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Digital Twins in Supply Chain: Catalyzing the change towards Circular Economy

Master's thesis in Production Engineering

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Cover:
Illustration of how Digital Twins are being in Supply Chain

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SUMMARY
This research explores the role of Digital Twin, a key technology in Industry 4.0, in facilitating the shift towards a circular economy via Supply Chains. It also addresses the potential obstacles that hinder the integration of Digital Twin into the Supply Chain. Data was gathered through a comprehensive literature review and interviews with researchers and company personnel to understand the degree to which Digital Twins are utilized in their organizations, and how it can guide them towards circularity in their supply chains.The study reveals that Digital Twins can enhance circularity in supply chains by extending the product lifespan through real-time monitoring and predictive maintenance, as well as by effectively tracking products returned by customers. However, implementing Digital Twin technology in extensive network like supply chains is challenging due to factors that complicate real-time data collection and time-consuming and costly process of modeling every asset. Therefore, in such large networks, a Digital Model could be a more practical and cost-effective solution.
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Keywords: Digital Twin, Supply Chain, Circular Economy, Logistics, Linear Economy.

Contents

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

DT	Digital Twin
PLM	Product Life Cycle Management
IoT	Internet of Things
CPS	Cyber-Physical System
SoS	System of System Level
DTP	Digital Twin Prototype
DTI	Digital Twin Instance
LE	Linear Economy
CE	Circular Economy
SC	Supply Chain
DSCT	Digital Supply Chain Twins
CLSC	Closed Loop Supply Chain
SC	Supply Chain

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1

Introduction

1.1 Background

Over the past decade, technological advancements have accelerated rapidly, with innovations gained through Industry 4.0 reshaping industries worldwide. Many sectors are moving toward digitization, recognizing the significant benefits, including faster information access, enhanced customer experiences, increased productivity, and improved decision making, all while reducing operating costs and enhancing safety (Rosin et al., 2020).

Digitization offers a variety of advantages in dealing with today's business challenges, particularly in volatile markets that require rapid responses to unexpected changes. A key example of such volatility was the COVID-19 pandemic in early 2020, which caused global disruptions. As the virus spread, supply chains were impacted by panic buying and delays resulting from workforce shortages across production and logistics (Chowdhury et al., 2021).

One technology with immense potential to address these issues is digital twins. There are many ways to define DT, but one definition is that DT is a digital clone of a physical system or process that can be used to simulate, predict, and optimize the physical system's performance (Kamble et al., 2022). This capability has led to the adoption of DTs in various fields, including manufacturing, transportation, and healthcare. In supply chain management, DTs are particularly useful, enabling enhanced supply chain performance (SCP) in today's increasingly complex logistics and supply chain systems (Rauniyar et al, 2022).

The adoption of DTs holds significant promise for society, the economy, businesses, and the environment (Le et al, 2022). By integrating data from multiple sources and allowing interactions across diverse stakeholders, DTs provide a foundation for improved modeling, simulation, operations, and management of supply chains (Rana et al, 2022). This increase in operational efficiency ensures faster product delivery, especially crucial for perishable goods and medicines (Trabuccoet al, 2021). Furthermore, DTs enable near real-time connection between virtual and physical infrastructure, allowing for scenario testing without disturbing the physical infrastructure and experimentation that strengthen both theoretical and practical decision-making (Bianco et al, 2023). These capabilities help reduce disruptions, ensuring supply chains remain resilient and adaptable to changing conditions (Sassanelli et al, 2023). Additionally, DTs support predictive maintenance, risk mitigation, and enhanced sustainability—building resilience against crises, such as epidemics or natural disasters, and maintaining effective supply chain operations in the face of global and economic fluctuations.

While a well-managed supply chain is essential, many companies today operate in a linear model where resources are extracted, processed, used, and ultimately discarded which means the materials won't be able to be used again (Berg et al, 2019). One method that aims to combat this is the use of circular economy. Circular economy could be defined as "an industrial economy that is restorative or regenerative by intention and design" (Ellen MacArthur Foundation, 2013). This approach fosters greater sustainability in supply chains by enhancing operational, economic, and social responsibility (Dulebenets, 2018), especially in sectors with complex networks, like the automotive industry, where environmental impacts are significant (Masoumi et al, 2019).

This new supply chain model requires a lot of work to get started. For example, information would be required about the different materials and of where the products are in the supply chain where a significant development potential is seen for DT in the context of the circular economy (Preut, 2021). Digitization concepts have the potential to enable better information management and more transparency regarding relevant information for the circulation of materials and products (Yang et al, 2018). This leads to the aim of our thesis.

1.2 Research Questions

This thesis aim is to investigate if it is suitable for this purpose by answering these two research questions.

(1) How can Digital twins support the transition from linear economy to circular economy in supply chain.

This question's aim is the basis of the thesis. Linear economy is how things have always been done within production so hopefully there can be ways to make circular economy more attainable with the suggested example here being to use digital twins. There are definitely multiple different ways to attain a circular economy but in this thesis the focus is on specifically how digital twins can be used. So this research question should clearly explain what the research is aiming towards.

(2) What are the challenges for implementing and integrating Digital twins in a closed loop supply chain.

This question instead aims to focus on what the challenges of the use of digital twins to implement circular economy can be. Because even if clear ways to use it can be found it isn't enough if there are too big challenges stopping parties from implementing it. By finding and defining these challenges they can be more easily overcome which in turn makes possible uses of digital twins more attractive for the companies looking to use it. Because it is not enough to find the uses for digital twins if there are too big risks making it seem like an uncertain investment. So the goal of this question is to find the challenges to see if the gain from digital twins is worth it.

By researching these questions hopefully some new understandings about this new technology can be gathered.

1.3 Delimitations

The delimitation of this thesis study is multifaceted. Firstly, the data collection process was constrained by the limited availability of researchers for conducting interviews, which restricted the breadth of data that could be gathered. Secondly, a significant number of company personnel interviewed lacked a comprehensive understanding of Digital Twins, further complicating the data collection process.

Additionally, time constraints hindered the ability to thoroughly gather all necessary data from the companies and correlate it with the insights from researchers' interviews and literature studies. A notable challenge encountered during the literature review was the lack of precise definition of a Digital Twin in previously published works.

Moreover, there was a strong belief among the researchers that Digital Twins may not be applicable across all areas of the supply chain. Specifically, they suggested that Digital Twins are more suited for smaller networks and may not be effective for larger networks such as supply chains. These factors collectively form the delimitations of this study and have shaped the scope and direction of the result.

2
Theory

This chapter provides the theoretical foundation necessary to understand the research conducted in this thesis. It aims to equip the reader with the essential knowledge to understand this report.

This chapter is structured as follows: First, we delve into the concept of Industry 4.0 and why DT is a groundbreaking technology in Industry 4.0. Then we discuss the origin, main components, classification, application, and advantages of DT.

Next, we will explore the idea of CE, its impacts, and what stops the organization from being more circular. Then we will look into how Industry 4.0 can help the organization towards a circular economy with the help of DT. Finally, we will delve into the concept of Supply Chain, being one of the critical components in achieving the goals of CE, and how DT can help SC to be more closed loop.

2.1 Industry 4.0

The concept of Industry 4.0 was first introduced in 2011 in Germany at the Hannover Fair (Yang Gu, 2021). It was formally declared by the German government as a significant project to advance the industrial revolution. The first three industrial revolutions signaled the start of a new phase in the history of the industrial revolution. Around the end of the eighteenth century, the first industrial revolution got underway with the increasing usage of steam and waterpower, which resulted in a shift from human to machine manufacturing methods. Beginning in the late 1800's electric power was widespread which marked the second industrial revolution because of which industries were able to mass produce the products. The third industrial revolution began in the 1970s when industries began using electronics, the internet and digitalization in addition to mechanized production.

The fourth stage of this industrial revolution, known as Industry 4.0, is defined by the application of the Internet of Things (IoT) and services, as well as the integration of Cyber-Physical systems (CPS) into manufacturing processes and logistics (Yang Gu, 2021) This allows the real world to be reflected in a virtual world, as a result, the term "Digital Twin" has been developed.

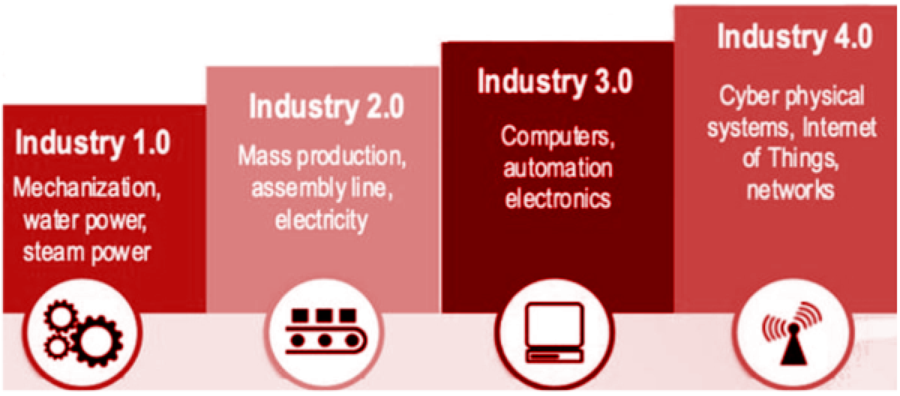

Figure 2.1: Industrial Evolution (Attaran et al., 2023)

The idea of Digital twin is a big leap in the world of Industry 4.0 (Attaran et al., 2023). As we use more digital methods in production, the digital twin becomes a key tool. It helps us try out and fine-tune new setups and designs. By making a digital copy of the real world, the digital twin technology allows organizations to make real-time changes in the physical object based on the results obtained from the virtual object. Because of this, Digital Twins has helped to decrease the cost of creating new manufacturing processes in recent years. This has also led to fewer differences between batches, increased productivity, and also decreased waste significantly.

Digital Twin and Industry 4.0 are being widely used, moving beyond abstract ideas and into practical uses (Yang Gu, 2021). Its applications are widespread and have a great impact on almost everyone. On a national and international scale, modifications are beginning to become apparent as we adjust to new developments

2.2 Digital Twins

2.2.1 Origin

The term "Digital Twin" was first mentioned in a NASA report in 2010, which marks the beginning of this groundbreaking technology (J. Guo Lv, 2022). Interestingly, its initial application occurred in 1970 during the Apollo 13 mission, where NASA used a computer model of the spacecraft to identify and solve a serious issue caused due to an oxygen tank explosion. This event is often recognized as the starting point for the Digital Twin technology. In 2002, Micheal Grieves, expanded on this technology in a talk to business executives at the University of Michigan, promoting the use of Product Life Cycle Management (PLM). This model is termed as 'Mirrored Spaces Models' which has three main components: real space, virtual space, and a linking mechanism for data flow between the two (Singh et al., 2023a). This concept which was proposed by Micheal Grieves was similar to David Gelernter's 1991 'Mirror Worlds' concept. This model was refined in 2006, which highlights bi-directional links and multiple virtual spaces for a single real space, which was then renamed the 'Information Mirroring Model'. It was not until 2010 that the term "Digital Twin" was formally defined in a NASA roadmap report by John

Wicks. This is considered a crucial moment in the evolution of the Digital Twins concept, which paved the way for the development and application of Digital Twins across various industries.

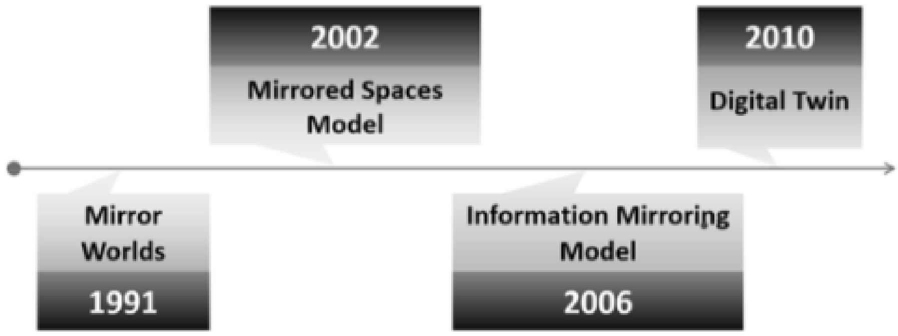

Figure 2.2: Evolution of Digital Twin (Singh et al., 2023)

2.2.2 Main Components of Digital Twin

The Digital Twin consists of three main components. They are Physical objects, Digital objects, and connection between Physical and Digital objects (Juarez et al., 2021a)

The physical object is the primary part of the Digital Twin. The Digital Twin aims to imitate this physical object in the form of a virtual representation. The physical object can be something as easy as an automobile engine or as complicated as the infrastructure of a city. The physical object consists of Devices and Sensors. Devices are those from which Digital Twin is meant to be created, and in those Devices, sensors are placed to collect statistics, which are used as data for Digital objects. It is the essential element in Digital Twin because it gives the information that powers Digital Twin.

