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Supply chain Digital twins: Foundations and Implications for Business Model Innovation

TESI DI LAUREA MAGISTRALE IN
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Abstract

Supply chain networks are becoming increasingly complex and strategic due to technological breakthroughs. Digital connectivity, computing power, and manufacturing automation enable autonomous, self-organizing, and integrated systems linked together via seamlessly connected supply networks. The next order of industries – I4.0 is formed on the foundations of digital technology. In turn, the tech advancements change the picture of supply chain operations, expectantly getting multi-fold.

The two-decade long advancements in conceptualizing virtual, digital equivalent to a physical product have led to the Digital Twin becoming an interesting and potentially useful concept. The Supply chain digital twin is a software-driven transformation that combines hardware, software, and data to drive the optimum design and operation of a product or service. Digital twins provide real-time and remote monitoring of Supply chain and associated risks and are powerful data-driven tools and control towers for businesses. They can be used to reconfigure the supply chain design in the light of anticipated disruptions, leading to better decisions in a risk-riddled world.

Nevertheless, this digital transition creates new organizational models and influences relationships in supply chains, thus affecting structural changes in business models. The value propositions that companies offer to clients/customers must also be reviewed in light of these developments because the digitization of Supply network characterizes a more customer centric business approach. The need to think carefully about how to provide new products and services while also capturing profit from doing so has been heightened by this new environment. Therefore, the major drivers and barriers that would be faced in terms of implementing Supply chain digital twin industry wide, and the organizational transformations that are brought about, are further presented in this research paper.

Keywords: Supply chain, Digital transformations, Digital Twin, decision-making, disruption management, Business model innovation.

Abstract in lingua italiana

Le reti della catena di approvvigionamento stanno diventando sempre più complesse e strategiche grazie ai progressi tecnologici. La connettività digitale, la potenza di calcolo e l'automazione della produzione consentono di creare sistemi autonomi, auto-organizzati e integrati, collegati tra loro da reti di fornitura senza soluzione di continuità. Il prossimo ordine di industrie - I4.0 - si forma sulle fondamenta della tecnologia digitale. A loro volta, i progressi tecnologici cambiano il quadro delle operazioni della supply chain, che si prevede diventi molteplice.

I progressi di due decenni nella concettualizzazione dell'equivalente virtuale e digitale di un prodotto fisico hanno portato il gemello digitale a diventare un concetto interessante e potenzialmente utile. Il gemello digitale della supply chain è una trasformazione guidata dal software che combina hardware, software e dati per guidare la progettazione e il funzionamento ottimali di un prodotto o di un servizio. I gemelli digitali forniscono un monitoraggio in tempo reale e a distanza della Supply chain e dei rischi associati e sono potenti strumenti basati sui dati e torri di controllo per le aziende. Possono essere utilizzati per riconfigurare il design della supply chain alla luce delle interruzioni previste, portando a decisioni migliori in un mondo pieno di rischi.

Tuttavia, questa transizione digitale crea nuovi modelli organizzativi e influenza le relazioni all'interno delle catene di fornitura, influenzando così i cambiamenti strutturali nei modelli di business. Anche le proposte di valore che le aziende offrono ai clienti devono essere riviste alla luce di questi sviluppi, perché la digitalizzazione della rete di fornitura caratterizza un approccio aziendale più incentrato sul cliente. La necessità di riflettere attentamente su come fornire nuovi prodotti e servizi e allo stesso tempo trarne profitto è stata accentuata da questo nuovo ambiente. Pertanto, in questo documento di ricerca vengono presentati i principali driver e le barriere che si dovrebbero affrontare in termini di implementazione del gemello digitale della supply chain a livello industriale e le trasformazioni organizzative che ne derivano.

Parole chiave: Supply chain, trasformazioni digitali, Digital Twin, processo decisionale, gestione delle interruzioni, innovazione dei modelli di business.

Contents

1. Introduction

1.1 Motivation and Problem Statement

Supply chain network, spanning multiple business sectors are crucial to the global company and for the progression of day-to-day life alike (MacCarthy et al., 2016). Moreover, Supply chain operations are moving on to become more extensive, with number of parties that are involved to the level of visibility throughout the supply network. Mapping out supply chains are not only getting more and more complex by each second ahead, but also strategic with the technological breakthrough over the years. From being able to define market to determine prospects for future, supply chain and supply chain planning is crucial.

Also, given the fact that the recent times are a testimony to the statement **'innovation at each turn'**, wave after wave of disruptive technologies, that are turning the wheels to driving higher degrees of digital maturity. With the enhanced *"digital connectivity, computing power, and manufacturing automation"* (Srai et al., 2019) enables *"autonomous, self-organizing, and integrated systems linked together via seamlessly connected supply networks"* (Srai et al., 2019). New applications are emerging from the integration of real and virtual space, finding roots from intensive research and development of digitization (Paiola & Gebauer, 2020). Future industry leadership positions are ultimately determined by key digital decisions to scale and in adopting new technology.

Especially, the concepts including *'self-thinking supply chains'* (Srai et al., 2019) from the academic literature imply that the generation of a sizable amount of data through *'connected, sensing items is sufficient to make precise forecasts and act autonomously'* outside the purview of individual enterprises (van der Valk et al., 2022). Furthermore, Digitization is at the forefront of transforming everything, especially supply chain (Björkdahl, 2020). Digital transformations are therefore shifting Business paradigms. It is redefining established businesses and creating new business ventures.

The two-decade long advancements in conceptualizing virtual, digital equivalent to a physical product or the Digital Twin - Virtual products are rich representations of products that are virtually indistinguishable from their physical counterparts (Y. Wang et al., 2020). Given these advances, it is timely to explore how the Digital Twin can move from an interesting and potentially useful concept – that has enormous untapped potential especially in the field of Supply chain. Also, Taking the context of globalization, the process of value creation is becoming more complex, exposed to greater risks for companies, partners, and customers. Moreover, modern digital technologies, such as the use of digital twin technology, can increase the use of geographically dispersed work teams and contribute to value creation. However, *"the digital transition creates new organizational models and influences relationships in supply chains, thus affecting structural changes in business models"* (Koilo, 2022).

The present status industrywide demonstrates that Systems and products can be linked in a network, resulting in changes in the Supply Chain as well as the business model (Grieves, 2015). Therefore, to expect and forestudy the possible changes, especially from how business models could be transformed with such Supply chain digital twin and to establish a system inclusive of identifying the requirements and characteristics is undertaken in the study. New value propositions stem from *"new products"* and *"services can be stimulated by industrial IoT and emerging technologies"* (F. Li, 2020). And how these emerging technologies such as Supply chain Digital Twin acting as catalysts to drive digitization, what are the implications that come with the change? What would it be in the face of a society that is driven by data? The major drivers and barriers that would be faced in terms of implementing Supply chain digital twin industry wide, is further studied from an array of research articles and White papers.

1.2 Research Objective

The concept of Digital twins, though at its earlier stage has been involved in many manufacturing to life cycle management tracking to supply chain planning processes. However, considering supply chain perspective digital twins offer Real-time transparency across the entire supply network, including available capacities, disruptions, and process status information, Data Analysis - Predictions on forthcoming prospects of the system, for example, upcoming disruptions and capacity constraints and Extensive Decision Support - Process optimization by aiding in decision support for planning and handling of disruptions.

In the supply chain process, a digital twin can depict manufacturing machines, module components, transportation, warehouses, delivery trucks, assembly workers, and crane (Manca et al., 2021). The technology aids to visually monitor the projects/processes current condition and progress. A digital twin is a simulation and thorough representation of the system used to comprehend performance metrics, improve workflows, and significantly improve value-added operations (Sleiti et al., 2022).

Therefore, considering these capabilities of supply chain digital twin, it would be an interesting standpoint to view how such a technology *"with capabilities assumedly available in specialized Supply Chain Network Design and simulation"* (Neto et al., 2020) would transform supply chain, which in turn aids to develop new business strategies and business models (Abdelkafi & Pero, 2018).

The study spans to cover the business arena transformations that connects Supply chain digital twin and Business model innovation, presenting key findings under the following research questions:

RQ1: what are the foundations of Supply chain Digital Twin ?

RQ2: What are the Implications of Supply chain Digital Twin for Business Model Innovation?

The first research question asserts on the technologies and advancements, formulates a landscape in drawing out both requirements and barriers of Supply chain digital Twin. The second question posts the objective of the research, in exploring the how the Supply Chain digital Twin transforms, by extension innovates business model. The research study is conceptual in nature, extracting from vast available literature especially research articles and journals.

1.3 Research Procedure

Data gathering to data compiling is primary in conducting an academic study. The research procedure, thus comprises from

- What drives the recent business sectors – spotlighting supply chain organisations and supply chain concerned parties, in identifying opportunities to improve in a bolder manner of operations that genuinely embraces the prospects provided by cutting-edge technology capabilities.
- Aspects from a market perspective, especially the high and low-tide caused by any disruption similar to the 2020-Pandemic.
- Activities that transform the structure of both – intra and inter-organisations.

