which can help increase resilience and test contingency plans. The core technology that allows a fairly accurate DSCT to be developed is a combination of simulation, optimization, and data analytics. The goal of developing DT is to better manage SC risks, making them more dependable and resilient in the case of a breakdown (Barykin *et al.*, 2020).

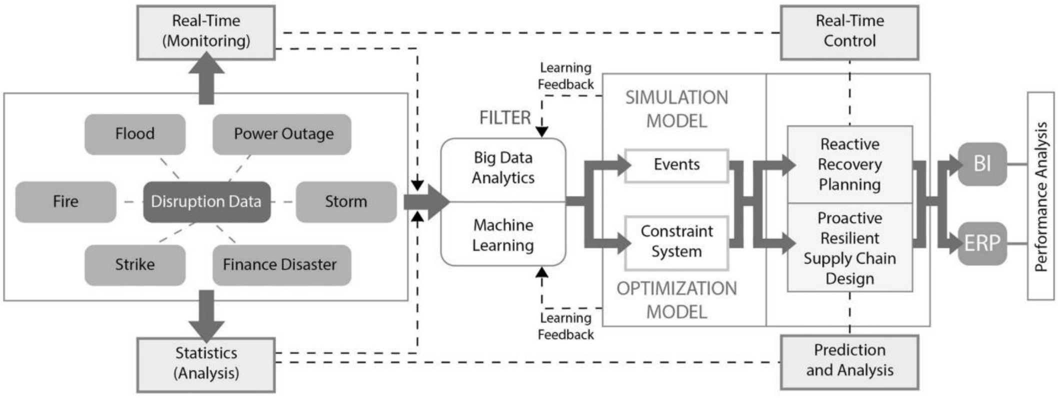

Figure 5: Representation of a digital supply chain twin (source : Ivanov and Dolgui, 2021)

Figure 5 shows Ivanov's and Dolgui's representation of a DSCT created with anyLogistix software, a software for managing SCs, with several possible sources of historical disruption data that it could use, for example, related to financial disasters, strike, storms, or power outages. If the data is feasible, the risk data monitoring module could thus spot a possible disruption in the SC based on historical data, alert the risk manager on it, and provide simulation and optimization models through big data and ML filters. The model in question could thus forecast a possible disruption propagation and quantify its impact, and transfer reactive and proactive solutions to ERP or BI systems, possibly activating reactions to solve the issue. (Ivanov and Dolgui, 2021) The authors also stressed the importance of completeness, fullness, validity, consistency, and timely availability of the data used for the DSCT, so that disruptions can be accurately predicted, and recovery policies efficiently deployed.

3.3 Case studies

In June 2021, Lee, D. and Lee, S. stated that the research concerning usage of DTs in SCs is still very limited and that the studies on DTs has focused mostly on shop floor management and production operations. This can be verified by looking into the studies in scientific article databases, where most of the case studies are focused on the mentioned areas and studies around SCs are mostly conceptual. Also, in 2018 Kritzinger et. al. stated that the studies concerning DTs are still in their infancy and the available literature is mostly conceptual and the research area is still lacking concrete case studies. This leaves room for future research.

In this section existing cases concerning DTs in SC risk analysis will be presented, however the lack of studies proved finding mentioned examples quite challenging. The aim is to present cases where DTs have been implemented on a SC and have been used to observe the risks in the SC process. Also, one example case is presented where DT is implemented on a filling line.

3.3.1 Case of pharmaceutical company

One of the first studies conducted on DTs and SCs is a case study on a pharmaceutical company in 2020 (Marmolejo-Saucedo, 2020). The DT developed in the study exchanges data between production, storage, and distribution. The system's overall performance is also monitored by this DT. Production scheduling and resource allocation can be done this way, and decision-making algorithms can be implemented as well. The DSCT is created in such a way that it can consider and integrate various forms of information between supply chain components. This enables for a more systematic and consistent integration of all parties involved. It also makes the SC more visible.

A Min-max (s, S) type inventory policy was used in the initial operating conditions. When the inventory level fell below a certain replenishment point, products were ordered under this policy. The ordered quantity is set to a value that equals S in the inventory quantity. Following that, the DT puts the various inventory policies to the test and employs ”safety stock estimation" feature included in the logistics software used. Finally, the optimal inventory method is discovered by DT to be Stock Security-Policy. The study found out that DTs decision to implement mentioned strategy lifted service level to 100% and reduced lead time within customer requirements.