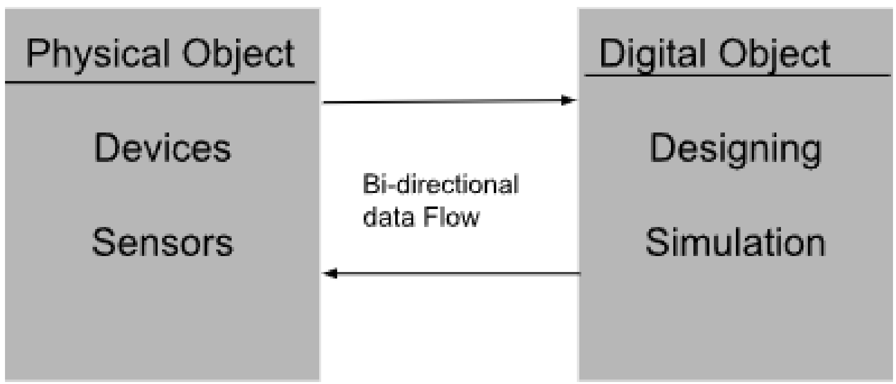

Figure 2.3: Components of Digital Twin

The Digital object is the virtual counterpart of the physical object within the virtual space. The Digital object is a model that replicates the physical object as closely as possible. It uses the information received from the physical world to mimic its behavior and state in real-time. In this Digital object, various experiments like change in design, and testing new changes in scenarios using simulation can be done without affecting the physical world

The connection between physical and digital objects is the part of Digital Twin where the information flows between physical and Digital objects.

2.2.3 The working of Digital Twin

The Digital Twin works in the loop of seven steps: Sampling,Storage, Modeling, Simulation, Learning, Prediction and Actuation. (Le and Fan, 2024)

Sampling is the first step on how DT works. This is a crucial step where the data is collected from the physical layer or real-world entity. The physical layer can be as small as a robot and can be as big as an entire organization. The data from these physical layer is collected with the help of the sensors, where the data represents the physical-layer's current state and operation.

Storage is when the data is collected from the physical-layer, it is then stored in the databases in the digital-layer. The databases where the data are stored can be located on a local server or in the cloud depending on how the DT is set up in the first place. When the data is stored in the database, it is in the form of raw data. It is then processed and transformed into a format that is suitable for analyzing and modeling.

Then the modelling step is When the data is collected and stored, as it has the information about all the details such as properties, behaviors it is used to create a digital model of the physical-layer from which the data has been collected. The created digital model is updated continuously, as the data is collected in real-time and is updated regularly.

After that comes simulation where once the digital model is created, simulation of the physical-layer in the digital model is executed. The simulation consists of complex algorithms like machine learning and AI algorithms which can create different scenarios to see how the system will respond and the results are generated. This will help to find out the bottlenecks and inefficiencies of the physical-layer

The learning step starts once the results are generated, the DT system can improve its digital model which involves adjusting the parameters of the model, changing the relationship between the entities or even changing the type of model. As the learning process is continuous, it will lead to continuous improvements as the data are collected continuously.

Prediction happens once the digital model is improved, it can help to predict the future which can be a demand in supply chain, forecasting maintenance for equipment etc.

Lastly the actuation begins once the prediction has been made, the results are sent back to the physical-layer which actually helps to make important decisions in the physical- layer like predictive maintenance or optimization of a product or supply chain.

2.2.4 Classification of Digital Twins

Digital Twins are divided into various categories depending on its level of integration, application, hierarchy, maturity level and when it is created (Singh et al., 2023)

2.2.4.1 Classification of DT based on Level of Integration

Based on the level of integration, Digital Twin is classified into three: Digital Model, Digital Shadow and Digital Twin (Juarez et al., 2021)

Digital Model comes first and in this type of DT, the flow of data between physical and Digital objects are manually transmitted. So the changes in the Physical object are not reflected in the Digital object automatically and vice versa (Juarez et al., 2021)

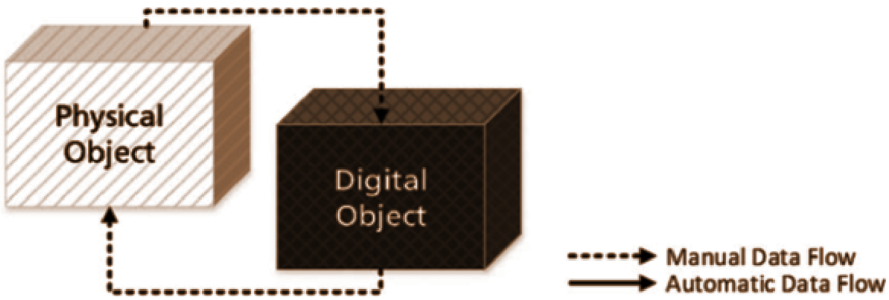

Figure 2.4: Flow of data in Digital Model (Juarez et al., 2021)

Then comes Digital Shadow and in this type of DT, the flow of data from Physical object to Digital object is transferred automatically, but the data flow from digital to physical object is done manually, hence the changes in the digital world do not reflect on the physical object (Juarez et al., 2021).

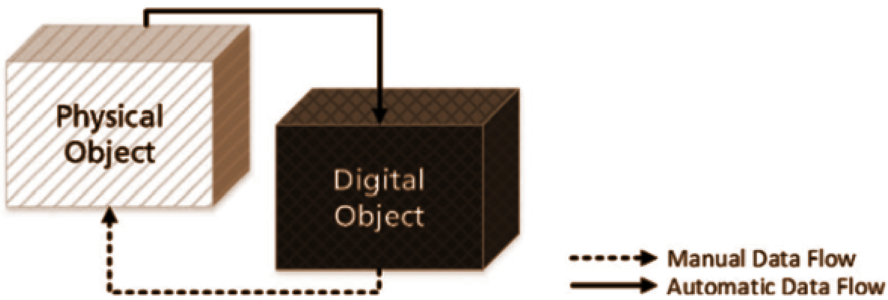

Figure 2.5: Flow of data in Digital Shadow (Juarez et al., 2021)

Lastly comes the actual Digital Twin where there is automatic bi-directional flow between the physical and digital object. Therefore, whenever there is a change in any of the objects, it reflects on its counterpart automatically (Juarez et al., 2021)

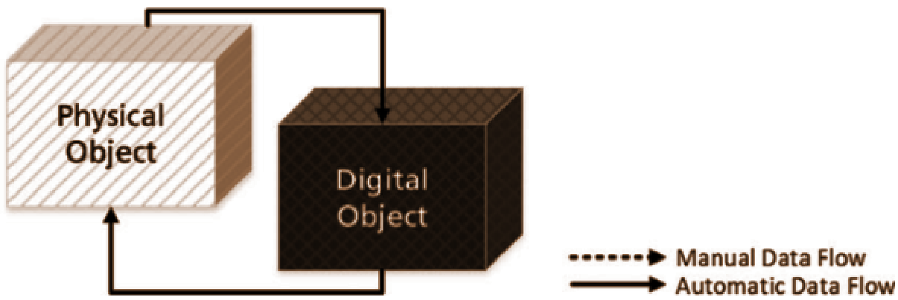

Figure 2.6: Flow of data in Digital Twin (Juarez et al., 2021)

2.2.4.2 Classification of DT based on Application

Predictive Digital Twins and Interrogation Digital Twins are the two categories into which the Digital Twin is divided according to its intended use (Singh et al., 2023). While Interrogative DT is used to interrogate the physical objects's past or present condition, the Predictive DT is used to forecast the behavior of physical objects in the future.

Moreover, Digital Twin is divided into three categories according to its application focus: Product DT, Production DT and Performance DT. Product DT is used in prototyping, where the product is analyzed under different conditions to monitor its behavior. Production DT is used to analyze a product before its actual production. Performance DT is used for making decisions by analyzing the data from the products.

2.2.4.3 Classification of DT based on Hierarchy

Digital Twin is classified into three types based on hierarchy perspective: Unit Level, System Level and System of System level (Singh et al., 2023)

Unit level is a kind of Digital Twin that is the smallest unit used in manufacturing, such as a piece of machinery, a material or an environmental factor. It is based in functional, geometric and behavioral simulation of physical object

System level is a combination of several Unit level DT that comprises a System level DT like production line, shop floor or factory.

System of Systems Level is then when multiple System Level DT are joined together in SoS-Level DT, which facilitates collaboration with many organizations or divisions within a company, including supply chain, design, service and maintenance ect.,

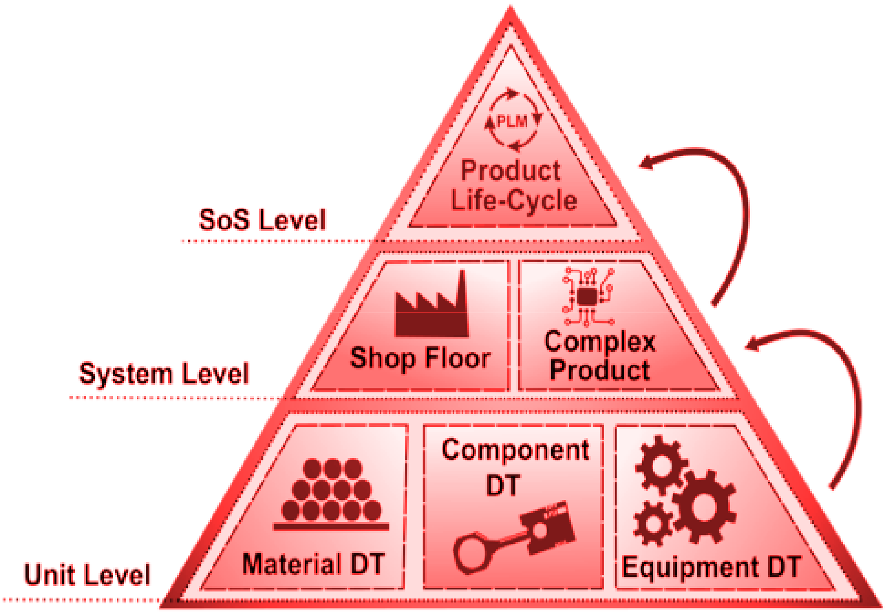

Figure 2.7: Classification of DT based on hierarchy (Singh et al., 2023)

2.2.4.4 Classification of DT based on Maturity Level

Based on Maturity Level Digital Twins is classified into Partial DT, Clone DT, Augmented DT. The Maturity Level describes the level of quantity and quality of the data obtained from the Physical object (Singh et al., 2023)

In partial DT, only a small amount of data is collected from the physical object. It can be speed, force, acceleration, temperature ect.,

The clone DT consists of all measurable data from the Physical object which can be used to create a prototype of a product or system.

The Augmented DT consists of historical data of Physical objects and it uses algorithms and analytics to extract and correlate the relevant data.

2.2.4.5 Classification of DT based on DT creation Time

Digital Twin is classified into two types depending on the time of its creation: Digital Twin Prototype (DTP) and Digital Twin Instance (DTI) (Singh et al., 2021).

Digital Twin Prototype is defined as the DT which has all the set of information that is required to develop a physical object from the virtual object. Usually this type of DT is created before the production phase.

Digital Twin Instance is a type of DT that is created during the production phase and is connected to the physical object throughout its life cycle. Once the Physical object is built, the data is transferred to its Digital counterpart and vice versa which can be used to check whether the product or system is working as expected and to predict any undesirable scenarios has been eliminated successfully.

2.2.5 Applications of Digital Twin

The following are some instances of many fields in which Digital Twins are used.

In Industrial production, DT assists the designers to design or develop a prototype that allows them to improve the product design and mimic product reliability (Guo and Lv, 2022a). In manufacturing, DT is used to forecast machine maintenance. DT will assist in conducting residual life analysis and remanufacturing evaluation for products when their life cycle is completed.

In Healthcare, DT is used to simulate and predict the spread of disease within the human body or throughout larger regions like hospitals, cities or globally (Guo and Lv, 2022a). This technique appropriately predicted the spread of Covid -19 globally. In addition it aids the surgeons for the preparation of surgery, allowing them to regulate operating environment, monitor patient's organs etcAdditionally, DT is used for designing the surgical equipment, allowing simulations that decorates the tools accuracy for the duration of actual surgeries.

In Aviation, DT are used for enhancing safety and efficiency. During the pre-launch phase of an aircraft (Guo and Lv, 2022a). DT are employed in 'test flight' to analyze the influence of various task parameters and to validate strategies for handling a spectrum of abnormal situations. This simulation is vital for ensuring that any issues are addressed before the aircraft's maiden voyage. Once airborne, DT maintains to play a crucial role via monitoring the actual flight situations, helps in real-time tracking of aircraft which includes load, temperature and structural integrity.

In Agriculture, DT helps the farmers to watch over the crops and it helps to predict how the changes in environment will affect the crops growth and also predicts the amount of resources like water, fertilizer ect., are needed (Guo and Lv, 2022a). This application of DT is important because it helps to create a strong and lasting way to do farming that can be adjusted according to the change in weather and climate.

2.2.6 Advantages of Digital Twin

Digital Twin technology offers several benefits across a broad spectrum of application.

Prototyping and re-designing is one advantage. DT technology accelerates the analysis cycles with the aid of allowing simulations of various scenarios, thus simplifying and speeding up prototyping and redesigning methods (Singh et al., 2021). Once carried out, DT can be applied in any stage of production, from conceptualization to finishing the product. It additionally enables product customization based on customer needs. As DT stays related to its physical counterpart, it allows to simulate and predict the performance of the products. This enables engineers and product designers to rethink the assumption underlying the product's design.