Thus, the study is materialised into the following sections:

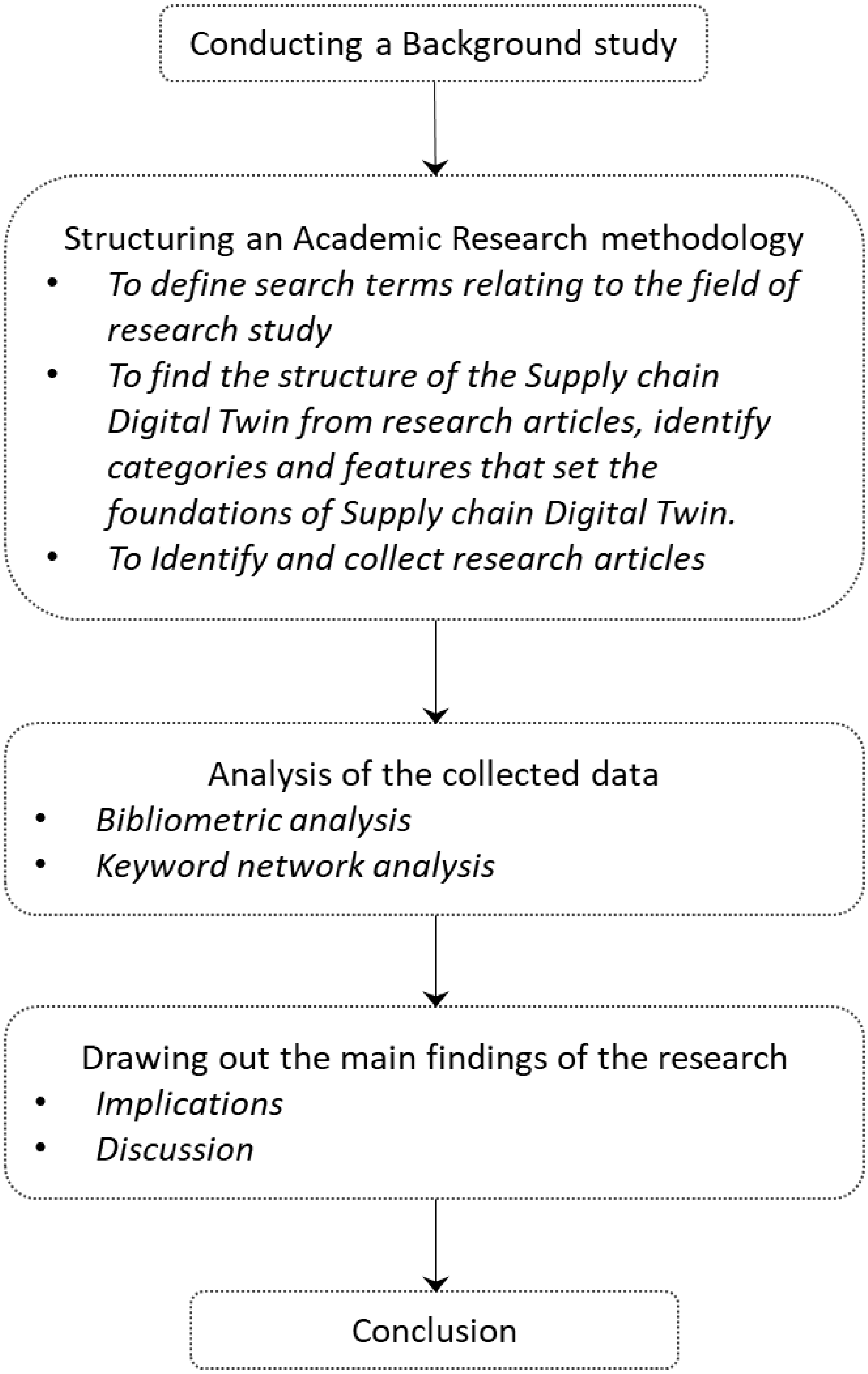

Figure 1.1: Research Procedure

2. Litrature Background

2.1 Supply Chain and Supply Chain Management

The supply chain is a vast, complex, intricate network of different, autonomous, and connected businesses that collaborate to produce value for customers (Esfahbodi et al., 2023). **Supply chain planning** is not only about ensuring structural comprehensiveness, responsiveness and flexibility but also about the assistance in eluding incoherency and non-consistencies in the operations (Assumpção et al., 2022). The group of entities involve in the design and development of new goods and services, the acquisition of raw materials, the transformation of those resources into semifinished and finished goods, and the delivery of those goods to the final consumers (Badakhshan et al., 2022). These intricate yet complex global network of structures - organizational, informational, procedural, financial, and energy ones, make up supply chains (Rad et al., 2022).

In the real world of supply chains, the maker/owner/manufacturer/producer works in tandem with its customers and suppliers to develop new products and product lines while also collaborating with them throughout the whole product life cycle (Ivanov & Dolgui, 2019). Thus, Customers, suppliers, and a supply chain owner are all involved in supply chain management. A genuine supply chain environment and a virtual alliance/partnership environment make up the organizational structure. Therefore, the necessity of taking supply chains into account on multiple levels, as the structures age, changes in one structure may result in changes in the others. As it is evident that *"Supply chains are multi-structurally dynamic"* (Ivanov et al., 2010).

Another aspect of the industry sector in the present and near future, is that customer demand and business operation become more diversified. The corporate environment in the Supply Chain tends to be more complex, which puts forward higher requirements for the planning, management, and control of each echelon in Supply Chain. It is necessary to develop an integrated Supply Chain to promote deep business integration and value chain reshaping in all echelons of the Supply Chain.

Supply chain management thus, encompasses these networks of organizations that are either involved directly or indirectly, in various processes and transactions or forms, "*integrated into a connected chain of actions*" (Voipio et al., 2022), responsible for planning, monitoring, and controlling a Supply Chain. Additionally, Supply chain management also concerns the functions of finance and marketing the product to the market, distribution and management of returns, and customer service, spanning across and within each company or organization (Ivanov et al., 2017).

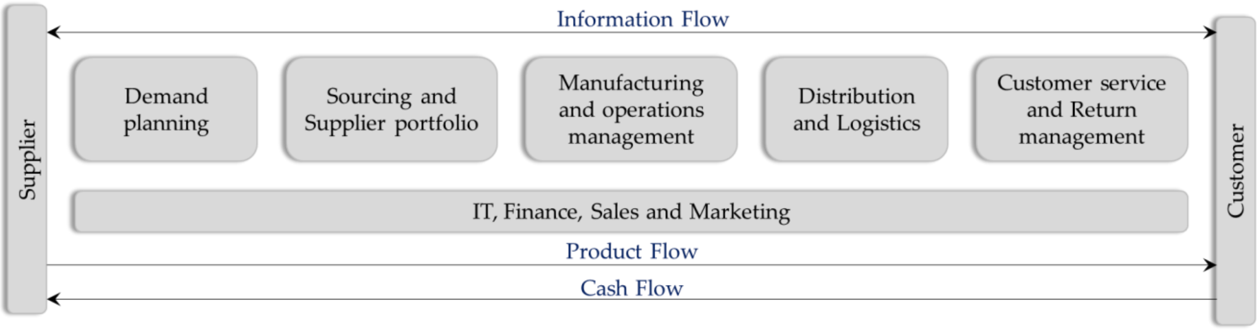

Figure 2.1: Basic schematic of Supply chain Flow

Supply chain management cuts across a number of geographical and functional domains. This adds complexity to the supply chain design and implementation. Especially considering the Globalization scenario, there is an increasing complexity of supply chains, especially to cater to the ever-changing customer behaviour and extended cross-border economic integration of companies (Busse et al., 2021). As well, supply chain environments are becoming more dynamic and unpredictable as a result of factors such as product demand, product variety, and product life cycle.

Consequently, Companies are required to implement supply chain strategies to overcome volatile environments in order to improve their market competitiveness (Maddikunta et al., 2022; Nguyen et al., 2022). An important part of Supply Chain Management thus, thereby encompasses :

2.1.1 Supply chain Strategy:

Supply Chain strategy, relating to the way that a company manages the issues concerning the product sourcing, predictability, raw material conversion, demand management, the communication with other actors involved in the supply chain, and the delivery of products and services especially in terms of demand and capacity management between and among the companies (Dolgui et al., 2020). The supply chain management strategies used by businesses directly affect a number of regular consumer interactions.

Supply Chain strategies describe the objectives and goals and reflect the character of Supply Chains. Strategies are directed to impact the product-market dynamics such as "*product demand, product variety and product life cycle* (Hallavo, 2015)". When considering the SC Strategies, two of the most used and well-known strategies:

Fisher's Model: The models take into account the product attributes to define the strategy of the SC. This model places a product into either functional or innovative, thus, matching it with efficient SC strategy or responsive SC strategy, respectively.

Hau Lee's Model: This model takes into account both the supply-side and demand-side characteristics in determining SC strategy. Also, this model outlines the Supply-side processes to match with the demand volatility to help find a way to dynamically change SC strategies as necessary. Thus, conceptualising four different SC strategies namely: Lean Supply Chain, Risk Hedging Supply Chain, Responsive Supply Chain and Agile Supply Chain.

These SC strategies resonate according to the market dynamics and scale up to transform the organisations' way of business conducts; a few of the factors affecting the SC strategies and SC transformations are listed as follows:

Table 2.1: Supply Chain Strategy

Operations	Market requirement	SC strategy	Business practices stemming from SC strategy
Manufacturing	Mass customisation	Shifting customisation at the end	Smart manufacturing, Additive manufacturing
		Altering the operations to Make-to-order, design-to-order, etc	
Logistics	Sustainable practices	Circular Supply chain	Digital Platforms
	Last mile	Locker services, Delivery-as-a-service, On demand delivery	
Material Handling	Capability to handle multiple products with multiple requirements, in a faster pace	Robotic handling and Automated systems	3PL exclusively to support in managing ERP systems, Control tower, TMS

2.1.2 Supply chain in Industry 5.0

The topic of Industry 5.0 (I5.0) although nascent, is still paramount. Recent surmising state that some of the researches are already debating this brand-new revolutionary phenomenon. Industry 5.0 is the period of the social smart factory because every component of a CPPS (cyber-physical production systems) is about developing communication with people through the corporate social networks, while Industry 4.0 lays the groundwork for the smart factory (Le et al., 2022).