3.3.2 Case of modular construction project

In June 2021 Lee, D. and Lee, S. conducted a case study with a modular construction project and how a DT can be applied on its logistics and thus used to predict its SC risks. Modular construction defined by Wuni and Shen (2019) “Modular integrated construction (MiC) is an innovative construction approach which transforms the fragmented linear site-based construction of buildings into an integrated production and assembly of value-added prefabricated prefinished modules.” In this study Lee, D. and Lee, S. developed a DT framework that integrated BIM (Building Information Modeling) and GIS (Geographic Information System) for real-time logistics simulation.

The authors used a 6-story building construction project with 80 modules as an example project. Logistics simulations were performed to uncover logistics risks and alternate routes based on the suggested DT framework, revealing total of 12 risk types. Lee and Lee started by creating a digital counterpart of the project. The DTs back-end system received the project's BIM data (e.g., module geometry, weight, and assembly schedule). In the Bing Maps application, GIS data (such as traffic, geographic data, road accessibility, regulation, curfew, and accident area) was updated in real-time. Taking the risks into account, DT for example requested an alternative route in which the truck could turn, as one of the risks involved the truck's minimum turning radius.

As a conclusion the study found out that the usage of DT can lead to more accurate ETA predictions and can save idle time, in the study a total of 157.5 hours was saved due to usage of DT. The authors stated that based on credible modeling, DT can forecast probable logistics hazards and an accurate ETA. Furthermore, reliable risk prediction and ETA computation can help project participants coordinate their supply chains more effectively and enable 'just-in-time' module delivery and thus avoid any delivery time deviation risks. (Lee and Lee, 2021)

3.3.3 Case of German food retailer

Another case study (Burgos and Ivanov, 2021) studied the impact of Covid-19 on German food retail company and their SCs. With the help of anyLogistix DSCT, authors designed and deployed a discrete-event simulation to investigate SC operations and performance aspects based on real-life Covid-19 pandemic circumstances in Germany.

The simulation was targeted on German food retail company and focused on 10 product categories and 28 supermarkets operating in 5 countries (Germany, Austria, the Czech Republic, Italy, and Hungary). The DSCT created observed demand, lead time, continuous inventory control with a reorder point and targeted stock setting, production control, and transportation control, with a goal of creating more visibility and thus create a more resilient supply chain. For the study the authors created a simulation based on the retailers data and applied several disruptions on the simulation, such as temporary bottlenecks in transport, shutdown in suppliers' factories, and increasing demand, accordingly to Covid-19.

Burgos and Ivanov (ibid.) compared the simulations and real-life scenarios, leading to the statement that Covid-19 had a large effect on SCs. The authors also presented a need for enhanced end-to-end visibility for the SC to improve its resilience and stated the DT could answer to this need as DT was used successfully to map the SC in the simulation.

3.3.4 Case of German pharmaceutical company

Yet another case study from 2021 (Spindler, Kec and Ley, 2021) presented a simulation model on German pharmaceutical company Roche Diagnostics GmbH in Mannheim, Germany. A digital model for a pharmaceutical filling line was built in this research, with the intention of eventually extending it to a DT. The model was used in manufacturing to evaluate potentials for efficient scheduling, lead-time, and delivery breakdown risk reduction, as well as decision support.

The findings demonstrated that simulation may be used to evaluate and improve very complex and dynamic manufacturing processes. While the study was not performed with a DT but with a simulation, the authors claim that the results promise remarkable potentials by projecting the outcomes of this one-time simulation study onto a real-time DT that runs simulations continuously and based on the most up-to-date data from the shopfloor. Sensitivity analysis could thus identify process steps that not only have a large overall impact on lead times, but also need to be addressed based on the present state and critical process path at any given time. Even though targeted on a filling line instead of an entire SC, the study speaks highly for the role of simulation and DTs in risk management overall in terms of lead times and delivery risks.

3.4 Discussion about the cases

When observing the presented cases, common factors can be found. In each of the studies DTs took advantage of already existing information systems, indicating that the timing, quality, amount, and nature of the data used is in the key role to build a successful DT. The cases discussed found advantages like more accurate ETA, lower lead time for a process, raising a service level to its maximum and finding a optimal safety stock policy. The cases did not address the costs of a DT, leaving a lot of room for future research on the profitability on the matter.

The lack of existing use of DTs also made a need for simulations, which may not always present the real-life event enough. Burgos and Ivanov (2021) pointed out that the simulations were run using data from a variety of secondary sources, which might lead to erroneous assumptions and inconsistencies. Another disadvantage is the limited time frame for observing the consequences of prospective improvements in disruption scenarios. This leaves room for questions like how much new data should be acquired when building a DT and what kind of tradeoff this acquirement will create comparing to traditional SCRM methods. For example, how much will the data gathering cost if its not provided in advance and how good its quality is.