Improved maintenance is an advantage where, in the Industrial sector, maintenance is usually performed when a machine breaks down or based on heuristic experience (Singh et al., 2023). However, DT has the ability to predict machine flaws ahead of time, allowing for planned maintenance that can increase productivity by minimizing the downtime of machines.

Thirdly there is accessibility. With the help of DT, the physical objects can be monitored and controlled remotely irrespective of their geographical location (Guo and Lv, 2022a). This remote monitoring and controlling of equipment is beneficial during pandemic situations like Covid-19, where lockdowns have been enforced by the Government.

There is also Waste reduction and circularity. DT can reduce the waste produced when an actual prototype is benign created by assisting in the prediction of the performance of the product or system prototype in a virtual environment (Singh et al., 2023). By reducing the amount of natural resources used worldwide, this promotes greater sustainability. By anticipating the material or product's end of life, it also facilitates the possibility of remanufacturing and recycling the product or materials used in the products, which promotes more circular economy practices (Guo and Lv, 2022a).

2.3 Linear Economy

Linear Economy (LE) is an economic model that follows the 'take-make-dispose' concept (Upadhayay Alqassimi, 2018), where the raw materials are extracted from the natural resources, and it is manufactured into the product which creates a value for the customer. And once the value is created or the product reaches its end-of-life, it is usually thrown away as waste. Historically, LE is predominantly used in most industries. Due to this, the earth's natural resources get depleted at a faster rate along with an increase in waste which is considered to be unsustainable.

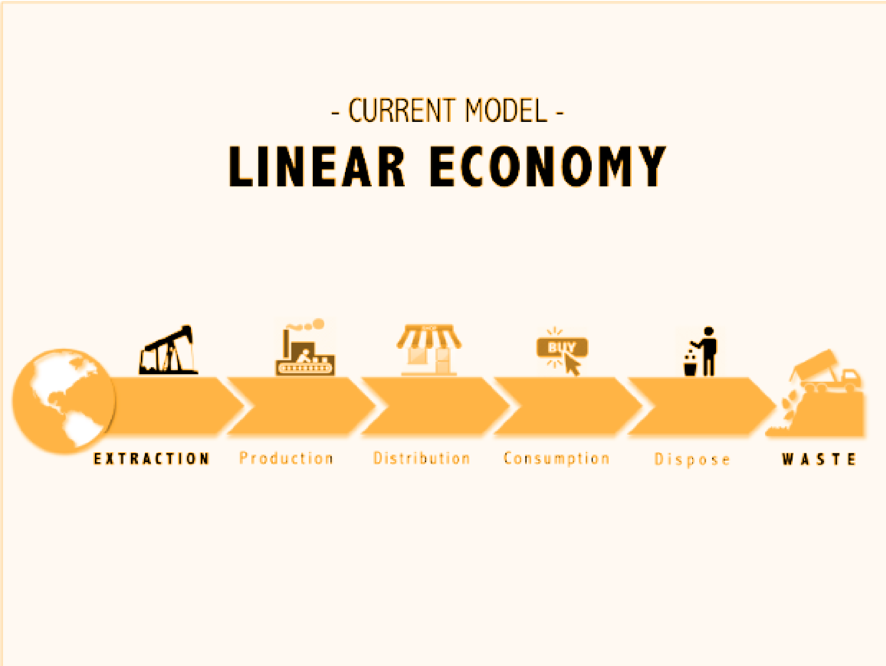

Figure 2.8: Schematic definition of Linear Economy

It is proven that, when a product is designed under LE model and if it contains plastics, only 14% of this is recycled annually and if this continues, there will be more waste in the ocean than fish. It not only impacts the sustainability factor, but also impacts economically as it is proven that around $13 billion loss in tourism, shipping and fishing industries annually.

2.4 Circular Economy

The circular economy (CE) is an economic model, which is developed around the concept of minimizing waste and utilizing the resources of the world more efficiently (Han et al., 2023). CE is different from the traditional linear economy, which follows the 'take-make-dispose' concept where the resources are extracted from nature and used to create a product, which is then used by the customers to create value. Once the value is created and when the product reaches its end life, it is then disposed of or thrown away as waste. But in CE, the products are encouraged to be designed in a way so that they can be reused, repaired, or recycled because of which the materials can be used for as long as possible making it a closed-loop system. Through the use of reverse logistics and closed-loop supply chains, CE provides equal consideration to both forward and reverse material flow.

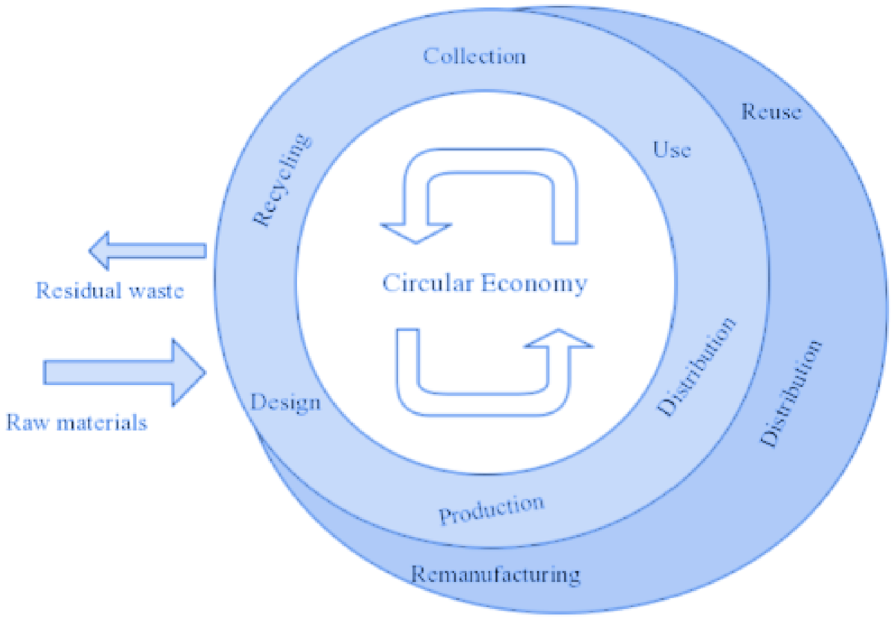

Figure 2.9: Closed-loop diagram of circular economy (Han et al., 2023)

2.4.1 Why Circular Economy

The transition from a linear economy to a circular economy is expected to increase the Gross Domestic Product (GDP) by 7% in the European Union alone (Virlanuta et al., n.d.). In addition to the economic impact, the circular economy will also lead to a significant rise in employment, particularly in the waste management industry, which is considered the cornerstone of the circular economy framework. Furthermore, the circular economy will drive innovation in environmentally friendly product design and manufacturing. Product designers and manufacturers are encouraged to consider how to create products that facilitate reuse, recycling, and remanufacturing. This not only opens up new markets for their companies but also presents opportunities in the global market. With regards to environmental impact, the circular economy is forecasted to reduce greenhouse gas emissions by approximately 450 million tonnes annually, contributing to a 2-4% decrease per year. This is crucial in the battle against climate change and aligns with the global commitment to sustainability and reducing carbon footprint (Ekins et al., 2020)

2.4.2 Barriers and Drivers

When shifting to a circular economy (CE), several considerations come into play, including cultural and social issues, economic factors, and the rebound effect, which can serve as both motivators and barriers.

Cultural and Social Issues is the factor that refers to the norms that are followed by the society and the attitude of the people which can act as a barrier in adapting CE. For example, most people will have a negative perception towards refurbished or second-hand products which will hinder the growth or adaption of CE in various organizations. Alternatively, in recent times, sustainability and reasonable consumption of resources are being considered by the society and organizations which is considered to be one of the main drivers for the CE

Economic consideration in organizations which mostly depend on the linear economy model will resist the change towards the circular economy as there might be huge investment to be made to change their methods of production, material used ect., So this will also be one of the barriers to the shift towards CE. However, as mentioned before, CE will create new job opportunities and provide new business models which will boost the economic opportunities of both individuals and the organization will act as a driver for transition to CE.

The Rebound Effect refers to the phenomena, where the cost savings achieved from implementing CE measures can sometimes lead to increased consumption of raw materials which will have a negative impact on the environmental benefits achieved, thereby considered as one of the main barriers to the CE.

2.4.3 Role of Industry 4.0 in Circular Economy

It is found that using Industry 4.0 in CE significantly improves logistics, resource efficiency, safety, product quality and reduces fossil carbon footprint as it features virtualization,automation, traceability and flexibility (Han et al., 2023). The CE model considers the entire lifecycle of the products, where DT can assist in this entire process. DT can be used in all stages of the product life: Beginning-of-Life Stage(BoL), Middle-of-Life Stage(MoL) and End-of-Life Stage(EOL) (Mügge et al., 2024)). In BoL, DT can be used to design the products, so that it can be optimized for reuse, remanufacturing and recycling. Addition to this DT can predict indicators such as recycling rates which will be a crucial factor during the material selection for the products. In MoL, DT can predict how long the product will be in better condition by collecting the data such as user behavior and providing information about when there will be a need for maintenance. One of the main challenges of CE is returning the products or materials used in the product after their end of life, because the return of materials used is one of the main factors that enables reuse, remanufacturing and recycling which are considered as the factors that formulates CE .DT can be used to rectify the problem. In a Products Life Cycle, DT can provide information about the product's condition because of which it can forecast the period of return of the products and it can facilitate tracking of the products that are no longer in use thus ensuring a closed loop chain. In EoL, DT can help in decision making about the appropriate method which can be used for reusing or remanufacturing parts by collecting the information about the condition of the material as well as its history. DT also helps the complexity of disassembling the products by providing efficient information about the disassembly process and supports virtual disassembling of the products.

2.5 Supply Chain

A supply chain (SC) is a complex network that encompasses all the activities and processes involved in delivering a product or service to the customer from the suppliers (De Angelis et al., 2018). This includes everything from sourcing raw materials, manufacturing, transportation, storage, and ultimately distributing the product to the customer. The supply chain network involves multiple stakeholders such as manufacturers, government, suppliers, retailers, and customers.

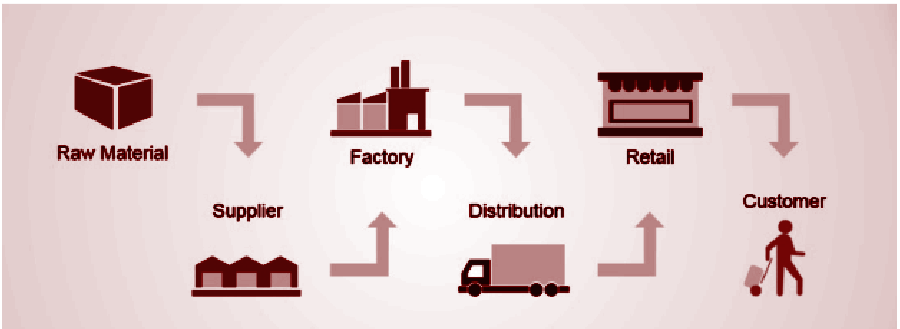

Figure 2.10: Schematic representation of Supply Chain

2.5.1 Digital Twins in SupplyChain

The integration of Digital Twins (DT) in the Supply Chain (SC) is referred to as Digital Supply Chain Twins (DCST) (Gerlach et al., 2021). DCST is a dynamic simulation model of the entire real-world supply chain network. It allows for obtaining real-time data from the actual supply chain and using its digital counterpart to make informed changes, predictions, and improvements without directly altering the real-world system. The primary objective of DCST is to enhance the performance of the supply chain across the entire customer order process. In the logistics system, DCST can be utilized at three different levels: Network level, Site level, and Unit level.

At the Network level, DCST encompasses a multi-stakeholder value network, which includes government entities and stakeholders from manufacturers and suppliers. At the Site level, DCST comprises a value network of a logistics site, such as warehouses and production facilities. Meanwhile, at the Asset level, DCST encompasses individual systems within the supply chain network, such as trucks, forklifts, and AGVs used within production sites.

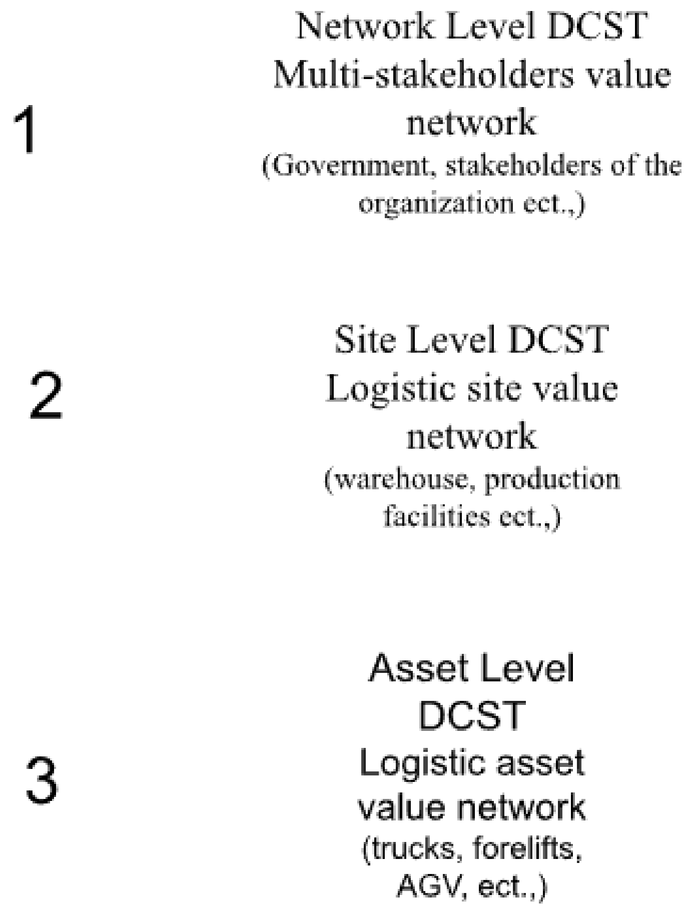

Figure 2.11: DCST scopes in Supply chains (Gerlach et al., 2021a)

2.5.2 Closed Loop or Circular Supply Chain

When a product reaches the end of its use life in the traditional supply chain, it is typically thrown away or disposed of as garbage, which results in the need to employ additional resources to make more products and excess landfill waste, both of which is considered unsustainable.