Industry 5.0 encompasses numerous up and coming technologies, combined with the imagination and creativity of people, with the power of sophisticated, accurate, and precise machinery (Maddikunta et al., 2022). Industry 5.0 is anticipated to benefit from a such a variety of these promising technologies and applications, that will enable enhanced production and quicker delivery of customised products (X. Wang et al., 2021). Supply chain management is auxiliary in I5.0 in integrating of deliverables to the customer (Ivanov & Dolgui, 2021).

As a matter of fact, when disruptive technologies like Digital Twin, cobots, 5G and beyond, and IoT are combined with human ingenuity and intelligence, the sectors would quickly fulfil customer demand and create individualised and customised products and services (Glatt et al., 2021). **Cobots** have a significant potential in Supply chain management, as they are capable of carrying out mundane/dangerous tasks like packaging, routine quality checks, transporting heavy goods, etc. without human intervention at all, whilst human expertise can be used for more complicated and thoughtful tasks (Maddikunta et al., 2022).

All supply chain actors should be able to perceive interruptions and receive instructions in real-time, is a necessity in the futuristic Supply chain management (Palkina, 2022). Therefore, Automation in the arena of data administration is crucial for businesses that rely on data to make decisions, like pricing and/or inventory planning (Ghosh et al., 2021).

Supply Chain Management thus, proceeds to extend cooperative administration within the value chain, as numerous companies are moving forward with key partnerships through the supply chain . More recently, organizations are outsourcing the operations that are deemed as their "non-special" (Holopainen et al., 2022) to third-party companies and work around their competitive operations.

The Literary observations make it clear that Supply chain management is projected to become more complex and complicated, with the development from technological trends of smart manufacturing, on-demand manufacturing extending to *"public partnership in the designing and marketing process"*(Rahmanzadeh et al., 2022), *"product customization and personalization"* (Blecker & Abdelkafi, 2006) in the recent past.

2.2 Supply Chain and Digitalization

Primary concerns in Supply chains operations are -*"enable recovery and adaptation"* (Marmolejo-Saucedo, 2020) when the supply chains are exposed to and impacted by changes in operational and environmental conditions. One such important and developing development is the digitalization of businesses and society.

"Digitization is disrupting the way organizations collaborate and compete, leading to the development of new collaborative value creation networks such as digital business ecosystems" (Suuronen et al., 2022a). Digitalization can give competitive advantage new dimensions. For instance, incorporating personal data from smart manufacturing, such as weight, health, exercise, and emotional status, can assist from creating models to comprehend worker circumstances and personal well-being. This can aid in the development of human-centred, human-machine collaboration techniques.

In extension, Digitalization makes it possible to share product or service information, and combine internal and external information, allowing for the creation of new services and the maintenance of existing ones (Lee & Lee, 2021). Moreover, Digitization allows for the decentralised delivery of *"relevant information"* to the *"right actor at the right time"* (Preut et al., 2021). An organization can fill important resource shortfalls by taking advantage of network linkages. Digital platforms generally have the capacity to restructure industries, leading to effective ecosystems and reduced production costs (Santos et al., 2020).

The possibility of obtaining a better forecast considerate of the dynamic functioning of the Supply chain is now, made possible through digitalization. The futuristic scenarios, especially in Industry 4.0 and the advanced Industry 5.0 (Adel, 2022), is primarily driven by digital transformation, which develops digitalized, networked, intelligent supply chains and logistics. It is apparent that nations and logistics companies need to get a competitive advantage in terms of digitalization in order to be relevant in global supply chains (Abideen, Sundram, et al., 2021).

Digital technology innovations have an impact on the creation of new paradigms, principles, and models in Supply chain management, including the likes of :

- **Optimization and simulation models** can generate significant insights at the proactive level, which can be deployed in situations where the likelihood of a disruption can be roughly predicted (T. Deng et al., 2021).
- The sophisticated **trace and tracking systems** and big data analytics may aid in disruption prediction and provide more precise data to create complex resilient supply chain architecture for such scenarios (Ivanov & Dolgui, 2019). Through real-time coordination in the activation of contingency measures, advanced trace and tracking systems may simplify integrated Supply Chain planning and reduce supply and time risks.

- **Big data analytics**, for instance, may lower supply and demand risks through improved Supply Chain visibility and forecast accuracy, a decrease in the risk of information disruption, and better quality of contingency plan activation (Putz et al., 2021).
- Supply Chains, taking the example of pandemic-2020, has a necessity to be guarded against impending interruptions utilizing techniques like risk mitigation inventories, capacity reservations, and backup sources. Particularly when disruptions do not occur for extended periods of time, such treatments are expensive and challenging to justify. By keeping a record of actions and the data required for recovery in terms of synchronized contingency plans, **blockchain systems** could help to decrease these inefficiencies (Bhandal et al., 2022).
- The decentralized control principles in the upcoming manufacturing systems make it possible to diversify risks and reduce the need for structural Supply Chain redundancy through *"digitalised information sharing"* (Ivanov et al., 2021), to improvise flexibility and capability utilisation (Gasparin et al., 2022).

The phrase "digital supply network," describes the increasing possibility of reaching a network of partners, describes how many supply chains today are evolving from a static sequence into a dynamic, interconnected system and eventually changing to a more ideal state (Barykin et al., 2020). Digital supply networks make it possible to regulate the physical manufacturing and distribution process by combining data from various sources and locations (Pan et al., 2021).

Digital technology may have a substantial impact on Supply chains' performance in terms of agility, adaptability, and alignment. The Digitization of operations, however, requires the implementation of various technologies that improve an organization's ability to collect, combine, process, and use business data. Digital transformation is widely recognized as a major technological revolution ushering in a new economic paradigm that will affect industry structure, interactions with consumer demand, and the rules of competition (Battistoni et al., 2023; Ivanov et al., 2017).

2.3 Digital Twin

The Digital Twin is an emerging paradigm focusing on an Industrial/Enterprise asset – usually, a system, product, or process, along its lifecycle. The idea of a "Digital Twin" was first developed in the framework of **Product Lifecycle Management (PLM)** ***in 2002 at the University of Michigan*** (Manca et al., 2021). Its foundation is the notion that a digital information model about a real or a physical system could be developed as a **standalone entity** (Sleiti et al., 2022). This digital data would be a "twin" of the data stored internally in the physical device. Through the course of their complete life cycle, the two are closely bonded and change together.

In fact, the main objective is to virtually model the systems as identical as possible to the physical assets. Although, the concept of the digital twin gained increasing attention over the past decade, there is no consistent definition for the term digital twin.

2.3.1 Development of definition of Digital Twin:

i. 'A digital twin is a detailed simulation model of a real-world entity or system which uses real-time data to predict its dynamics and enable understanding, learning, and reasoning' (Preut et al., 2021).
ii. 'Digital twin technology involves building virtual clones of the things or processes that imitate its behaviour, in order to study an object's efficacy or behaviour, or in some situations, to improve it' (Marmolejo-Saucedo, 2020).
iii. 'Digital twin is a technology used in virtual model simulation technology to explore and anticipate the unknown world, develop better ways to inspire human innovation, and pursue optimal progress' (Chen & Huang, 2021).
iv. 'A digital twin is made up of a physical element, a virtual element, and associated data that connects the two elements and enables self-evolution, interaction, and reflection in real time' (Cirullies & Schwede, 2021).
v. 'The term "Digital Twin" describes the description of a part, product, or system by a group of coherent executable models linked to a collection of pertinent digital artefacts, such as engineering data, operational data, and behavioural descriptions via various simulation models' (Horváth et al., 2018).
vi. A collection of virtual information constructs that completely describe a prospective or real physical product, system, *or process from the micro to the macro level* (Manca et al., 2021) is also one another way of defining a digital twin.

Furthermore, the Digital Twin describes operational states, which are gathered from sensors and current, past, and future data. Additionally, it integrates sensor data, fleet (historical) data, and further data that describe a physical object. In fact, a Digital Twin shows considerable similarities to simulation approaches. Nevertheless, an in-depth analysis shows that simulation approaches and Digital Twins are related but not the same concept (van der Valk et al., 2022).

Therefore, the idea centres around - Digital twin technology creating a relatively close connectivity between both the virtual and physical worlds, to monitor and command systems and components remotely. Also extending the functionalities to run simulation models to test and forecast resource and process-related changes in various "what-if" (Marmolejo-Saucedo, 2020; Neto et al., 2020) scenarios. Hence, organizations are now getting significant benefits from digital twin technology that assists in mapping and analysing details related to operations performance, product, and service innovation, and shorter on time delivery (Abideen, Sundram, et al., 2021).

Digital twins, which are virtual replicas of physical entities and their interactions, encompasses all the enabling technologies and analytics capabilities. However, the technology could be misunderstood that the digital twins are themselves sensors, 3D models, simulators, or applications of AI technology.