3.5 Challenges in DT implementations

It is crucial to understand the possible challenges when implementing DTs, as they are such a fresh topic in digital business and might require large investments from companies. The presented case studies discussed very little about the challenges faced when implementing DTs specifically to SCs. In this section, the overall challenges of DT implementations will be discussed according to existing research on DTs. Also, a discussion will be presented at the end of the thesis on whether these challenges can be mirrored to DSCT.

Rasheed et al. (2020) divided the challenges posed by DT implementations into four areas that should be focused on when implementing DTs to usable applications. The first section stresses the importance of two-way data stream that should be in real time. The authors also mentioned the importance of large data volumes, large data generation rates, large variety of data, and the online processing of data. The second section addresses the importance of keeping the DT up to date. If something structural is changed in the physical asset, a similar change needs to be made in the DT. The third section addresses security concerning DTs. If a DT is made of something physical that, for example, requires higher security measures, this needs to be noted when creating and modelling the DT. The authors presented that in such DTs there is a need for greater transparency and interpretability of the decisions taken. The fourth section discussed the need to make DT as indistinguishable from the physical asset as possible, and that the operating on DT could be intuitive and as natural as using the physical object. As Rasheed et al. (2020) have pointed out, the nature, amount, quality, and timing of the data is potentially the biggest challenge in the implementation of a DT. Also, several challenges can be seen in safety factors and the usability on the implementation.

Tao and Zhang (2017) discussed similar findings about DT implementation's challenges in the shopfloor industry. The authors stressed the importance of maintaining adequate two-way connections between the twins and physical objects, and addressed the challenges in technology (sensors, communication, databases etc.) that may occur. Also, uncertainty in the physical counterpart was addressed. Tao and Zhang (ibid.) also mentioned that as the continuous physical space and discrete digital space have different scales, it is difficult to overcome the divergence and achieve seamless integration of the two sides.

Atalaya et al. (2022) also pointed out several challenges in DT implementation to practice. The authors pointed out that standardization and interoperability are two notable challenges concerning the usage of DTs. Also, a similar factor with the security was found that Rasheed et al noted on their third section of the DT implementation challenges. It was noted that similarly to every information technology solution, cyber-threats such as malware attacks, phishing and cross site scripting need to be prepared for. Atalaya et al. also noted challenges in DTs costs, complexity, quality control and technological infrastructure and interfaces.

Ding et al. (2019) discussed the challenges in DT implementations from the point of Cyber-Physical Production Systems and addressed two major challenges in DT implementations. First, the study discussed insufficient data synchronization between the physical and the digital asset, in this case a physical shopfloor (PSF) and a digital shopfloor (DSF). The reasons for this were found in undeveloped industrial networks, lack of sufficient data computing and weak data transmission and exchange. The second issue discussed by the authors is that in real life scenarios, the accuracy of existing simulation models are less than acceptable to be used in practice, and therefore, more suitable models must be developed for practice.

3.6 Findings

Overall, the existing literature indicates that theoretically, the usage of DTs in managing SC risks could be a feasible solution for companies. Literature indicates that more visible and resilient supply chains provides easier access to deployment of backup plans when disruption occurs. The system should allow visualization of SC risks, assessment of supplier risks, estimate of possible supply disruptions, and computation of complementary supply network topologies and alternative routes with assessment of ETAs during the SC design phase and in pre-disruption state (Ivanov and Dolgui, 2021). Ivanov and Dolgui (ibid.) states that these methods could then be reported to companies' ERP-systems and quantified by KPIs to observe them in terms of profitability, revenues or for example, on-time delivery.

The four case studies presented observed DSCTs from different aspects, and benefits of the implementation were found in several aspects of business. Advantages were found in keeping service level at 100%, finding a optimal safety stock policy, creating more accurate estimated time of arrival, lowering lead times and idle times and making the SC more visible. These findings could possibly benefit the companies using a DSCT to manage risks, however the challenges needs to be noted on the matter. Future research is required for example on the cost and security of the DT and if the benefits exceed the challenges.

4 Discussion and conclusions

The rising amount and the content of the available literature on the subject indicates that DTs hold potential to answer various needs for companies, consumers, and the public sector. There are numerous studies about DTs in general, however, the research on DSCTs is still very limited and a need for more research is essential. The goal of this thesis was to answer the following research questions based on existing studies about DTs and their usage in supply chain management:

i) Can Digital Twins be used to develop company's supply chain risk management?
ii) Can the implementation of a Digital Twin increase profit through supply chain risk management?
iii) What kind of challenges does the implementation of a Digital Twin pose to company?

As was stated in the methodology section, these questions were addressed with a thorough literature review on the topic. This section of the thesis will summarise and assess the findings in the thesis and discuss the practical implications and possibilities for future research on the topic.