To be more sustainable, either the product needs to have an extended life period, or when it reaches its end of life, the product has to return to the manufacturers, to reduce the waste, usage of raw materials by recycling, remanufacturing and refurbishing the end-of-life products. To enable this, the products need to somehow return to the manufacturer, after it has provided the value to the customer. So, the concept of Closed Loop Supply Chain (CLSC) or reverse logistics emerges, where the products are bought back into the supply chain after the end of its life which leads to more sustainability and paves the way for circularity.

A CLSC or reverse logistics is defined as a concept which aims to maximize the value of the materials or the products after its end of life or during its entire life cycle, where the products are no longer needed by the customer due to various reasons is brought back into the supply chain, and treated as potential resource for the future use through recycling, remanufacturing and reuse rather than considering it as a waste ((De Angelis et al., 2018)

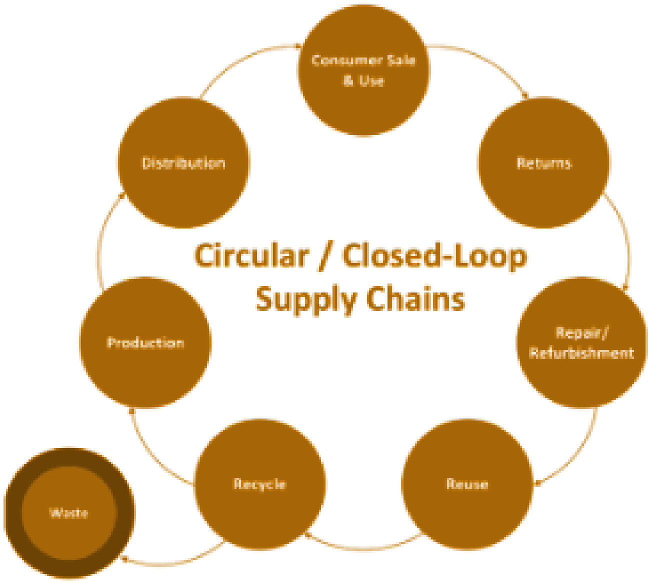

Figure 2.12: Schematic representation of Closed Loop Supply Chains.

2.5.3 Implementing Closed Loop in Supply Chain challenges

There are various challenges in implementing CLSC. They are Investment in resources, collaboration across industries and structural flexibility.

The structural flexibility is imprtant since when implementing CLSC, a company should design their supply chain in a way that not only allows the flow of products from the manufacturers to the customers but also accommodates the flow of product back to the manufacturers from the customers. This can be challenging because most of the supply chain is designed in a traditional way.

Collaboration Across Industries
Collaboration across industries can become a problem because there will be a need for the manufacturers to work along with other industrial sectors because there might be a need for another company or supply chain provider whose supply chain accommodates reverse logistics and they might need collaboration with recycling companies to ensure that the materials from the returned products are recycled properly.

Investment in resources is very challenging since implementing CLSC will require a lot of resources, because companies may need to invest in new technologies and infrastructure so that they can make reverse logistics possible in their existing system. This includes collecting and transporting returned products, new machines or production techniques which facilitates recycling and remanufacturing, and technologies for tracking and managing the products when returning back.

2.5.4 Harnessing DT for CLSC

As mentioned before, in CLSC, products are returned back to the supply chain after its use or at the end of their life and using DT, the loop can be optimized in several ways (Guo and Han, 2022)

First there is through Real-Time Monitoring and Control where, With the help of DT, the real-time monitoring of the product is feasible, which enables the manufacturer to monitor the condition of the physical product with the help of sensors (Guo and Han, 2022). So, if the product is wearing out faster than expected, the digital twin can help to identify this, so that it will help the manufactureres to take the product back into the supply chain or can offer maintenance to the product to increase their life. By this way, DT can help to extend the products life and reduce waste

The data that are collected by the digital twins can also be used by the manufacturers for predictive maintenance (Guo and Han, 2022). By using the data collected, manufacturers can predict when the products need maintenance, and by doing this, they can extend the life of the products significantly which also leads to reduction in waste and also improves customer satisfaction.

Supply Chain Optimization is a process whose main focus is to make the right decision at the right time about the resources involved in the production of the product and in its delivery (Guo and Han, 2022). It involves various factors, including cost, efficiency and sustainability. In this DT can simulate the flow of products in the supply chain and can identify bottlenecks and inefficiencies which slowed down the entire process. By this DT can help in reducing the cost. Along with this, DT can predict the outcome of changes to the supply chain which helps the organization to make important decisions and the impact of the decision before they were actually employed in the real world. Additionally, due to real-time continuous update of data, DT can help with making adjustments in the supply chain. For example, DT can predict the real-time traffic condition of an area and can help to identify alternative routes, so that the products can reach the customers on time.

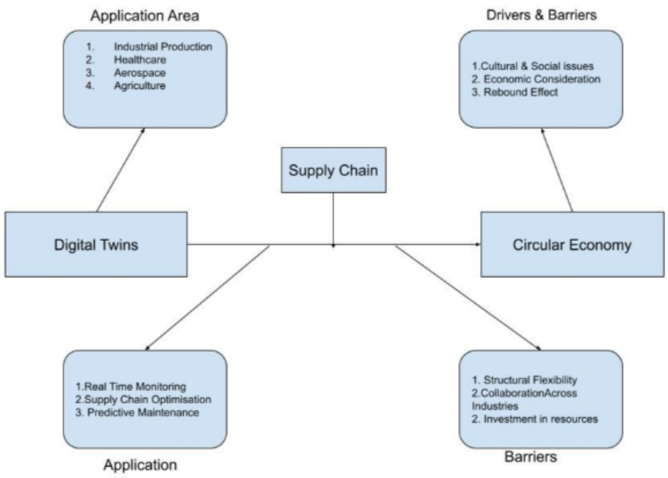

Figure 2.13: Correlation of Digital twind, Supply chain and Circular economy

3
Methodology

The following chapter outlines the research design and methodology used in this study.

The research design consists of a seven-step process that forms the foundation of our thesis. Each step is carefully planned and executed to maintain the overall integrity of the thesis and guide us from the initial stage to the final stage.

An essential part of our methodology is the literature review, which involves an extensive study of existing literature relevant to our research area. This helps us build the necessary background knowledge for the thesis.

The core of our thesis is the solution generation phase, in which we utilized a quantitative research approach to collect data through a detailed case study. We conducted interviews with company personnel and researchers whose insights have been valuable in shaping our thesis.

Lastly, we place a strong emphasis on ensuring high-quality research. We have implemented measures to ensure the reliability, replicability, and validity of our findings, demonstrating that our research results are consistent and can be replicated by other researchers.

3.1 Research Design

For the initial phase of the research, a detailed research strategy was developed, structured according to the comprehensive steps outlined in "Business Research Methods" by Bell et al. (2019) ensuring a systematic and thorough exploration of the research subjects.

The step-by-step framework is presented in the figure . The first step was to define the research area which involves identifying specific topics of interest and establishing its relevance and potential impact. The next step involved formulating the research question based on the topic of interest. The next step includes Literature study, which is used to understand the subject area. The next step is solution Generation for the research questions. For this information was collected from a case company along with the interviews with the researchers. Lastly, results were generated by combining the data from the case study and from the interviews.

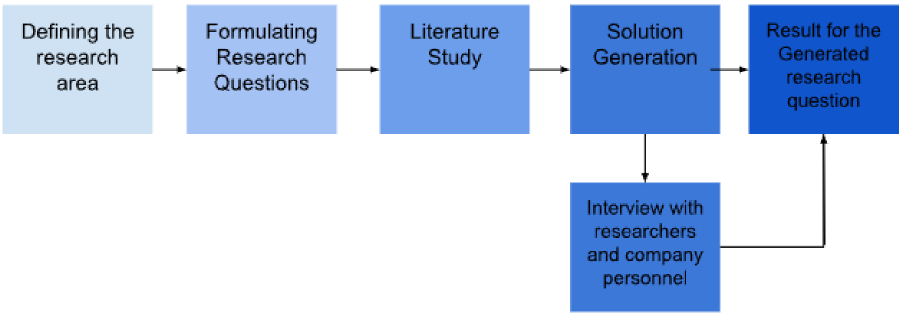

Figure 3.1: Roadmap used in the research design.

To illustrate the thesis schedule for the implementation of the research design's various phases, a GANTT chart has been developed.

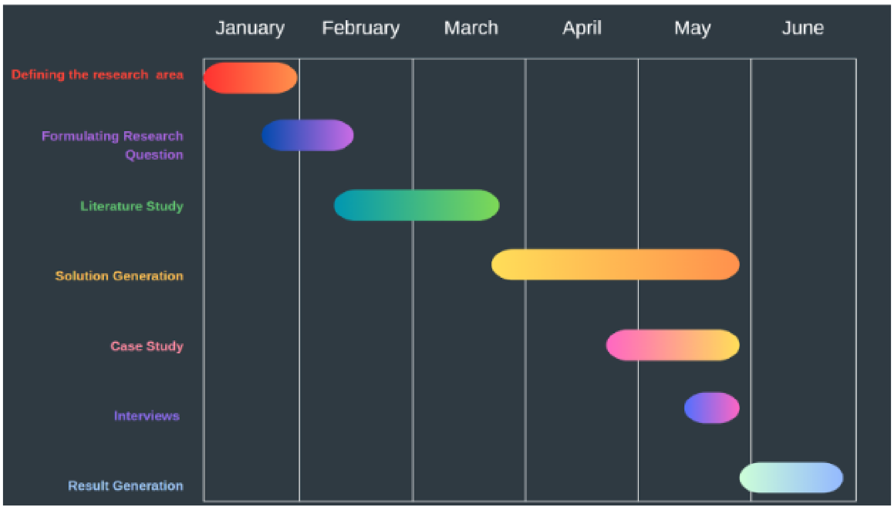

Figure 3.2: Rough time plan for when the proposed steps in the research design were planned to be carried out.

3.2 Literature Review

The literature review is a crucial component of this research, aiding in the identification of existing knowledge and gaps in the field of study. For this Master's thesis, the literature review was conducted using two primary sources: Google Scholar and Scopus. These platforms played a significant role in gathering all the necessary literature relevant to the topic.

To comprehend the concept of Digital Twin in the supply chain and its applications, extensive use of Scopus was made. Specific keywords and literature were utilized to search. This approach facilitated the identification and understanding of the current state of research and applications of Digital Twins in the realm of supply chain and logistics.

In addition to the study of Digital Twin in supply chains, the thesis also delved into the theme of Circular Economy. The objective was to understand the role and potential of Digital Twins within this context. Literature related to this area was gathered using both Google Scholar and Scopus.
The literature review was conducted systematically and thoroughly to ensure a comprehensive understanding of the research area. These findings not only helped in gaining theoretical knowledge about the research area but also in identifying potential gaps, thereby justifying the need for this literature study.

The utilization of reputable sources such as Google Scholar and Scopus lends credibility to the entire process.