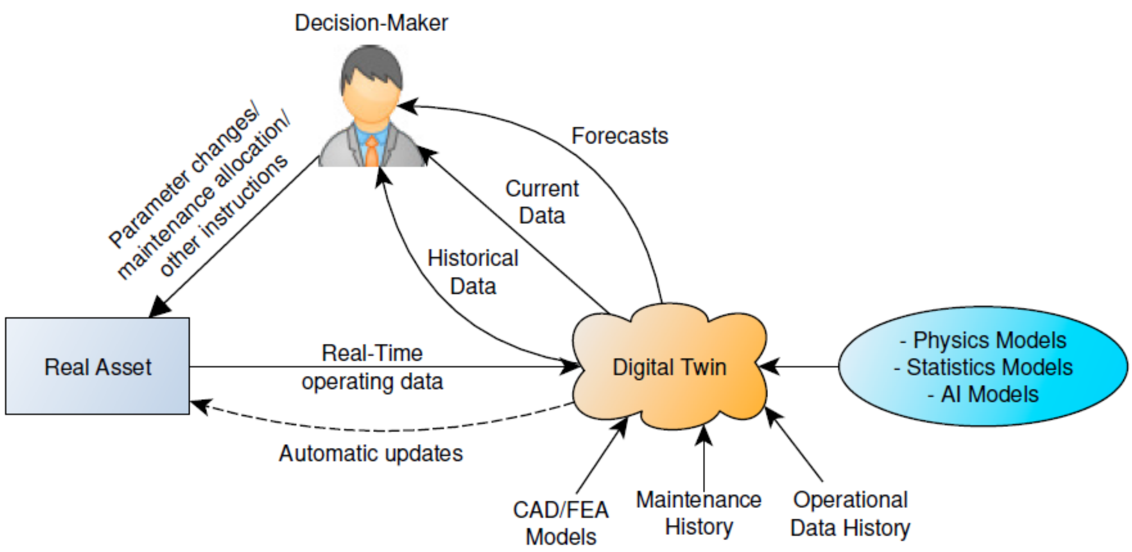

Figure 2.2: Basic schematic of Digital Twin (source Santos et al., 2020)

Several enabling technologies, including sensors, cloud computing, AI and advanced analytics, simulation, visualization, and augmented and virtual reality, are combined to create digital twins. Depending on their requirements and expectations, businesses can deploy a customized combination of technology (Liotine, 2020). The ability of digital twins to emulate human talents, support essential decision-making, and even make decisions in place of humans is what sets them apart and gives them such power (Kohtamäki et al., 2022).

2.3.2 Digital Twin – In Supply chain Management:

Digital twins interact with people, objects, and other networked digital twins to learn from this information and its contexts as well as to observe their physical environment using a network of sensors (Chen & Huang, 2021) that dynamically collect real-time data (Burgos & Ivanov, 2021). Since they may constantly communicate and work together with their connected physical and digital things as well as with people thanks to this capability, digital twins are active and social tools (M. Deng et al., 2021). Through **end-to-end visibility and traceability** supported by digital twins, supply chain analysts are able to identify patterns of extremely complex and dynamic behaviour (Bertoni & Bertoni, 2022).

Digital twins can create nonlinear supply chain models and keep track of numerous internal and external moving pieces in end-to-end supply chains (Y. Wang et al., 2020). More importantly, the technology learns from these choices and develops over time thanks to their capacity to calculate thousands of **what-if scenarios** (Chen & Huang, 2021). The dynamic nature of digitalization needs studies that may assist analysis, understanding, and investigation of its drivers, facilitators, and performances, such outcomes could range from time to competitiveness to risk management and resilience (Dolgui et al., 2020). As a result, managers are able to make decisions that have a significant influence over the long term at a far reduced cost (Julien & Martin, 2021).

A digital replica in the supply chain starting from the manufacturer to all the parties', warehouses, inventory positions, assets, and logistics can be created using Digital Twin (Barykin et al., 2020). The distribution facilities, customer locations, transportation lanes, factories, suppliers, contract manufacturers, factories, and transportation lanes are all included in the Digital Twin. Digital Twin assists throughout the Supply Chains entire lifecycle (Kamble et al., 2022), from the design phase through construction, commissioning, and operations.

Digital Twin is equipped with the ability to detect data from IoT sensors in the real world by simulating real-time Supply Chain Management systems. Big data, Machine Learning, etc. can make use of these data to anticipate issues that will arise during various Supply Chain phases (Brintrup et al., 2021; Ivanov & Dolgui, 2021). As a result, industries can take preventative measures to reduce losses and errors during various Supply Chain phases and assist in quickly delivering customized products to customers.

3. Research Methodology

3.1 Systematic Literature Review

In conducting an explorative study to understand 'Supply chain digital Twins', the starting point is a *"systematic literature review based on the framework of Webster and Watson"* (van der Valk et al., 2022). Systemic Literature review is a methodological approach to *"review, identify and synthesize the complete research available on research topic"* (X. Wang et al., 2021).

The Systematic Literature Review:

(i) incorporate all the points of interest fundamental to carry out future research that can replicate or amplify the study (Karagiannis et al., 2022);
(ii) seek to summarise research studies pertaining to a specific research question in a fair, rigorous, and auditable manner (Niemeyer et al., 2022);
(iii) allows to also, focus on a subset of studies in this chosen field based on availability and/or author preference (Parmar et al., 2020).

A systematic literature review on supply chain digital twin involves a comprehensive analysis and synthesis of the existing research on the topic, aiming to identify the key themes, trends, and research gaps related to the implementation and impact of digital twin technology in supply chain management. Furthermore, the research study aims at developing a systematic search strategy to identify relevant sources of information. This could involve searching online databases, academic journals, conference proceedings, and industry reports using keywords related to supply chain digital twin.

The significance of the Supply chain Management will continue to extend within the future (Suuronen et al., 2022b). The current status and advancement, moreover, embroils an expanding curiosity in the combination of Supply chain Management and the concept of the Digital Twin (Kamble et al., 2022). The study is concentrated on exploring about the Digital Twins and the transformation that the technology requires, and the advancement that is begotten out of it. This study aims to narrate on the incidence of business model innovation resulting from supply chain. This study interprets Business Model Innovation to specifically refer to innovation in company structures and processes that offer new ways of creating and extracting value (Martins et al., 2015).

The studies analysed are, primarily verified for the connection to the development and central to the ideation of Supply chain digital twin. Moreover, the digitalization is an observed trend that is in fact an enabling factor to the Supply chain Digital twin. Not only the nurturing factors, but the study explores the cases of barriers and challenges in the face of implementing the technology. Following that, Research had been carried out to draw out conclusions on the insights that connect the technology of Supply chain digital twin with the business model transformation.

3.1.1 Defining the Search term:

The search term definition is the primary step in the explorative study as the study is set in outlining the academic articles and research journals in the field of Supply chain and Digital twin. Moreover, the primary goal was set to identify as many recent studies as possible, as to also note the directions and scope involved with respect to Supply chain.

The keywords were found after a thorough search of academic and practice-based works on digital twins to identify the terminology that authors used while discussing the subject: *" Supply chain" and "Digital Twin"* and *"Supply chain digital twin".* In particular, a supply chain digital twin refers to a virtual version that represents a supply chain network and its components, such as suppliers, manufacturers, distributors, and customers. This digital twin is built using real-time data and advanced analytics to create a virtual replica of the physical supply chain, which can be used to test and optimize different scenarios and improve the efficiency and resiliency of the supply chain. Moreover, a search for "supply chain digital twin" would typically yield results related to the technology, applications, benefits, and implementation of digital twin in supply chain management.

3.1.2 Data source:

This Study comprises of data gathered from various scientific papers from the evasive Scopus and Science Direct databases, primarily. The databases consist of a great range of published research papers to journals in large volumes in comparison to any others. These scientific articles aid in theory-building research with connections, variables, and dynamics within the particular domain.

These scientific studies facilitate as it holds authenticated concepts and framework that clarifies the key concepts being researched in these ***developing theories*** (Marikyan et al., 2022). Scientific journals use a rigorous peer-review process to evaluate and validate the quality and reliability of research articles before publication. This process ensures that the research is of high quality and meets certain standards for scientific integrity and accuracy. Moreover, these journals publish original research that is conducted using rigorous methodologies and that *advances knowledge* (Kolomoyets & Dickinger, 2023) and understanding in a particular field.

This research is typically based on new data or insights that have not been previously published or widely known, inclusive of specialized knowledge and expertise that may not be available through other sources. They offer *in-depth analysis* (Aarikka-Stenroos et al., 2022) of specific topics, including new theories, methods, and techniques that may be useful to researchers and practitioners in the field. In this study, the research papers connect Digital Twin, and Supply Chain Management in the context of manufacturing using secondary literature sources creating a framework in value quantification and a representation of Supply Chain and Digital Twin dynamics.

3.2 Literature Identification and Selection

3.2.1 Data collection from Scientific Database

The Study of Digital twins, however have been ongoing since a decade, has recently been gaining momentum with the advent of digital era. Taking a count of the publications in the recent times, from Scopus database presented that the research relating to 'Supply chain Digital Twin' is in an increasing fashion year on year.

The idea behind selecting research articles is to have a wider perspective on the topic of interests from the authors, in the Supply chain network. To have an understanding of how Digital twin could be useful in each and every system/sub-system involved in Supply chain, from Supply planning, demand planning to risk management across the industrial operations.