4.1 Review of the findings and their implications to practice

The existing literature was identified and reviewed to answer the research questions. The background theory indicates that today's SCs are becoming more and more broad and complex, and concerning risk management, more visible and resilient SCs are required. The literature reviewed indicates that making risk management decisions with just offline-data can lead to flawed disruption scenarios for analysis, and erroneous recovery policy, and thus generate higher costs and lost revenues, indicating that the need for more accurate risk management systems using live data are possibly needed. The research on DSCTs is still mostly conceptual, and many articles published are frameworks without empirical research. This is mostly derived from the infancy of the topic, as was mentioned in the background literature. The conceptual literature on the topic states that a DSCT is a model, which represents the state of the SC at any given moment, and discusses the possibility to use it to manage SC risks, for example, by better SC visualization, assessment of supplier disruption risks, computation of alternative supplier network topologies, and by creating more sufficient disaster recovery through big data. (Ivanov and Dolgui, 2021; Hosseini, Ivanov and Dolgui, 2019; Papadopoulos *et al.*, 2017)

While the amount of existing case studies is small, a few reliable studies were identified and reviewed in this thesis. The case studies presented on the subject advocate strongly for a DSCT as a factor in managing risks. The benefits vary depending on the industry and case. The applied framework in the case of DSCT in modular construction (Lee and Lee, 2021) resulted in more accurate prediction of risks in the logistics process and in more accurate estimated time of arrival based on optimized backup routes suggested by the DT. More accurate estimated time of arrival and better predicted logistics hazards can result in more effective SCs, and thus possibly lower costs in the SC process. As the case of pharmaceutical company presented (Marmolejo-Saucedo, 2020) shows, the benefits of DSCT can be gained also by managing safety stock estimation. With the DT successfully employing more effective safety stock policy to usage, the service level was raised to 100% and the lead times dropped within customer requirements. Shorter lead times can possibly result in faster refills of stock to prevent stockouts, lost sales, lost customers and thus lead to greater profits. They can also provide better flexibility in possible fast market shifts. The case of the German food retailer (Burgos and Ivanov, 2021) also indicates DSCT to be a feasible solution, as it provides greater visibility and thus more easily planned SC. Overall, these case studies leave a lot of room for future research on the topic, but the existing results indicate that a DSCT can be a feasible way to enhance SCRM and overall productivity of a company, possibly leading to higher profits.

The conceptual literature and the cases presented in this thesis discussed very little about the possible challenges in the implementation, thus the challenges were discussed based on general literature on DTs. Since an effective DSCT requires already existing data, the amount and timing of suitable data is a critical factor in the implementation, as mentioned by Ivanov and Dolgui (2021). This is supported by studies from Rasheed et al. (2020) and Tao and Zhang (2017), who discussed the importance of a two-way data flow.

The reviewed literature indicates that for the DT to be accurate and effective, the correct timing and quality of the data stream is crucial, as it has a straight connection to SC management and measures taken in case of disruption. Thus, for example, erroneous data flows could possibly lead to mistaken counter measures in case of SC disruption. The discussion in Rasheed et al. (2020) and Atalaya et al. (2022) about the challenges in security of DT is directly relevant to supply chain DTs as well. In the SC process and its risk management, security is something to look after as its failure may lead to severe consequences and economical losses. Atalaya et al.'s (2022) notes about the need to prepare for malware attacks, phishing and cross site scripting can be placed into the context of a DSCT similarly to any other information technology application. Atalaya et al.'s discussion on the standardization and interoperability challenges could also be addressed in the context of a DSCT, especially interoperability, as a DSCT would likely have multiple variables and factors that need to work together flawlessly. Also, the cost, complexity, quality control and technological infrastructure and interface as mentioned by Atalaya e. al. are directly comparable to a DSCT. Currently there is not much literature about the costs of creating a DT, leaving a lot of room for necessary future research on cost and profitability aspects.

4.2 Limitations and future research

As the reviewed literature indicates, the DSCTs show great promise and potential to answer several needs of companies. However, while the research topic is still in its infancy and most of the literature is conceptual, more empirical studies are required. For example, case studies in real-life should be carried out and analyzed to create more accurate and realistic frameworks.

While this thesis was carried out as a literature review on research on usage of DTs in SC risk management, it should be noted that a financial analysis on the cost and profitability of DSCTs was not pursued as the existing studies did not contain details about the costs of the implementation. Thus, business case calculations on the profitability of DTs as an investment was not performed. Real-life examples could provide financial data on the implementation of DSCTs, enabling business case calculations and thus deeper analysis on the feasibility of DSCTs and its usage in risk management.

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