A quick overview of the reviewed literature is in figure 3.3

Figure 3.3: The literature that was reviewed

Name of the Literature	Authors	Description	Application Area
5G in manufacturing: a literature review and future research	(Cheng et al., 2022)	This paper first analyzed the communication requirements for machine-to-machine, manufacturing Internet of Things, cyber-physical system-based manufacturing, logistics and supply chain, industrial Internet platform and digital twin–driven manufacturing	Manufacturing
A Bibliometric Analysis of Digital Twin in Supply Chain	(Lam et al., 2023)	Gives detailed information about Digital twin and gives information about the trends in Digital twins in the supply chain.	Supply chain
A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0	(Ivanov and Dolgui, 2021)	Try to see how digital twins can be used to make supply chains more resilient to unexpected events. They mostly built on earlier research but they found new ways to use digital twins to enhance their resilience	Disruption Resilience
A Framework of digital twin solution for 5PL operators	(Nicoletti and Appolloni, 2024)	The literature talks about how DT can be used in logistics industry at network, site and asset level.	Logistics
A smart palletising planning and control model in Logistics 4.0 framework	(Borangiu and Răileanu, 2023)	The paper describes a smart model for palletising	Logistics
Application of Digital Twins in multiple fields	(Guo and Lv, 2022b)	They list several different areas (industrial production, medical field, smart cities, field of aerospace, the business world) and how DT is used in them	Multiple fields
Applying digital twins for inventory and cash management in supply chains under physical and financial disruptions	(Badakhshan and Ball, 2023)	They researched how the covid-19 pandemic affected supply chains and how a good use of digital twins would have made the impact less severe	Supply Chains
Automated Digital twin generation of manufacturing system with complex material flow	(Lugaresi and Matta, 2023)	They developed a way to create a model of a manufacturing system more easily. Big manufacturing systems are hard to model so this is a step towards making it more feasible but their model had several limitations so it's not ready for real use.	Manufacturing
Big Data enterprise supply chain under green financial system based on Digital Twin Technology	(Li and Li, 2024)	It is found that using DT problems which cannot be solved by using traditional technology can be solved and it also helps to increase the efficiency, reduce cost and bring many new opportunities for organizations, yet there are many deficiency in this study.	Supply Chains
Big Data provision for Digital twins in Industry 4.0 Logistics process	(Figueiras et al., 2021)	Talks about the development and phases of the Big data supported digital twin in Logistics (Optimization of stock, inventory ect...) to make it more efficient in the Automotive industry.	Logistics

Block chain enabled digital twin technology for next gen transportation system	(Banerjee et al., 2023)	Combining Blockchain with DT enables simulation of different scenarios in controlled environment which shows improvement in some aspects of logistics and using Blockchain also ensures the safety of data which includes different stakeholders. Conclusion: Though the experiment is done theoretically, it lacks practical implementation.	Logistics
Cognitive Digital Twins for freight parking management in last mile delivery under smart cities paradigm	(Liu et al., 2023)	Though case study was done it has many limitations. but it focuses more on the capabilities of cognitive digital twins.	Freight parking
CONCEPTUAL MODELING FOR SUPPLY CHAIN DIGITAL TWIN	(Ko et al., 2022)	They propose a very basic SCDT but it is no way near being able to be implemented	Supply Chains
Conceptualisation of a 7-element digital twin framework in supply chain and operations management	(Ivanov, 2023)	seven major elements of a digital twin in SCOM: technology, people, management, organization, scope, task, and modeling. They also distinguish five major types of digital twins in SCOM: product, process, organization, supply chain and network-of-networks	Supply Chains(
Construction of Digital Twin System for Cold Chain Logistics Stereo Warehouse	(Hu et al., 2023b)	A 5D DT model is proposed with full mapping and multidimensional simulation based on a generic algorithm and then use it to cold chain warehouse so that improvements in freshness cost reduction and efficiency is made	Logistics
Convergence of distributed ledger technologies with digital twins, iot, and ai for fresh food logistics: challenges and opportunities	(Vilas-Boas et al., 2023)	How DT and DLT can be used to improve the logistics in fresh food process Conclusion: The results show improvement on a theoretical level but lack practical implementation.	Logistics
Digital Supply Chain Twins for Sustainable Planning of a Logistics System	(Zarnitz et al., 2023)	Here, on the basis of historical data, it is conceptually worked out when the DSCT could have predicted a proactive demolition of the delivery capability on the basis of its characteristics and which transport routes, which were non-transparent up to this point, can be shown by the created visibility of the network by the DSCT for sustainability assessment.	Supply Chains
Digital Supply chain Twins in urban logistics system - Conception of integrative platform	(Bähring et al., 2023)	A Frameworks with eight functional modules were introduced to make improvement in urban logistics.	Urban logistics
Digital Supply Chain Twins—Conceptual Clarification, Use Cases and Benefits	(Gerlach et al., 2021b)	The five areas Risk management, Multi-echelon inventory management and production planning, material lifecycle management and sustainability assessment and transport planning. The ranking over which of these are the most common. Also the 14 use-cases within these five areas.	Supply Chains
Digital twin application in the construction industry: A literature review	(Opoku et al., 2021)	Different fields have different definitions of digital twins so a unified definition needs to be reached. They found that for their definition there were 6 different use cases for digital twins which were building information modeling, structural system integrity, facilities management,	Constructi on

Digital twin for complex logistics system the case study of a large scale automated order picking and fulfillment system	(Ashrafian and Pedersen, 2023)	In this paper a simulation based DT with full automated order picking and fulfillment a warehouse with a DES model is created. It also talks about how data are collected which are used in DES Conclusion: When all the required data which is required for DT is produced, it is shown that it will enhance the performance of complex logistics system especially in order picking, and the fulfillment system. It also shows that using DT in real case helps performance managers to dynamically adjust operating system parameters under varying condition.	Logistics
Digital Twin Based Real-time Production Logistics Synchronization System in a Multi-level Computing Architecture	(Pan et al., 2021)	This paper proposes a multi-level cloud computing enabled digital twin system for the real-time monitor, decision and control of a synchronized production logistics system.	Logistics
Digital Twin driven supply chain visibility with logistics	(Moshood et al., 2021)	This literature talks about implementing Digital twin in logistics company, how DT can help dealing with supply chain visibility in logistics field, and tackling the barriers in implementing DT in logistic industries. The result shows DT can help logistic companies in predicting metrics, projection and physical assets description in logistics.	Supply Chains
Digital Twin for Logistics and Supply chain system	(Le and Fan, 2024)	This literature provides detailed information about LSCS and DT. And explains the need for new DT framework for more sustainable and efficient LSCS by discussing a new conceptual DT framework. The provided conceptual DT framework helps in structuring and aligning logistics and supply chain operation for organization. Further research is required to provide a more trustworthy Digital twin framework for LSCS.	Supply Chains
Digital twin for railway: A comprehensive survey	(Ghaboura et al., 2023)	This is a survey paper on to what extend the emerging DT is used in railway industry both in designing and developers And it also talks about challenges and opportunities for DTR in future. DT is not used in railways to greater extent because of lack of exploration on DT technology. It also concludes a proper framework is required in future to integrate DT in railway industry	Railway
Digital twin for supply chain coordination in modular construction	(Lee and Lee, 2021)	They aim to develop a digital twin framework for real-time logistics simulation, which can predict potential logistics risks and accurate module arrival time	Constructi on
Digital Twin models in Industrial operation	(Melesse et al., 2020)	This literature provides literature review of 25 papers on how Digital twin is used in different industrial sectors and also gives information about the challenges in implementation of DT in industrial operation. Further research and improvement is needed to develop and improve the application of DT in industrial operations.	Industrial

Digital twin for complex logistics system the case study of a large scale automated order picking and fulfillment system	(Ashrafian and Pedersen, 2023)	In this paper a simulation based DT with full automated order picking and fulfillment a warehouse with a DES model is created. It also talks about how data are collected which are used in DES Conclusion: When all the required data which is required for DT is produced, it is shown that it will enhance the performance of complex logistics system especially in order picking, and the fulfillment system. It also shows that using DT in real case helps performance managers to dynamically adjust operating system parameters under varying condition.	Logistics
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Digital Twin of Food Supply Chain for Cyber Exercises	(Sipola et al., 2023)	They created a DT to be used for cyber security training. It was good enough to simulate a certain type of cyber attack but it needs more varied attacks to sufficiently prepare workers for an actual attack	Supply Chains
Digital Twin opportunities and benefits in last mile logistics for Madrid value case	(Royo et al., 2023)	This paper gives a case study on last mile logistics during Covid 19 pandemic. It also talks about Madrid living lab that is located in city center and how they used DT for improved decision, shipment during covid 19 pandemic. It provides a clear conclusion that Madrid Living lab increased their shipment and decision making using DT but they have not used it to full potential.	Logistics
Digital twin-driven smart supply chain	(Wang et al., 2022)	They demonstrate the method for building a DTSC. Implementing DTs take time but it is worth is especially in today's time where supply chains are so widespread that a small disturbance in one place can mess up the entire production	Supply Chains
Digital twin: Current shifts and their future implications in the conditions of technological disruption	(Kaivo-Oja et al., 2020)	They present five scenarios of disruptions where digital twins are useful	Disruption Resilience
Digital twins are coming: Will we need them in supply chains of fresh horticultural produce?	(Defraeye et al., 2021)	The goal to identify the key advantages of digital twins and how the horticultural produce can benefit from it. Which gave the result that it can show the state of the produce but also why it is in the state it is since it can see the state of the surroundings	Supply Chains
Digital Twins for the Circular Economy	(Preut et al., 2021)	They define DTs and the different Rs of the circular economy. They also list several benefits from using DTs in circular economy but they also stress that it is very product dependent so thorough research needs to be done in the specific product what benefits can be gained in that specific case.	Circularity
Digital Twins on the Resilience of Supply Chain Under COVID-19 Pandemic	(Lv et al., 2022)	Shows that in pandemic disruptions digital twins can help a lot, especially in the specific case presented in the article	Disruption Resilience
Digital-twin based real-time resource allocation for hull parts picking and processing	(Wang et al., 2024)	a real-time resource allocation method based on digital twins for hull part smart picking and processing system is proposed which reduces uncertainties for workers of when parts will arrive	Prediction
Digital-twin-based implementation framework of production service system for highly dynamic production logistics operation	(Jiang et al., 2020)	This study proposes a digital-twin-based implementation framework of production service system for highly dynamic production logistics operations	Logistics

Empowering End-of-Life Vehicle Decision Making with Cross-Company Data Exchange and Data Sovereignty via Catena-X	(Mügge et al., 2023)	They used the program GAIA-X to share information between partners in a secure way and they split up the process of buying and deconstructing a vehicle into five steps where they can share the relevant information for which step they are on.	Circularity
In search of a circular supply chain archetype–a content-analysis-based literature review	(Batista et al., 2018)	They propose a conceptualization of circular supply chain archetype that integrates the the features used currently in the sustainable supply chain. They found that circular supply chain as a coordinated forward and reverse supply chain which supports the process of value creation from the products.	Circularity
Is digital twin a better solution to improve ESG evaluation for vaccine logistics supply chain: an evolutionary game analysis	(Zhang et al., 2024)	This paper systematically analyzes the influence of digital twin service (DTS) on ESG (environmental, social, and governance) evaluation and analytically investigates the long-term behavior of sustainability concerned stakeholders in the VLSC (vaccine logistics supply chain).	Supply Chains
Openness Of Digital Twins In Logistics - A Review	(Winkelmann, n.d.)	Most companies that use digital twins for logistics only use it within their own company to protect the data from others. They however use digital twins with other companies since they don't share information automatically.	logistics
Optimizing the postharvest supply chain of imported fresh produce with physics-based digital twins	(Shoji et al., 2022)	Show how digital twins can be used to measure effectiveness of produce shipments. The data given from the digital twins can then give new insight in to how to optimize supply chains to maximize the quality of the produce	Supply Chains
Peeking into the void: Digital twins for construction site logistics	(Greif et al., 2020)	Researched different areas in a construction site where digital twins could be used and then developed a digital twin for one of these areas.	Constructi on
Quantifying the benefits of Digital Supply chain twins - A simulation study in organic food supply chains	(Binsfeld and Gerlach, 2022)	Three simulations were done in Food supply chain in four different scenarios (Initial baseline scenario,Demand Increase, Supplier risk,Customer and Supplier risk) and their performance were measured along with providing a quantification method for understanding DCST benefits to evaluate LSCM in practice	Supply Chains
Research on Real-Time Robust Optimization of perishable supply chain systems based on Digital Twins,	(Wu et al., 2023)	This paper is about how to achieve real time robust optimization of perishable supply chain systems in complex environment such as natural disaster, public health crisis and wars that causes fluctuations in demands by designing a robust infinity controller to update data in real time. A simulation was done and it is seen that we can update the relevant data in real time due to the existence of Supply chain digital twins which helps to design more reasonable production strategy when compared td traditional optimization process.	Supply Chains

Roles of digital twins on material performance and utilization on upstream industry (The case of automotive Industry)	(Damtew, 2024)	This paper describes how DT impacts the production lines and supply chain performance such as supply chain visibility, innovation, optimization, risk and resource utilization in upstream industry. Here automotive industry is considered. Using DT improve supply chain visibility and innovation, digital market performance and the results of empirical investigation shows positive impacts.	Manufact uring
The architectural evolution of intelligent factory logistics digital twin from planning, implementation to operation	(Qiu et al., 2023)	This literature proposes a DT architecture for intelligent factory logistics which has physical layer, tow cyber layers and interface layer, how it evolves from planning implementation to operation stages in logistics system construction and also talks about how we can add humans in the decision making process. The proposed DT architecture increases the flexibility, scalability and adaptability of the intelligent factory and it also helps to develop sub DT and micro services that can be developed for specific scenarios.	logistics
The digital twin in Industry 4.0: A wide-angle perspective	(Kenett and Bortman, 2022)	This is about how to use digital twins in railways and big challenge that arose is that the people with the railways don't own the data of the trains which makes it hard for them to use digital twins without accessing data that they should not have access to.	Railway
Toward Digital twins of Multimodal Supply chain	(Busse et al., 2021)	This paper analyzes the barriers and limitation of DT in Multimodal and intermodal supply chains and how traceability in these supply chains affects the entire supply chain. A framework was proposed which aims to use DT in entire supply chain along with the use of some latest technological advancement	Supply Chains
Towards Digital Twin for sawmill production planning and control: opportunities and challenges	(Chabanet et al., 2023)	This literature gives detailed description about how DT can be used in Sawmill production planning and control and what are the benefits it will bring. Several benefits such as reducing uncertainties, increasing resource efficiency and coordinating production units were found using DT in Sawmill production. It is found that existing technologies and models can be used as building blocks for DT as well as to reduce the barriers that are needed to be solved like data availability and model validity. Future research suggest to develop and apply DT in areas such as supply chain coordination and data driven models.	Sawmill
Unlocking the Potential of Digital Twins: A Comprehensive Review of Concepts, Frameworks, and Industrial Applications	(Manickam et al., 2023)	Applications of Digital Twins, exploring their merits and limitations.	Digital Twins In General

3.3 Solution Generation

In order to gather data for the research question Qualitative study approach is chosen. The data for the thesis is collected through interviews. Interviews were conducted to researchers and company personnel to formulate the result generation of the thesis.