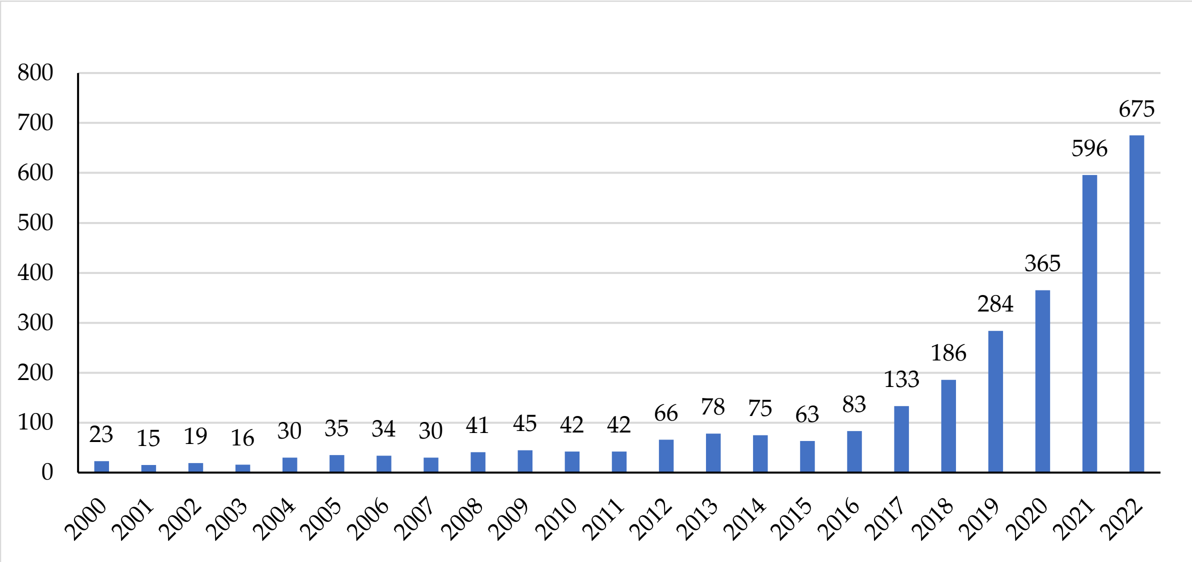

Figure 3.1: Trend of research articles in ScienceDirect Database

Table 1.1 represents the trend of available number of research articles with the search key terms and hits for the keyword "{Supply Chain Digital Twins}", over the years since 2000 till date, from the ScienceDirect database. The Systematic literature analysis aided in studying and constructing contextual factors, supportive to the main discussion. This analysis is rather a preliminary method in collecting articles. Figure 3.2 depicts the logic of the literature review performed.

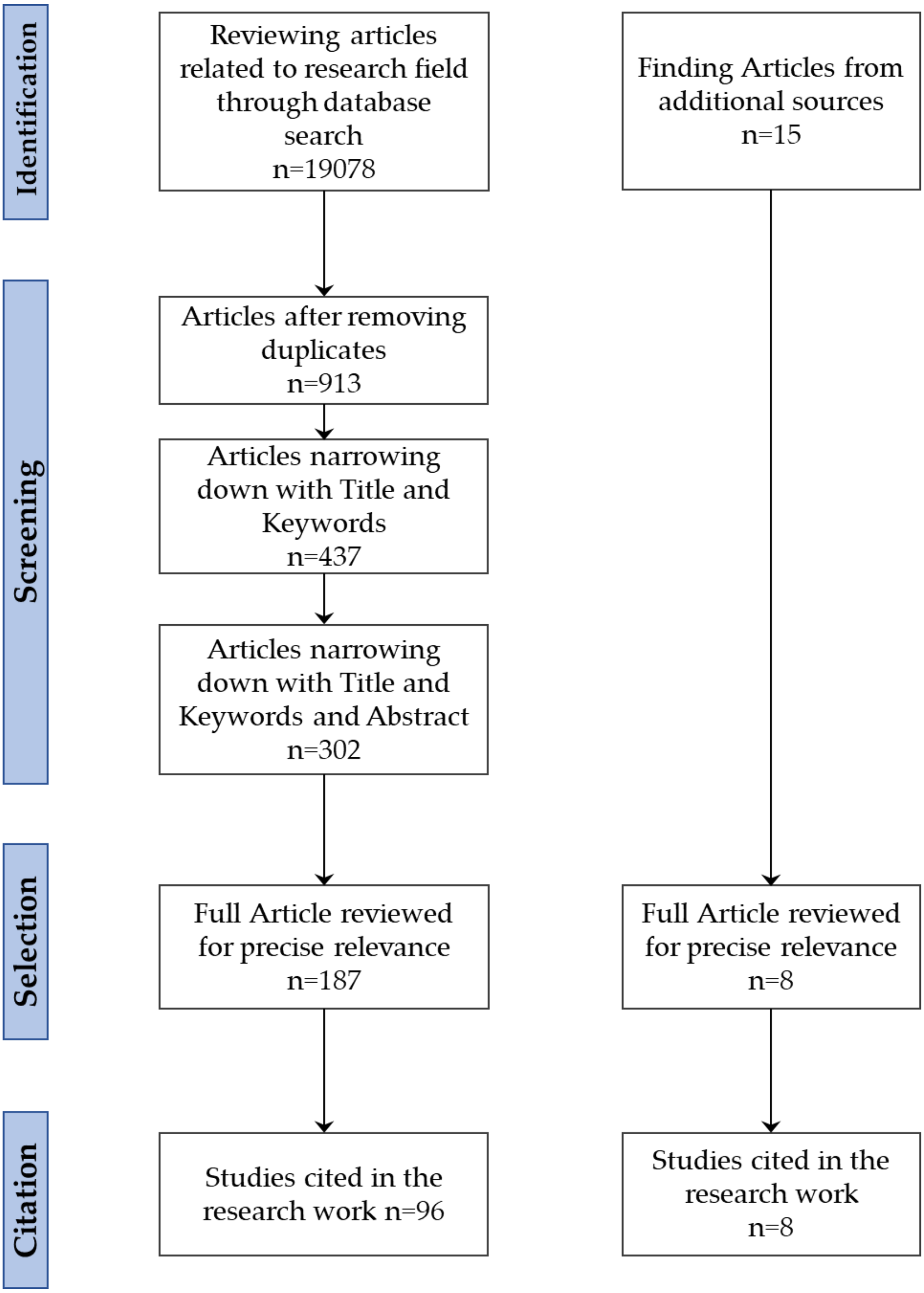

Figure 3.2: Literature Identification and selection

An overview of the collected papers, excluding the white papers indicate a strong connection between technologies and technical capabilities that correspond to the SCDT and how digitisation in supply chain improves in building more resilient and flexible supply chain. The following figure represents an overview of the linkages among various industrial operations that finds application in SCDT:

Table 3.1: Summary of Supply Chain Digital Twin applications observed from Selected literature

Supply chain Digital Twin	**Logistics**
	Prescriptive decision support platforms
	To create a digital supply chain twin – a model that always represents the state of the network in real-time.
	Enable data-analytics in predicting logistics risks and for finding alternative routes in real-time with ETA
	Information Management
	To share data among the complex Digital twin systems in the I4.0 set up
	Orchestrating digital twins to support PSS development
	Modelling a digital supply chain twin to form a framework of a decision support system for disruption risk management
	Creating a model that allows all the party involved in the supply network to share data as per requirement to the other actors to facilitate transparency in Collaborative Supply Networks
	Operations Management
	At each point of time, a digital twin represents the physical SC with the actual transportation, inventory, demand, and capacity data.
	A Digital twin system to consistently monitor all activities to stakeholders and decision-makers by delivering information regarding past and present tasks and performance indicators.
	A data-driven approach to enhance the decision-making process of omni-channel retail supply chains considering the assertiveness of demand forecasting, the integration of online and offline channels, the coordination of flows, and operations flexibility.
	Digital Twin aiding in deep synchronisation and dynamic interaction in supply chain planning.
	Business model Innovation
	Value co-creation from collaboration and partnerships in the actors in the supply chain
	Integrating Industry 4.0 and digital platforms in the "Supply Chain-as-a-Service"
	Real-time data collected, processed, and analysed by industrial IoT and CPS technologies allow designers to better understand customer requirements and organise customisation activities
	Circular Economy
	Material flow management in order to implementation of material and product cycles.

3.2.2 Data collection from Business pioneers

In addition to the research articles, a few White papers have been included in the study. These inclusions showcase how Digital twin could be employed in specific applications along the lines of the Supply chain planning and Supply operations execution. This is a way to obtain the broadest possible spectrum of diverse aspects, applications, and perspectives of Digital Twins in Supply Chains.

White papers present a problem or challenge and provide a specific solution or approach to address it. These documents are typically written by experts or companies in a particular field or industry and are used to educate readers on a specific topic or issue, as well as to promote a particular product or service.

Moreover, White papers include an executive summary, an introduction to the problem, a detailed analysis of the problem and proposed solution, and a conclusion, along with the data and statistics to support the proposed solution, as well as case studies or testimonials from users who have benefited from the solution.

White papers are often used in B2B (business-to-business) marketing to establish thought leadership and credibility, and to generate leads by providing valuable information and solutions to potential customers. They are also commonly used in government and public policy, as well as in academic and scientific research. Few references such as '*DHL's digital twin warehouse*' (Brintrup et al., 2021) *and 'Unilever's virtual versions of its physical factories'* (Brintrup et al., 2021) represent Industrial implementations relating to **Supply Chain Digital Twin.**

Table 3.2 represents the details of the White papers chosen for the study and a brief introduction of the discussion of the paper., with the number of times the papers are cited in other research papers.

Table 3.2: Summary of Selected White papers

Company	Title	Field of Discussion	Dated	Citations
DHL	The Logistics Trend Radar	Innovations in the recent decade that define and transform Logistics	2020	31
AnyLogistix	Supply Chain Digital Twins definition, the problems they solve, and how to develop them	Digital twin as an enabling simulation tool to aid in decision-making, on how to integrate into the exisiting operations as Supply chain control tower.	2021	30
Logility	How a Digital Twin Leads to Better Supply Chain Decisions in a Risk-Riddled World	Digital Twin provides with the ability to continuously improvise the plan and to evaluate the entire supply network up to the customer.	-	19
Engineering	Digital Twin	Digital Twin envisioned beyond manufacturing sector, its traditional ecosystem, into all sorts of service and goods-based businesses ranging from automotive to healthcare, envisioned as a Strategic Technology trend.	-	5
Ernest Young	How digital twin technology is transforming supply chains	Digital Twin to enable a successful supply chain network through a thorough end-to-end real time visibility.	2020	4
Delmia	Digital Twin: Manufacturing Excellence through Virtual Factory Replication	Digital Twin as a tool to digitally model, to foster innovation in the manufacture of quality products at reduced costs.	2014	-
Miebach Consulting	The Digital Twin in Intralogistics: Increase Planning Accuracy, Leverage Investments	To realise Digital twin as a key technology throughout supply planning and operations, shedding focus on the data-driven decision making with a practical example.	2020	-
Bosch Connected Industry	Data Homogenization in the Age of Industry 4.0	The Digital Twin System progressively develops ***consistent data homogeneity and interoperability*** to lay the groundwork for complete digitization of production and logistics.	2019	-

4. Descriptive Literature Analysis

Descriptive analysis is a statistical analysis technique that summarizes and describes the main characteristics in the collected dataset. This technique helps to make sense of large amounts of data and provides an overview of the dataset. This type of analysis is typically the first step in the data analysis process, and it involves examining the data to identify patterns, trends, and other important features. The purpose of this analysis is to describe the data in a meaningful way that allows researchers to gain insights.

Descriptive analysis generally involves creating visualizations, such as histograms or scatter plots, to help visualize the data and identify any patterns or trends. Thus, making the analysis that much simpler and more useful in a wide range of fields, from business and economics to social sciences and health care. It is often used to summarize and report data, to identify trends and patterns, and to provide a preliminary understanding of the data before more advanced statistical techniques are applied. The Literature analysis aims at exploring the premises of the research study, firstly on setting the scope for 'Supply chain digital Twin'.

The analysis is methodical employing two procedures in refining research papers based on the applicability and connection to the topic of discussion.

4.1 Bibliometric analysis:

A bibliometric analysis provides data summaries that gives a broad perspective on research activities and impact, particularly in terms of the most cited researchers, articles, keywords, countries, and universities. The analysis represents data on the basis of key researchers and universities, that are conducting research on Supply chain Digital Twin. Table 4.1 represents the contribution of journals in which the selected articles have been featured.

Table 4.1: Details on the source of Selected Articles

Source of Publication of Selected Articles			
Procedia CIRP	5	Competitiveness Review	1
Industrial Marketing Management	5	Production Planning and Control	1
Supply Chain Management	5	California Management Review	1
Journal of Cleaner Production	5	Technological Forecasting and Social Change	1
Technovation	4	Knowledge-Based Systems	1
Logistics	4	Problems and Perspectives in Management	1
Journal of Business Research	4	Applied Sciences (Switzerland)	1
IFAC-Papers Online	4	Journal of Industrial Information Integration	1
Computers in Industry	4	Mobile Networks and Applications	1
Long Range Planning	3	Strategic Entrepreneurship Journal	1
International Journal of Production Economics	3	Administrative Science Quarterly	1
Advanced Engineering Informatics	3	Journal of Enterprise Information Management	1
European Journal of Operational Research	2	Business Horizons	1
Sustainability (Switzerland)	2	Information Processing and Management	1
International Journal of Information Management	2	Annals of Operations Research	1
CIRP Journal of Manufacturing Science and Technology	2	Journal of Product Innovation Management	1
Business Process Management Journal	2	Organization & Environment	1
International Journal of Physical Distribution and Logistics Management	2	Measuring Business Excellence	1
Transportation Research Procedia	2	Journal of Manufacturing Systems	1
Management Decision	2	Journal of Network and Computer Applications	1
MIT Sloan Management Review	1	Journal of Purchasing and Supply Management	1
International Journal of Innovation Management	1	Journal of Management	1
International Journal of Mathematical, Engineering and Management Sciences	1	Journal of Information Technology in Construction	1
Journal of Management Science and Engineering	1	Digital business	1
International Journal of Production Research	1	Energy Reports	1
International Symposium on Tools and Methods of Competitive Engineering	1	*White Papers*	*8*

From the above table, Except for the 8 white papers and an energy report, other literary works are one of the two category – a conference paper or a research journal. This observation is further presented int eh following figure 4.1:

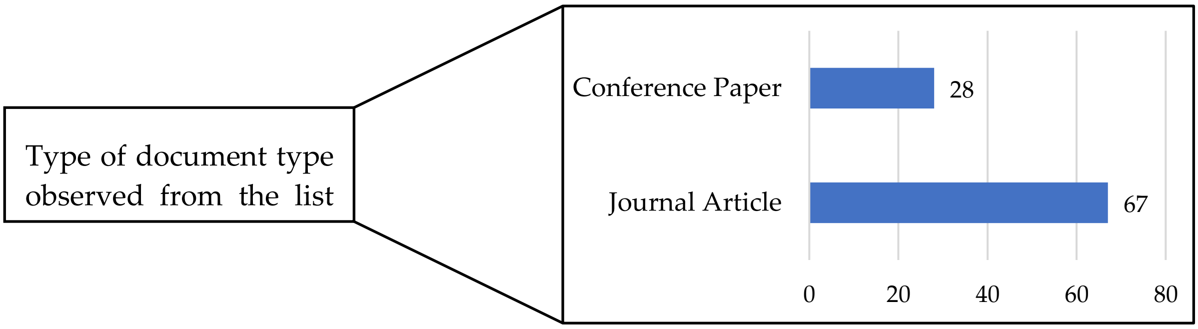

Figure 4.1: Comparison on the Document Type of Cited Research documents

4.2 Keyword network analysis:

The primary aspect of conducting the Keyword network analysis is to analyse and draw out the interconnected system of keywords from different research articles. Keyword network analysis is a method of analysing textual data by identifying and visualizing the relationships between keywords or terms in a dataset (Dolgui et al., 2020). This approach involves extracting keywords from the text, mapping their co-occurrence patterns, and representing them as a network or graph.

This analysis assists in identifying important nodes or clusters within the network, uncover patterns of co-occurrence and co-expression, and explore the semantic relationships between different concepts or ideas (Xie et al., 2022). Overall, keyword network analysis can be a powerful tool for discovering meaningful patterns and insights in unstructured textual data. The adaptable and multi-task architecture enables novel approaches to working with complex data sets and producing insightful visual aids (Dolgui et al., 2020).

The motive behind choosing this technique is to show the important points of the research paper as well as the relevance of the selected articles and documents, because keywords represent the main material of a study (Zott et al., 2011). As a result, by concentrating more on the content of the literature than the results, the Keyword network analysis can more properly summarize a chosen topic.

The Software VOS viewer is employed to analyse the dataset. The software includes a range of analysis tools, such as network clustering, community detection, and centrality measures, that is used in recognizing key nodes, groups, and structures in the network (Dolgui et al., 2020). VOS viewer provides simple and broad access to network data and aids in data specialising, filtering, navigating, manipulating, and clustering.

Keyword network analysis is performed using VOS viewer software and, with an extensive excel preparation to vet the study results. The VOS viewer is a tool used in creating network maps, to visualize and analyse the content in the documents. Using VOS viewer, networks of scholarly publications can be created on scientific publications, researchers, research institutions, nations, or concepts. Co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation linkages can be used to connect items in preparing or drawing these networks.

Frequency of keyword occurrence is a widely used approach in bibliometric analysis to detect **research subjects and *research frontiers*** (Nguyen et al., 2022). The network of *"keywords that appear in at least two"*(Perianes-Rodriguez et al., 2016) distinct articles is called the "**keyword co-occurrence network (KCN)**". A KCN is typically made up of keyword nodes linked by links, the thickness of which represents the frequency of the co-occurrence of the keyword pair. Keyword analysis can disclose the main points of the paper as well as the relevance of two or more documents because keywords represent the *main content of a research* (Nguyen et al., 2022; Perianes-Rodriguez et al., 2016) article. As a result, by concentrating more on the content of the literature than the results, the KCN can more accurately summarize a chosen subject.

4.2.1.1 *Full counting Vs Fractional counting*

The foundation of keyword network analysis is the notion that a research article's references reflect its primary theme and, as a result, that studies with similar references are connected. Both the Full counting and fractional counting establishes in the context of number of *"links every keyword has"*(Perianes-Rodriguez et al., 2016).

In Full counting method, the keywords with a higher link strength have a greater impact on the study meaning the analysis yields smaller number of clusters that are more closely related to one another. Therefore, it could be said that the reference to the highly cited keyword in the articles is considered to be more indicative of the subject of study, than the reference to the lowly cited keywords.

In Fractional counting method, by realising the interconnectedness as a fraction of keyword to the number of links it has, each keyword cited in the research articles has relatively same impact. This basically means that each keyword is regarded as equally representative of the articles. Thus, the clusters yielded are wider but sparsely connected.

Table 4.2: Full counting V. Fractional Counting – Keyword Network Analysis

Full counting	Fractional Counting
Full counting gives the count of connection between the keywords .	Fractional counting gives the strength as the ratio of the count of connection between the keywords to the total number of keywords in the journal.
Each Link has the weight of 1	Each link has the weight of 1/N; N denoting the number of links
Minimum search occurrence set at 5, resulting in 8 clusters with 88 keywords.	Minimum search occurrence set at 5, resulting in 10 clusters of 88 keywords.