3.4 Qualitative Study

Qualitative study is a type of research that enables us to develop an understanding of human and social sciences and to delve into the way people think and feel (Gelo et al., 2008). This method involves collecting and analyzing non-numerical data such as text, video, or audio to comprehend the concepts, opinions, and experiences from people's perspectives. It offers a thorough analysis of a problem and facilitates the generation of new research ideas. Qualitative study is frequently used to explore complex phenomena or to gain insight into people's experiences and perspectives on a specific topic.

The reason for choosing this approach for this research is that it allows for a more detailed evaluation of subject materials and places less emphasis on the metrics of collected data. Additionally, it facilitates a deeper understanding of the topic and offers flexibility to adapt our research based on the collected data. Moreover, it has aided us in understanding the research topic discussed in this thesis from a human perspective.

3.5 Interviews

To support the literature review and gain a deeper understanding of the real-world applications of the research topic, a series of interviews were conducted. These interviews involved two distinct groups: researchers in the field and company personnel, to understand the extent to which they are utilizing the research field in their organization.

The researchers provided valuable information about the theoretical aspects of the research area, while the company personnel provided a practical perspective on the application of these theories in the business world. This combination of theoretical and practical knowledge helped to generate answers to the research questions and ensured a comprehensive understanding of the topic.

All interviews were conducted online using Microsoft Teams, ensuring a consistent and efficient process. The use of this digital platform helped us to interview researchers and company personnel regardless of their geographical location. Before all interviews, permission was requested of the interviewees to record and transcribe the meeting for future reference.

To maintain consistency and accuracy in the information gathered, a standard set of questions was used for each group. The researchers were asked the same set of questions as the company personnel. This ensured that the data collected was comparable and easily analyzable.

Figure 3.4: Interviewees

Interviewee	Background of interviewee
1	Industrial engineering management engineering PhD digital industrial architecyure for enabling sustainability transition
2	Logistics department, cross brand coordinator
3	Associate professor, research about predicitive maintenance and analytics for maintenance and simulation for production system.
4	Research about circle economy
5	Assistant professor, Production logistics, Different projects within digital twins
6	Professor in automation engineering, Production engineering, Research in simulation based optimisation
7	Logistics director
8	Professor in supply and operations management. Research in Circular economy
9	Assistant professor, Research toward a circular economy and industry 5.0

3.6 Ensuring High-Quality Research

To conduct high-quality research three key criteria are used. They are Ethical Consideration, Reliability, and Replicability

3.6.1 Ethical Consideration

Ethical considerations are extremely important in research because they ensure that no harm comes to those who participate in the study. Before conducting the actual interviews, all participants were informed about the purpose of the study. Their anonymity was guaranteed, and the results obtained from their interviews will only be used for this study. Additionally, the use of reputable sources such as Google Scholar and Scopus for collecting literature ensures that the research adheres to ethical standards and academic integrity.

3.6.2 Reliability

Reliability and replicability are essential aspects of research. Reliability encompasses the consistency of research findings, which was ensured in this study by using reputable sources for literature and providing standardized interview questions. Digital platforms such as Google Scholar, Scopus, and Microsoft Teams also contributed to reliability by facilitating consistent and efficient data collection.

3.6.3 Replicability

On the other hand, replicability refers to the study's ability to be replicated by other researchers to validate the findings. To ensure replicability, this research will provide a detailed methodology description, including the data collection process, literature study, and data analysis techniques. This transparency will enable other researchers to follow the same procedures and compare their results with this study.

4
Results

The following chapter presents the findings obtained from the in-depth interviews conducted as part of this thesis. The interviews aimed to provide insights into the role of digital transformation in driving the transition towards a circular economy.

The responses from the interviewees have been thoroughly analyzed and are presented here in an organized manner. Each response has been carefully considered to ensure that the most relevant information is included, and that the data accurately represents the views and experiences of the participants.

4.1 Digital Twins: A deep Understanding

4.1.1 Understanding Digital Twins

Digital Twin is a concept that has been around for a while, but there is still no standardized definition for it. Many researchers and organizations consider Digital Twin to be a buzzword. As one of the researchers quoted

"I think Digital twins definitely relate to simulation and a few years ago I would say that digital twins is more like a buzz word to me"

One researcher defined a Digital Twin as a technology that establishes a real-time connection between a physical object and its digital representation. This connection works both ways, meaning changes in the physical object affect the digital model, and vice versa. The digital model is created using data collected from its physical counterpart, which can include its current state and behavior. This data is then sent to the digital model, where simulations are conducted under different scenarios. The results are analyzed, optimized, and used to improve the physical world. The flow of data between the physical and digital models allows Digital Twins to be defined in three steps: Digital Model, Digital Shadow, and finally, Digital Twin. The Digital Model involves the manual transfer of data between the physical and digital objects, the Digital Shadow automatically transfers data from the physical to the digital world, while the Digital Twin involves automatic bidirectional data flow, forming a closed feedback loop.

"We define Digital twin with three different steps, so it can exist as a digital model that can be then a simulation model for example, then it can exist as a digital shadow. That

is, when the digital model is updated in real-time and then digital twin is when the digital model receives real-time data. The data from the physical system and then it is able to give feedback. So it is a closed loop, generating a control opportunity to the physical world. So this is what we define as a Digital Twin"

4.1.2 Economic Impacts of Digital Twins

Digital Twin (DT) can significantly help organizations reduce costs in various ways. One way is by creating a digital prototype of a new product, which serves as a replica of the physical product that needs to be manufactured, including all its characteristics such as behavior, structure, and composition. Traditionally, organizations use physical prototypes to test products, which is time and cost-consuming. However, designers and manufacturers can use DT to reduce costs. One obstacle to using DT in this scenario is that creating a digital model replica of the physical object takes a lot of time and investment.
. As one of the researchers quoted

"It's very costly to create a digital model"

4.1.3 Organizational Impact of Digital Twins

Many organizations today are eager to integrate digital transformation (DT) into their systems as a way to drive improvement. DT allows organizations to simulate, predict, and optimize their systems in a virtual environment before making real-world changes. This approach can lead to increased efficiency and productivity. Moreover, DT enables organizations to identify potential issues and risks early in the product development or system design phase, which can help them address setbacks and achieve more positive outcomes.

Despite these benefits, many organizations' management may not fully understand what DT entails and how it can be utilized. Furthermore, some organizations are not yet prepared to implement DT due to their slow adoption of recent technological advancements. This lack of readiness may stem from limited resources, a shortage of technical expertise, or resistance to change within their organizational culture. Consequently, these organizations struggle to effectively integrate new technologies, thus impeding their DT transformation efforts. As one of the researchers stated that

"I think we are at least 30 to 40 years behind when it comes to adopting new technologies within the industries"

4.1.4 Sustainability Impact of Digital Twins

When it comes to sustainability, Digital Twin (DT) is a game-changer. By creating a virtual model of its physical counterpart, it can significantly enhance sustainability practices across various sectors. Enabling the simulation, prediction, and optimization of the performance of physical assets, DT can lead to substantial improvements in resource efficiency, waste reduction, and overall sustainability.

In terms of resource optimization, DT enables precise monitoring and simulation of physical assets by analyzing real-time data. Organizations can optimize resource usage, ensuring more efficient consumption of materials and energy. It also allows for the optimization of product design and manufacturing processes, leading to the creation of more sustainable products with reduced material usage, energy consumption, and lower emissions during production. Additionally, DT facilitates predictive maintenance by continuously monitoring the condition of machinery and equipment, which helps to identify issues before they become critical, thereby extending the lifespan of assets and minimizing the environmental impact of manufacturing new parts. Through all these ways, DT provides a positive impact on sustainability. As one of the researchers quoted

"Digital Twin technology can enhance a lot of improvement in terms of sustainability because if we are able to create the virtual counterpart of the process and let the communication between the digital and the virtual, of course the embedded capability of the digital twin can optimize the physical assets in terms of sustainability"

4.2 Understanding Circular Economy

Then there were the questions relating to the CE which is a more well-defined term that both researchers and workers in the industry agree on. The way they define it is that CE is a model that researchers have identified as an economic strategy. Its goal is to recycle, remanufacture, and refurbish certain product components, returning them to the manufacturer. One interviewee said

"Okay, I think that the circular economy is one of the main important pillars of sustainability nowadays for manufacturing processes. Considering the evolution of sustainable manufacturing in our societies that historically try to improve the efficiency of natural resource consumption within the manufacturing processes."

so, CE can be seen as one of the most important steps for the entire world to become sustainable.
That is a big reason as to why companies would want to move to CE and there are several drivers that the interviews showed to why companies would want to implement CE.

The first driver is as previously mentioned that it's a more efficient use of natural resources. The world only has so much of the natural resources and by implementing CE less raw material is needed which lessens how much needs to be extracted. Since the gathering of natural resources requires energy and there is a risk of running out of most materials this is an important step that needs to be implemented to be able to keep up production for the future.

Another driver is closely related to the first and that is the waste reduction. This isn't necessarily something that the companies can take advantage of since in many cases they are not held responsible for what happens with the products after the consumers are done with them. One interviewee did say “they should treat the whole part of the process that comes after the use phase, the same way that you would treat the process that comes before the use phase” where they meant that as much care and responsibility should be taken for the products even after the user is done with them. If all companies adopted that viewpoint the amount of waste that gets produced would be severely reduced and a good way to gather used up products is important for a good CE.

That leads to one more driver that is government support. For many the act of collecting waste is more costly than it is worth but, in some countries, there are grants that are given out to companies that do so. This government support can be given out for many reasons but for countries that have it is a potentially huge driver. All companies strive for a good economic situation so if there is money involved, they will be more inclined to try it. So, this also leads to some countries outpacing others when it comes to adopting CE. One interviewer pointed out that the development towards CE is not uniform across the globe and one big factor to that is that some countries have big incentives to adopt it while others do not.

These are several good reasons that the interviews gave but of course there are also several challenges or barriers that are stopping companies from implementing CE. Otherwise, it would have been more widespread to use it. Probably the biggest barrier that was pointed out was the fact that most companies already operate on a linear model. So, moving to a circular model can be too cumbersome. Especially since linear model is what people know. If you start a company, it is easier to base it on the model of other companies that have been proven to work. Doing something a bit rarer like CE is a big step into the unknown which can be too much of a gamble. This is especially true if the management is unable to find a good reason to move to circularity. To just do it for no reason is clearly not a good idea which makes it hard to move to CE, especially if they are not sure what to gain from it as pointed out in one answer *“It’s because, as most companies work in a linear flow, they have a very hard time making a business case to argue OK, should we actually jump in to creating this new type of business In circularity and if there is no business case, then obviously the decision will be well, we will maintain our current way of working”* So, if they are profitable as is with their more standard linear model, a move to circularity is both costly and riskier. If the move fails it could be the end of the company.

This is all connected to another of the biggest challenges which of course is that it is a big investment to implement CE even if it is on a small scale. There needs to be a way to gather all the used-up products, which requires a system to be developed which incentivizes customers to return after use. That is something which is clearly not going to happen by itself so just that step is a big investment. Then the products have to be analyzed to decide what to do with them after they have been returned. The different states of the returned products mean they can’t all be returned to the supply chain in the same way so that analysis is also an investment. After that the actual recycling, refurbishing or so on takes place and all these different methods of reusing them require different methods to be done which potentially require different machines. This also usually requires a new building to house this entire part of the production. These are just some steps that have to be taken and there are many investments along the way. So, if no clear case for how this can benefit the company can be found then they can't implement it. One researcher also mentioned examples of companies that wanted to change to a circular model and did research into how to implement it but came to the conclusion that their products would become way too expensive if they used recycled materials. People wouldn't be able to afford their products anymore so even though they tried they just could not use CE.

One of the company representatives that was interviewed said they had a lot of success when reusing their products and it saved money for both the company and the customers. In some cases, though they had to use a traditional linear model since it sometimes required more resources and produced more pollution to reuse the products instead of creating new ones. So, in some cases, the problem with CE isn't economical but instead environmental, that it is worse for the environment to reuse. This particular example was connected to shipping so to reuse the products they would have to be shipped back to the factory and this company sends products all over the world. To send it away for use was no problem but to gather them up required more energy than to simply make new products.

One other challenge that companies face is that in a linear model it's more predictable how much raw material is required to keep the production going. They usually have a plan as to how many products to make every month so they can have a rough estimate of how much raw material is needed. In a CE however some parts of the materials come from old products where they sometimes don't know when they get back. As one researcher said it is easy to estimate when store packaging can be expected to return so in that case the return time becomes predictable. In the case of user products though it is much harder to know how long they are going to use it. For some items like cellphones, it could be a difference of several years. This means the raw material needed for any given month becomes very hard to estimate. They could get a huge load of old products, or they could get none. By hoping they get a certain number of old products they could face the possibility that production stops due to lack of material. Or if they order enough that production can keep going anyway, they need to have storage for a potentially large amount of extra material. Either way it leads to a more challenging economic citation compared to using a linear model.