4.2.1.2 Steps Performed in KNA:

The Keyword network analysis is performed in the software following these instructions:

1. The bibliometric data is exported from the ScienceDirect database as an .ris (Research information system) file.
2. These files are then imported into the VOS viewer software, and the computation method is set - to create a map from the bibliometric data.
3. Following the data insertion, A keyword Co-occurrence analysis with full counting as well as fractional counting has been conducted, the results of the analysis are as follows:

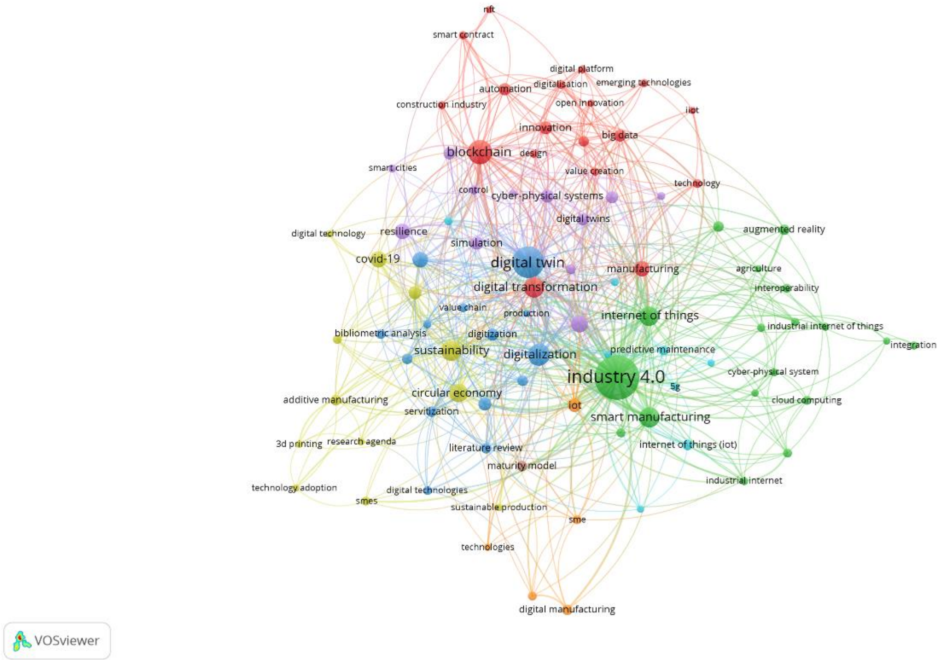

Figure 4.2: Keyword Network observed with Full counting Analysis

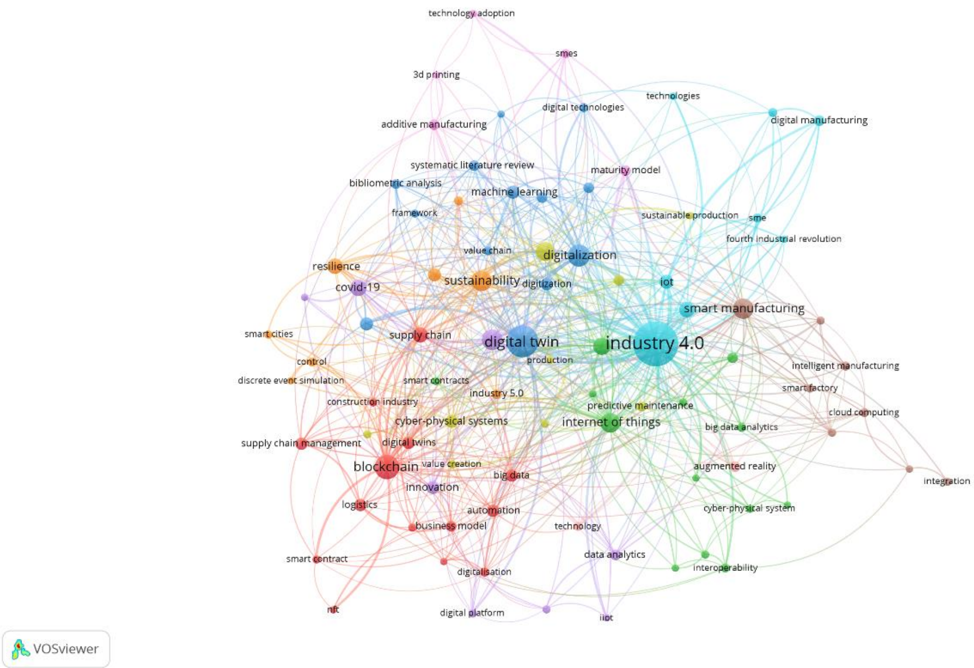

Figure 4.3: Keyword Network observed with Fractional counting Analysis

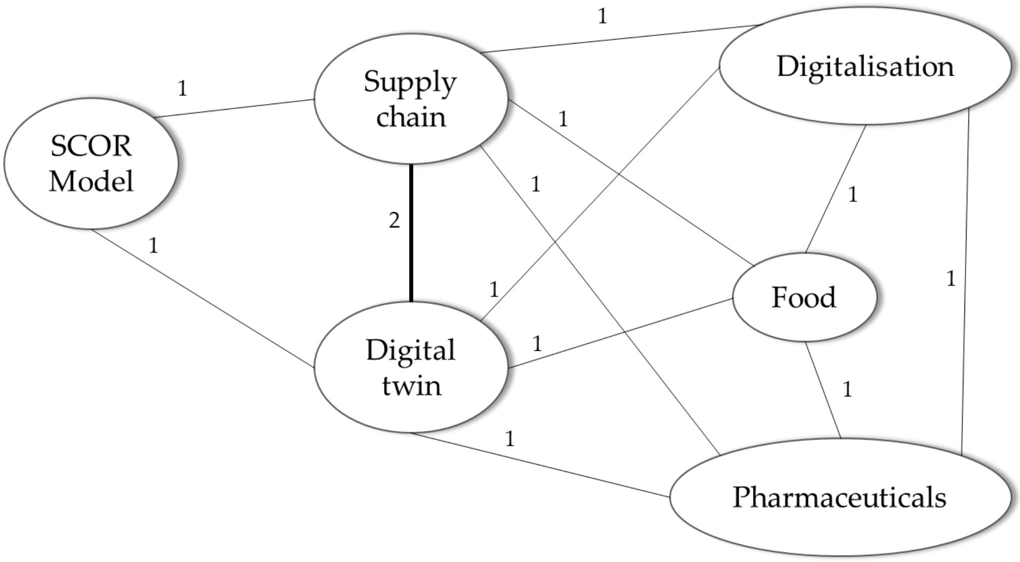

Figure 4.4: Example of keyword occurrence network

Figure 4.4 represents an example of keyword occurrence network. The construction shows the relation between the keywords from two articles, which is further followed by the Table 4.3 describing the occurrences and the two different counting methods used in KNA.

Table 4.3: Example portraying difference between full and fractional counting

Research Articles	Keywords	Occurrence	Full counting (∑N)	Fractional Counting (1/∑N)
Article 1	**Digital twin**	2	5	0.20
	Supply Chain	2	5	0.20
	SCOR Model	1	2	0.50
Article 2	**Digital twin**	2	5	0.20
	Supply Chain	2	5	0.20
	Pharmaceuticals	1	4	0.25
	Food	1	4	0.25
	Digitalisation	1	4	0.25

The table showcases the top 25 keywords based on the no. of occurrences observed from the chosen literature.

Table 4.4: Keyword occurrences with link strength

S.No	Keyword	Occurrences	Total link strength	
			Full counting	Fractional counting
1	***industry 4.0***	***161***	***283***	***134***
2	***digital twin***	***82***	***98***	***52***
3	***supply chain***	***48***	***87***	***42***
4	***sustainability***	***35***	***74***	***31***
5	blockchain	40	67	30
6	digitalization	35	63	30
7	smart manufacturing	31	74	27
8	internet of things	35	51	26
9	digital transformation	28	48	22
10	circular economy	25	57	22
11	artificial intelligence	20	39	18
12	manufacturing	19	36	18
13	covid-19	21	36	17
14	resilience	19	36	15
15	iot	16	44	15
16	cyber-physical systems	15	30	14
17	simulation	14	25	14
18	machine learning	15	26	12
19	innovation	15	24	11
20	sustainable development	15	24	11
21	business model	12	17	11
22	digitization	12	25	11
23	logistics	13	20	10
24	industry 5.0	10	21	10
25	sustainable manufacturing	10	19	10

Taking the top **four keywords, four prominent clusters** can be mapped. Each cluster shows a keyword and the sub-set of other keywords connected to the network. Similar-coloured circles indicate the distribution of comparative areas. **"Industry 4.0", "digital Twin", "Supply chain",** and **"Sustainability"** are identified as the keywords with higher link strength.

Conducting an **Overlay visualisation** in addition to Network visualisation allows to add additional information to a bibliometric network visualization. With this method, it further widens the network visualization based the year of publication in which an article was published. Overlay visualization helps in revealing new insights and patterns in this data; in exploring complex relationships between different data sets.