Lastly, some researchers pointed out that products made from recycled materials are sometimes of lower quality. This has the consequence of the consumer having to buy new products more often if they buy those. Even if the price of the recycled product is lower the consumer could still save money on buying a product from virgin material that lasts longer.

Those were some of the drivers and challenges from DT and CE that were gained from the interviews.

4.3 Digital Twins in Circular Economy

DT can be utilized in CE in several ways. Firstly, DT can predict the condition of a product, enabling it to be used for a longer time. This allows companies to perform predictive maintenance. However, many customers are unwilling to share real-time data of the products they are using.

Secondly, DT can assist in tracking the product. Once the product reaches its end of life, it can be returned to the manufacturers through reverse logistics. However, as reverse logistics is part of the supply chain, which is a network of groups, using DT can be challenging. The collection of real-time data is difficult because not all assets used in logistics have a digital model, and there can be delays in data collection, meaning the data required for DT is not uploaded instantly.

According to researchers, real-time uploading means 2ms, where data from small appliances like robots can be collected and integrated into the system instantly, but not in the supply chain.

In CE, an AI could make decisions such as what amount of the returned product could be recycled, refurbished, or reused automatically without the need for human input, as they monitor the life cycle of the products regularly. This would be useful in a fully automatic factory.

Most companies are very human-centric, where human workers are the ones making decisions, so a real-time updating model might be pointlessly specific for many organizations. A normal digital model for a supply chain can be updated manually when changes are happening, and usually, that is enough, so the need for a DT might not be there.

The need for a bidirectional flow of information isn't there in most cases. Since one of the big problems for companies with adapting CE is that they need good tracking of their products, a digital shadow is usually sufficient.

Today's supply chains involve many different stakeholders, and everyone is not open to share information about their companies. This makes DT not acceptable for many since it gathers a lot of data that they are not willing to share with others.

However, in smaller supply chains that only have a few stakeholders or maybe even only one and with a lot fewer moving parts, then DT might be able to be implemented.

5
Discussion

After conducting an extensive literature review and interviewing experts in the field, several significant points about Digital Twins (DT) in Civil Engineering (CE) emerged. Both the literature and the interviews highlighted many factors that complement each other and provide a more complete view of the subject as a whole.

One key aspect emphasized in both the interviews and the literature is the need for a unified definition of DT. While most researchers and papers in the field of DT agree on its definition, the challenge lies in ensuring that researchers and company staff with limited knowledge of DT do not misuse the term. Some individuals prefer using the term DT because it sounds more advanced than phrases such as "digital model" or "digital shadow." Therefore, a crucial step in implementing DT in any field, including CE, is to widely disseminate an accurate definition to prevent misinformation about its usefulness and challenges.

Another recurring topic of discussion was data security and privacy. Implementing DT in any supply chain faces resistance from management due to concerns about sharing data among stakeholders. Smaller companies may struggle to implement CE independently and might require the assistance of a third party. However, hiring a third party may involve sharing a significant amount of company data through the use of DT, posing a major barrier. Furthermore, obtaining data from customer products is challenging because customers are typically reluctant to be monitored extensively. Recognizing this barrier, researchers have taken steps to mitigate it. For example, (Attaran et al., 2023) proposed a method of using DT in CE that allows the sharing only specific data with stakeholders and monitoring products without compromising customer privacy.

One barrier mentioned in the interviews is that a circular economy (CE) is less predictable, as it's harder to predict the influx of old products compared to the influx of virgin material. However, several reports discuss how digital technology (DT) can improve predictability in supply chains and circular economy practices. References such as Kaivo-Oja et al. (2020), Lv et al. (2022), Ivanov and Dolgui (2021), and Badakhshan and Ball (2023) explore how DT can be used to address unpredictability and enhance system robustness. DT has proven successful in mitigating this particular barrier for circular practices.

Other potential solutions to barriers in the circular economy are outlined in Banerjee et al. (2023), where DT is employed to test different logistics scenarios for faster implementation of new methods. Such approaches could expedite the adoption of circular practices and reduce associated risks, allowing more companies to explore these methods without committing entirely to an unknown concept. As highlighted in interviews and as noted by Preut et al. (2021), circular economy practices are not universally suitable. However, with the aid of DT, it may become easier to assess whether they are suitable for specific cases.

The interview also highlighted that modeling an entire supply chain is a complex process that requires a significant investment in digital transformation (DT). However, Lugaresi and Matta (2023) have researched ways to speed up the modeling process. Accelerating the modeling process would result in faster DT implementation, although it may not be sufficient at present. Efforts are underway to address this challenge.

Another obstacle to circular economy (CE) is efficiently retrieving old products to maximize their value. Digital transformation (DT) can be leveraged for optimization, as demonstrated by Ashrafian and Pedersen (2023), who discussed the use of DT to optimize a large-scale logistics system. While not directly related to retrieval, this example illustrates how DT can optimize logistics, potentially enabling efficient product retrieval that yields greater value than the effort involved.

5.1 research Questions

With all this combined we come to the answers reached to our research questions.

RQ1: How can Digital Twins support the transition from Linear Economy to Circular Economy in supply chain

First of all it can be used to predict the condition of products both before and after the use-phase. This makes it easier to put the products back into circularity. It is also useful for tracking products in reverse logistics. By knowing where the products are it is much easier to have them get sent back to production. This tracking of where products are and what condition they are in leads to the company being able to predict how much virgin material is needed. The unpredictability of circular economy is a potential source of huge losses so this extra level of predictability makes the entire process more reliable. The implementation of CE can take a long time but with DT the different scenarios of the circularity can be simulated to speed up the implementation process. Lastly by using it during the design phase it can help the manufacturers choose suitable materials for circularity.

RQ2: What are the challenges for implementing and integrating Digital Twins in a supply chain

The big obvious challenge with implementing DT is of course that it is expensive. It can lead to the company being more profitable but it is a big investment to start. Another commonly stated barrier is data security and data privacy. Neither companies nor users are willing to share too much data which makes the implementation harder. Companies being as human-centric as they generally are now means it’s harder to track things in the supply chain so a more digitalised organization would be more suitable for DT. A supply chain is a large network with many moving parts and creating models for everything is a big undertaking. There is also a need for special competence to know what data to gather in the supply chain for the DT to be useful. Lastly and maybe most relevant as a first challenge to overcome is the need to know what to use the bi-directional controls for. If no use for that can be discerned then there is no reason to implement DT.

6
Conclusion

In summary, the integration of Digital Twin (DT) technology in a closed-loop supply chain can significantly enhance circularity. A closed-loop supply chain encompasses the entire process of delivering a product or service to the customer and reclaiming the products when they reach the end of their life cycle for reuse or recycling. When DT is implemented in specific segments of the closed-loop supply chain, it shows great potential by enabling efficient data collection and modeling of distinct physical processes, which can be more easily managed. However, integrating DT across the entire supply chain presents challenges. It requires extensive data collection and the development of numerous models, which is currently impractical for several reasons. Many organizations still rely heavily on human labor for their operations, making real-time data collection more challenging. In addition, not all supply chain assets have the corresponding digital models. DT technology depends on real-time data acquisition, and in a global supply chain, some assets are located in areas where bidirectional real-time data transfer is not feasible due to various constraints. Therefore, while DT can be highly effective when applied to individual assets within the supply chain, it may be more beneficial to utilize Digital Models for the entire supply chain. This approach allows for manual data collection from all assets and subsequent updates to their digital counterparts, facilitating real-world improvements based on enhanced data.

6.1 Future Research direction

To enhance the effectiveness of Digital Twins in both small assets and large network like supply chains, several key areas require attention in future research.

Standardization of Digital Twin Knowledge is an important step. Despite the longstanding concept of DT, there is a lack of uniform understanding and application among researchers and organizations. Establishing a standardized framework and common terminology for DT is crucial to make better communication, collaboration and implementation across various sectors.
Digital Integration of Industrial Processes is another big step. For DT to be fully effective, industries must advance towards digitalization of their entire processes. These include automatic data collection and the creation of digital models, which can significantly reduce the complexities and improve accuracy of DT application.
Transparency in Data collection from consumers would be an important way to add DT capabilities to products. When gathering data for purposes such as monitoring devices, organizations must be transparent with the consumers. They should clearly communicate

the types of data benign collected and the specific reasons for its collection. This transparency is essential to build trust among the customers, so that processes like monitoring and predictive maintenance can become more easy.
Lastly there needs to be a clear understanding of Digital Twin implementation. Organizations need to have a precise understanding of why they are adopting Digital Twin technology. Defining clear objectives and expected outcomes will help in aligning DT initiatives with business goals and ensuring that the technology is leveraged to its full potential.

7

Bibliography

Ashrafian, A., Pedersen, S., 2023. Digital Twin for Complex Logistics Systems: The Case Study of a Large-Scale Automated Order Picking and Fulfillment System. IFAC-Pap. 56, 11056–11061.
https://doi.org/10.1016/j.ifacol.2023.10.808

Attaran, M., Attaran, S., Celik, B.G., 2023. The impact of digital twins on the evolution of intelligent manufacturing and Industry 4.0. Adv. Comput. Intell. 3, 11. https://doi.org/10.1007/s43674-023-00058-y

Badakhshan, E., Ball, P., 2023. Applying digital twins for inventory and cash management in supply chains under physical and financial disruptions. Int. J. Prod. Res. 61, 5094–5116.
https://doi.org/10.1080/00207543.2022.2093682

Bähring, M., Gerlach, B., Tasche, L., 2023. Digital Supply Chain Twins in Urban Logistics System: Conception of an Integrative Platform. Teh. Glas. 17, 405–413.
https://doi.org/10.31803/tg-20230518081537

Banerjee, S., Das, D., Chatterjee, P., Ghosh, U., 2023. Blockchain-enabled Digital Twin Technology for Next-Generation Transportation Systems, in: 2023 IEEE 26th International Symposium on Real-Time Distributed Computing (ISORC). Presented at the 2023 IEEE 26th International Symposium on Real-Time Distributed Computing (ISORC), IEEE, Nashville, TN, USA, pp. 224–229.
https://doi.org/10.1109/ISORC58943.2023.00040

Batista, L., Bourlakis, M., Smart, P., Maull, R., 2018. In search of a circular supply chain archetype – a content-analysis-based literature review. Prod. Plan. Control 29, 438–451.
https://doi.org/10.1080/09537287.2017.1343502

Binsfeld, T., Gerlach, B., 2022. Quantifying the Benefits of Digital Supply Chain Twins—A Simulation Study in Organic Food Supply Chains. Logistics 6, 46.
https://doi.org/10.3390/logistics6030046

Borangiu, T., Răileanu, S., 2023. A smart palletising planning and control model in Logistics 4.0 framework. Int. J. Prod. Res. 61, 8580–8597.
https://doi.org/10.1080/00207543.2022.2154405

Busse, A., Gerlach, B., Lengeling, J.C., Poschmann, P., Werner, J., Zarnitz, S., 2021. Towards Digital Twins of Multimodal Supply Chains. Logistics 5, 25.
https://doi.org/10.3390/logistics5020025

Chabanet, S., Bril El-Haouzi, H., Morin, M., Gaudreault, J., Thomas, P., 2023. Toward digital twins for sawmill production planning and control: benefits, opportunities, and challenges. Int. J. Prod. Res. 61, 2190–2213.
https://doi.org/10.1080/00207543.2022.2068086

Cheng, J., Yang, Y., Zou, X., Zuo, Y., 2022. 5G in manufacturing: a literature review and future research. Int. J. Adv. Manuf. Technol.
https://doi.org/10.1007/s00170-022-08990-y

Damtew, A.W., 2024. Roles of digital twins on material performances and utilization on upstream industry (The case of automotive industry). Int. J. Adv. Manuf. Technol. 130, 3525–3536.
https://doi.org/10.1007/s00170-023-12706-1

De Angelis, R., Howard, M., Miemczyk, J., 2018. Supply chain management and the circular economy: towards the circular supply chain. Prod. Plan. Control 29, 425–437.
https://doi.org/10.1080/09537287.2018.1449244

Defraeye, T., Shrivastava, C., Berry, T., Verboven, P., Onwude, D., Schudel, S., Bühlmann, A., Cronje, P., Rossi, R.M., 2021. Digital twins are coming: Will we need them in supply chains of fresh horticultural produce? Trends Food Sci. Technol. 109, 245–258.
https://doi.org/10.1016/j.tifs.2021.01.025

Ekins, P., Domenech, T., Drummond, P., Bleischwitz, R., Hughes, N., Lotti, L., 2020. Managing Environmental and Energy Transitions for Regions and Cities. OECD.
https://doi.org/10.1787/f0c6621f-en

Figueiras, P., Lourenco, L., Costa, R., Graca, D., Garcia, G., Jardim-Goncalves, R., 2021. Big Data Provision for Digital Twins in Industry 4.0 Logistics Processes, in: 2021 IEEE International Workshop on Metrology for Industry 4.0 IoT (MetroInd4.0IoT). Presented at the 2021 IEEE International Workshop on Metrology for Industry 4.0 IoT (MetroInd4.0IoT), IEEE, Rome, Italy, pp. 516–521.
https://doi.org/10.1109/MetroInd4.0IoT51437.2021.9488507

Gelo, O., Braakmann, D., Benetka, G., 2008. Quantitative and Qualitative Research: Beyond the Debate. Integr. Psychol. Behav. Sci. 42, 266–290.
https://doi.org/10.1007/s12124-008-9078-3

Gerlach, B., Zarnitz, S., Nitsche, B., Straube, F., 2021a. Digital Supply Chain Twins—Conceptual Clarification, Use Cases and Benefits. Logistics 5, 86.
https://doi.org/10.3390/logistics5040086

Gerlach, B., Zarnitz, S., Nitsche, B., Straube, F., 2021b. Digital Supply Chain Twins—Conceptual Clarification, Use Cases and Benefits. Logistics 5, 86.
https://doi.org/10.3390/logistics5040086

Ghaboura, S., Ferdousi, R., Laamarti, F., Yang, C., Saddik, A.E., 2023. Digital Twin for Railway: A Comprehensive Survey. IEEE Access 11, 120237–120257.
https://doi.org/10.1109/ACCESS.2023.3327042

Greif, T., Stein, N., Flath, C.M., 2020. Peeking into the void: Digital twins for construction site logistics. Comput. Ind. 121.
https://doi.org/10.1016/j.compind.2020.103264

Guo, H., Han, Y., 2022. Research on Closed-Loop Supply Chain Based on Digital Twin, in: 2022 2nd International Conference on Algorithms, High Performance Computing and Artificial Intelligence (AHPCAI). Presented at the 2022 2nd International Conference on Algorithms, High Performance Computing and Artificial Intelligence (AHPCAI), IEEE, Guangzhou, China, pp. 270–273.
https://doi.org/10.1109/AHPCAI57455.2022.10087816

Guo, J., Lv, Z., 2022a. Application of Digital Twins in multiple fields. Multimed. Tools Appl. 81, 26941–26967.
https://doi.org/10.1007/s11042-022-12536-5

Guo, J., Lv, Z., 2022b. Application of Digital Twins in multiple fields. Multimed. Tools Appl. 81, 26941–26967.
https://doi.org/10.1007/s11042-022-12536-5

Han, Y., Shevchenko, T., Yannou, B., Ranjbari, M., Shams Esfandabadi, Z., Saidani, M., Bouillass, G., Bliumska-Danko, K., Li, G., 2023. Exploring How Digital Technologies Enable a Circular Economy of Products. Sustainability 15, 2067.
https://doi.org/10.3390/su15032067

Hu, B., Guo, H., Tao, X., Zhang, Y., 2023a. Construction of Digital Twin System for Cold Chain Logistics Stereo Warehouse. IEEE Access 11, 73850–73862.
https://doi.org/10.1109/ACCESS.2023.3295819

Hu, B., Guo, H., Tao, X., Zhang, Y., 2023b. Construction of Digital Twin System for Cold Chain Logistics Stereo Warehouse. IEEE Access 11, 73850–73862.
https://doi.org/10.1109/ACCESS.2023.3295819

Ivanov, D., 2023. Conceptualisation of a 7-element digital twin framework in supply chain and operations management. Int. J. Prod. Res.
https://doi.org/10.1080/00207543.2023.2217291

Ivanov, D., Dolgui, A., 2021. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. Prod. Plan. Control 32, 775–788.

https://doi.org/10.1080/09537287.2020.1768450

Jiang, H., Qu, T., Wan, M., Tang, L., Huang, G.Q., 2020. Digital-twin-based implementation framework of production service system for highly dynamic production logistics operation. IET Collab. Intell. Manuf. 2, 74–80.
https://doi.org/10.1049/iet-cim.2019.0065

Juarez, M.G., Botti, V.J., Giret, A.S., 2021. Digital Twins: Review and Challenges. J. Comput. Inf. Sci. Eng. 21, 030802.
https://doi.org/10.1115/1.4050244

Kaivo-Oja, J., Kuusi, O., Knudsen, M.S., Lauraéus, I.T., 2020. Digital twin: Current shifts and their future implications in the conditions of technological disruption. Int. J. Web Eng. Technol. 15, 170–188.
https://doi.org/10.1504/ijwet.2020.109730

Kenett, R.S., Bortman, J., 2022. The digital twin in Industry 4.0: A wide-angle perspective. Qual. Reliab. Eng. Int. 38, 1357–1366.
https://doi.org/10.1002/qre.2948

Ko, C.S., Lee, H., Kim, T., 2022. CONCEPTUAL MODELING FOR SUPPLY CHAIN DIGITAL TWIN. ICIC Express Lett. Part B Appl. 13, 495–501.
https://doi.org/10.24507/icicelb.13.05.495

Lam, W.S., Lam, W.H., Lee, P.F., 2023. A Bibliometric Analysis of Digital Twin in the Supply Chain. Mathematics 11, 3350. https://doi.org/10.3390/math11153350
Le, T.V., Fan, R., 2024. Digital twins for logistics and supply chain systems: Literature review, conceptual framework, research potential, and practical challenges. Comput. Ind. Eng. 187, 109768.
https://doi.org/10.1016/j.cie.2023.109768

Lee, D., Lee, S., 2021. Digital twin for supply chain coordination in modular construction. Appl. Sci. Switz. 11.
https://doi.org/10.3390/app11135909

Li, D., Li, J., 2024. Big data of enterprise supply chain under green financial system based on digital twin technology. Kybernetes 53, 543–556.
https://doi.org/10.1108/K-02-2023-0291

Liu, Y., Pan, S., Folz, P., Ramparany, F., Bolle, S., Ballot, E., Coupaye, T., 2023. Cognitive digital twins for freight parking management in last mile delivery under smart cities paradigm. Comput. Ind. 153, 104022.
https://doi.org/10.1016/j.compind.2023.104022

Lugaresi, G., Matta, A., 2023. Automated digital twin generation of manufacturing systems with complex material flows: graph model completion. Comput. Ind. 151, 103977.

https://doi.org/10.1016/j.compind.2023.103977

Lv, Z., Qiao, L., Mardani, A., Lv, H., 2022. Digital Twins on the Resilience of Supply Chain Under COVID-19 Pandemic. IEEE Trans. Eng. Manag. 1–12.
https://doi.org/10.1109/TEM.2022.3195903

Manickam, S., Yarlagadda, L., Gopalan, S.P., Chowdhary, C.L., 2023. Unlocking the Potential of Digital Twins: A Comprehensive Review of Concepts, Frameworks, and Industrial Applications. IEEE Access 11, 135147–135158.
https://doi.org/10.1109/ACCESS.2023.3338530

Melesse, T.Y., Pasquale, V.D., Riemma, S., 2020. Digital Twin Models in Industrial Operations: A Systematic Literature Review. Procedia Manuf. 42, 267–272.
https://doi.org/10.1016/j.promfg.2020.02.084

Moshood, T., Nawanir, G., Sorooshian, S., Okfalisa, O., 2021. Digital Twins Driven Supply Chain Visibility within Logistics: A New Paradigm for Future Logistics. Appl. Syst. Innov. 4, 29.
https://doi.org/10.3390/asi4020029

Mügge, J., Grosse Erdmann, J., Riedelsheimer, T., Manoury, M.M., Smolka, S.-O., Wichmann, S., Lindow, K., 2023. Empowering End-of-Life Vehicle Decision Making with Cross-Company Data Exchange and Data Sovereignty via Catena-X. Sustainability 15, 7187.
https://doi.org/10.3390/su15097187

Mügge, J., Seegrün, A., Hoyer, T.-K., Riedelsheimer, T., Lindow, K., 2024. Digital Twins within the Circular Economy: Literature Review and Concept Presentation. Sustainability 16, 2748.
https://doi.org/10.3390/su16072748

Nicoletti, B., Appolloni, A., 2024. A framework for digital twins solutions for 5 PL operators. Technol. Soc. 76, 102415.
https://doi.org/10.1016/j.techsoc.2023.102415

Opoku, D.-G.J., Perera, S., Osei-Kyei, R., Rashidi, M., 2021. Digital twin application in the construction industry: A literature review. J. Build. Eng. 40.
https://doi.org/10.1016/j.jobe.2021.102726

Pan, Y.H., Qu, T., Wu, N.Q., Khalgui, M., Huang, G.Q., 2021. Digital Twin Based Real-time Production Logistics Synchronization System in a Multi-level Computing Architecture. J. Manuf. Syst. 58, 246–260.
https://doi.org/10.1016/j.jmsy.2020.10.015

Preut, A., Kopka, J.-P., Clausen, U., 2021. Digital Twins for the Circular Economy. Sustainability 13, 10467.

https://doi.org/10.3390/su131810467

Qiu, F., Chen, M., Wang, L., Ying, Y., Tang, T., 2023. The architecture evolution of intelligent factory logistics digital twin from planning, implement to operation. Adv. Mech. Eng. 15, 16878132231198339.
https://doi.org/10.1177/16878132231198339

Royo, B., Politaki, D., Gonzalez, J.N., Batalla, A., 2023. Digital Twin opportunities and benefits in last-mile logistics for Madrid value case. Transp. Res. Procedia 72, 1693–1699.
https://doi.org/10.1016/j.trpro.2023.11.642

Shoji, K., Schudel, S., Shrivastava, C., Onwude, D., Defraeye, T., 2022. Optimizing the postharvest supply chain of imported fresh produce with physics-based digital twins. J. Food Eng. 329.
https://doi.org/10.1016/j.jfoodeng.2022.111077

Singh, G., Singh, S., Daultani, Y., Chouhan, M., 2023. Measuring the influence of digital twins on the sustainability of manufacturing supply chain: A mediating role of supply chain resilience and performance. Comput. Ind. Eng. 186, 109711.
https://doi.org/10.1016/j.cie.2023.109711

Singh, M., Fuenmayor, E., Hinchy, E., Qiao, Y., Murray, N., Devine, D., 2021. Digital Twin: Origin to Future. Appl. Syst. Innov. 4, 36.
https://doi.org/10.3390/asi4020036

Sipola, T., Kokkonen, T., Puura, M., Riuttanen, K.-E., Pitkäniemi, K., Juutilainen, E., Kontio, T., 2023. Digital Twin of Food Supply Chain for Cyber Exercises. Appl. Sci. 13, 7138.
https://doi.org/10.3390/app13127138

Széchenyi István University, Győr, Hungary, Monek, G.D., Fischer, S., Széchenyi István University, Győr, Hungary, 2023. DES and IIoT fusion approach towards real-time synchronization of physical and digital components in manufacturing processes. Rep. Mech. Eng. 161–174.
https://doi.org/10.31181/rme040115092023m

Upadhayay, S., Alqassimi, O., 2018. Transition from Linear to Circular Economy. Westcliff Int. J. Appl. Res. 2, 62–74.
https://doi.org/10.47670/wuwijar201822OASU

Vilas-Boas, J.L., Rodrigues, J.J.P.C., Alberti, A.M., 2023. Convergence of Distributed Ledger Technologies with Digital Twins, IoT, and AI for fresh food logistics: Challenges and opportunities. J. Ind. Inf. Integr. 31, 100393.
https://doi.org/10.1016/j.jii.2022.100393

Virlanuta, F.O., David, S., Manea, L.D., n.d. THE TRANSITION FROM LINEAR ECONOMY TO CIRCULAR ECONOMY: A BEHAVIORAL CHANGE.

Wang, L., Deng, T., Shen, Z.-J.M., Hu, H., Qi, Y., 2022. Digital twin-driven smart supply chain. Front. Eng. Manag. 9, 56–70.
https://doi.org/10.1007/s42524-021-0186-9

Wang, X., Hu, X., Wan, J., 2024. Digital-twin based real-time resource allocation for hull parts picking and processing. J. Intell. Manuf. 35, 613–632.
https://doi.org/10.1007/s10845-022-02065-1

Winkelmann, S., n.d. Openness Of Digital Twins In Logistics ± A Review.

Wu, Y., Zhang, J., Li, Q., Tan, H., 2023. Research on Real-Time Robust Optimization of Perishable Supply-Chain Systems Based on Digital Twins. Sensors 23, 1850.
https://doi.org/10.3390/s23041850

Yang, F., Gu, S., 2021. Industry 4.0, a revolution that requires technology and national strategies. Complex Intell. Syst. 7, 1311–1325.
https://doi.org/10.1007/s40747-020-00267-9

Zarnitz, S., Straube, F., Nitsche, B., 2023. Digital Supply Chain Twins for Sustainable Planning of a Logistics System, in: Kohl, H., Seliger, G., Dietrich, F. (Eds.), Manufacturing Driving Circular Economy, Lecture Notes in Mechanical Engineering. Springer International Publishing, Cham, pp. 68–76.
https://doi.org/10.1007/978-3-031-28839-5_8

Zhang, M., Yang, W., Zhao, Z., Pratap, S., Wu, W., Huang, G.Q., 2024. Correction: Is digital twin a better solution to improve ESG evaluation for vaccine logistics supply chain: an evolutionary game analysis. Oper. Manag. Res. 17, 387–387.
https://doi.org/10.1007/s12063-023-00419-3

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