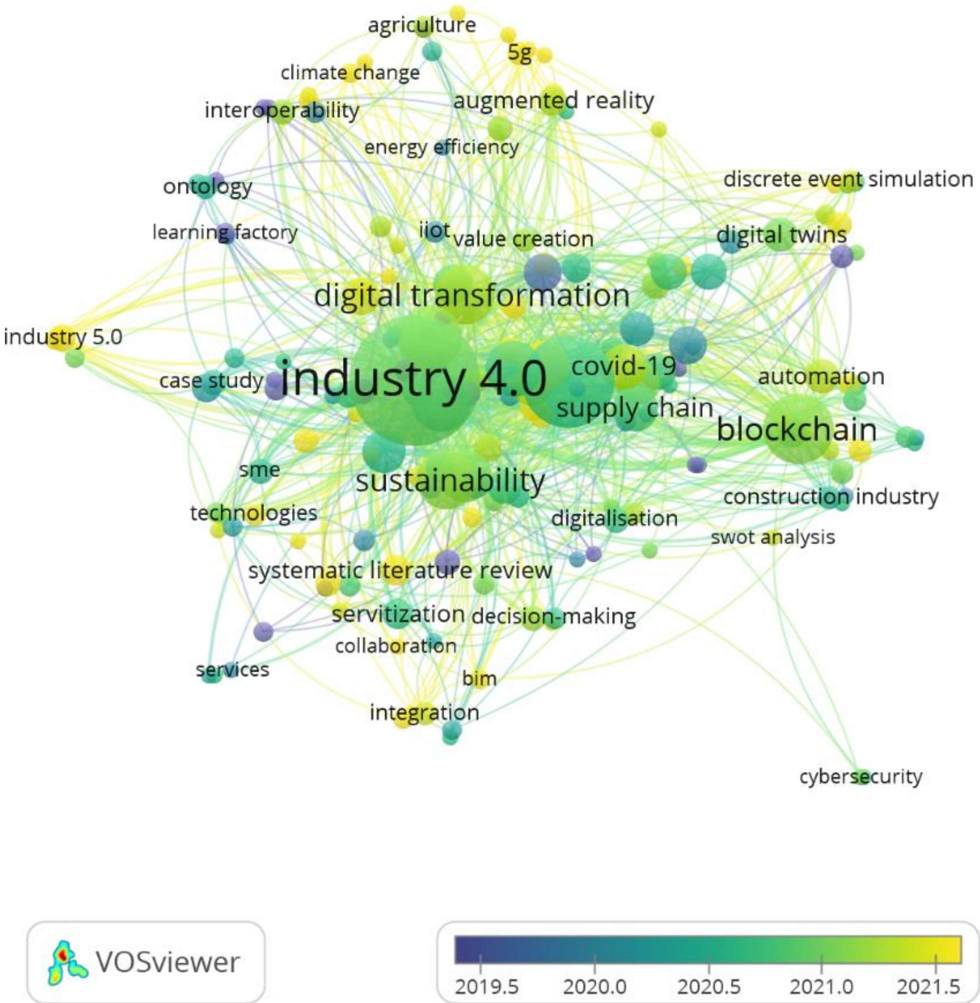

Figure 4.5: Overlay Visualization of the Keyword Network analysis

Table 4.5: Prominent Keyword Clusters

Industry 4.0	Digital Twin	Supply chain	Sustainability
IIOT; Interoperability; Cyber-physical system and Smart manufacturing.	Digitization; Digital transformation; Servitization; Digital manufacturing and sharing economy.	Blockchain; Value creation; Automation; Risk management and Resilience.	Circular economy; Industry 5.0; Technology adoption; Product life cycle management and Sustainable production.

4.2.1.3 Cluster 1: Industry 4.0

Industry 4.0 is a transformative concept that leverages technologies like IoT, cyber-physical systems, Cloud Computing, and Big Data to revolutionize manufacturing systems (Suuronen et al., 2022b). It offers intelligent products and systems a competitive edge (Rad et al., 2022), enabling digital transformation (Battistoni et al., 2023) and on-demand services (Pereira & Frazzon, 2021) in a distributed environment with high availability, scalability, and reliability.

From the analysis, Interoperability and smart manufacturing are two key concepts within Industry 4.0. Taking the context of Industry 4.0, interoperability is important because it enables different parts of the manufacturing process to work together seamlessly (Pan et al., 2021). For example, a machine on the production line might need to communicate with a robot that is responsible for transporting materials, or with a system that controls the overall production process. Interoperability allows these different components to work together smoothly (Ivanov & Dolgui, 2021), improving efficiency and reducing errors.

In a smart manufacturing (Björkdahl, 2020) environment, machines and systems are connected to each other and to a central control system (Battistoni et al., 2023) that collects and analyses data from across the production line. This data can be used to identify inefficiencies and areas for improvement, and to adjust production processes in real-time to optimize performance. Interoperability is critical to achieving smart manufacturing (Björkdahl, 2020; Suuronen et al., 2022b) because it enables different machines and systems to communicate and share data.

Consequently, Industry 4.0 utilises integration of various technologies, like the industrial Internet of Things and system integration (Karagiannis et al., 2022) to improve data collection and computation, while smart manufacturing (X. Wang et al., 2021) to promote a more data-driven decision-making approach.

4.2.1.4 Cluster 2: Digital Twin

Digital Twins are an extensive subject relating mainly to physical products. The concept of digital twin now, is extensively applied in the following:

- **re-designing the manufacturing industries**: In researching and implementing new ways to recycle and reuse waste products generated by manufacturing processes, by running data through AI generative algorithms (Rahmanzadeh et al., 2022).
- **along with smart manufacturing processes** (Rad et al., 2022), such as 3D printing techniques, can be scaled to the size of factories, creating production systems with unprecedented flexibility, potentially leading to fewer production lines that can produce a wider range of products, significantly reducing factories' carbon footprint.
- It is a key concept within **digital manufacturing**, which uses digital technologies to optimize the entire manufacturing process (M. Deng et al., 2021), from product design to production and delivery. Digital twins are used to simulate and test different manufacturing scenarios, allowing manufacturers to optimize production processes and reduce costs.
- in effectively connecting the machines/devices layer and the network layer, assisting in the collection, transfer, and **integration of fragmented knowledge** in the industrial system into the platform (Ivanov & Dolgui, 2021).
- **as a virtual reality integration technology**, digital twins can use sufficient data from physical and virtual spaces to compensate for the lack of data from the real world with virtual models (Bertoni & Bertoni, 2022). By comparing the simulation to sensor data, the location and even the cause of flaws in the system can be pinpointed with accuracy.

Digital twins are also connected to the sharing economy, which is a model of economic activity where assets and services are shared among individuals and organizations. In the context of manufacturing, the sharing economy is often referred to as "**manufacturing as a service**" or "**MaaS**" (Suuronen et al., 2022b). MaaS allows manufacturers to share their production capacity with other businesses that need it, creating a more flexible and efficient production ecosystem.

4.2.1.5 Cluster 3: Supply Chain

Given the major technological, conceptual, organizational, and social changes in the future of the supply chain environment, supply chain boundaries (Ivanov et al., 2022; van der Valk et al., 2022) are no longer clear, but defined by the people involved in supply chain activities.

The future of supply chain is likely to be shaped by a number of trends and technological advancements. The following are the mainly observed potential changes that would be referred to:

- **Increased use of automation:** Robotics and autonomous vehicles are likely to play a bigger role in supply chain operations, especially in areas such as warehousing, transportation, and packaging (Ivanov et al., 2022).
- **Greater emphasis on sustainability:** Environmental concerns are driving companies to look for ways to reduce waste and minimize their carbon footprint. This could include the use of alternative fuels, the adoption of circular economy models, and increased use of renewable energy.
- **Integration of blockchain technology:** Blockchain has the potential to revolutionize supply chain management by providing a secure and transparent way to track the movement of goods from the manufacturer to the end customer (Putz et al., 2021).
- **More efficient last-mile delivery:** Last-mile delivery, which involves getting goods from the warehouse to the customer's doorstep, is one of the most challenging aspects of the supply chain (MacCarthy et al., 2016). New technologies such as drones, and autonomous vehicles could help to make last-mile delivery more efficient and cost-effective.
- **Increased focus on data analytics**: Companies are likely to invest more heavily in data analytics tools to gain greater insight into supply chain operations (Liotine, 2020). This could help to identify areas for improvement and optimize processes to reduce costs and increase efficiency.

The supply chain of the future is likely to be characterized by greater efficiency, transparency, and sustainability, enabled by new technologies and innovative approaches to managing the movement of goods and materials.

4.2.1.6 Cluster 4: Sustainability

Sustainability in supply chains refers to the integration of environmentally and socially responsible practices throughout the entire supply chain process, from raw materials sourcing to product disposal (Assumpção et al., 2022). This includes ensuring that suppliers are following ethical and sustainable practices, reducing waste and emissions throughout the production process, and promoting fair labour practices (Le et al., 2022). The sustainable aspect in the supply chain transpires at both macro and micro levels, driven by changes that occur as visions of strategic environmental management. These practices are increasingly becoming embedded in policy and technology adoption.

The structure of the larger supply chain network in which companies operate influences their ability to achieve systemic sustainability goals. Through collaboration with supply chain partners, sustainable supply chain management enables manufacturing firms to produce cleaner products (Esfahbodi et al., 2023). As firms outsource more of their production, ensuring the supply of sustainable products necessitates commitments from the entire supply chain. As a result, **integrated Supply Chain Network** (Ivanov et al., 2010) can assist network members in reducing their individual and collective environmental footprint.

Technology adoption (Ivanov et al., 2021) refers to all innovations in software and hardware through product and process improvement, including the promotion of advanced energy-saving technologies, the use of renewable energy, pollution control, waste recycling, and the development of environmentally friendly products (Rahmanzadeh et al., 2022). Enterprises are advancing with combinations of commercial content, structure and leadership while creating and capturing value for all stakeholders forming a sustainable business.

The analysis yielded yet another interesting connection of Sustainability with that of Industry 5.0 (Le et al., 2022). Industry 5.0 is a proposed concept that builds on the principles of Industry 4.0 but incorporates a stronger focus on **human-centric manufacturing** (Maddikunta et al., 2022) and sustainability.

Industry 5.0 aims to incorporate sustainability principles into the entire manufacturing process. This includes reducing the environmental impact of production processes (Pereira & Frazzon, 2021) by using more efficient and sustainable materials and energy sources, as well as minimizing waste and emissions. It also involves creating more equitable and sustainable employment practices (Kohtamäki et al., 2022), such as providing fair wages and working conditions for all workers and ensuring that the benefits of manufacturing are distributed fairly across society. The concept of sustainability is therefore closely connected with Industry 5.0.

5. Analysis of the contents of the Literature: Drivers, Challenges and Foundations of Supply chain Digital Twins

5.1 Drivers:

From analysing the collected literature, the Supply chain digital twin has already begun to find its early adopters. In the scope and complexity, the software-driven transformation (Palkina, 2022) may be unlike anything that has been experienced before. Bringing together hardware, software, and data, digital twins drive the optimum design and operation of a product or service (Y. Wang et al., 2015).

There have been many contributing factors that made digital twin thrive in the Supply chain front. The factors include the technology drivers to the features and challenges are a few findings that addresses the foundations of Supply chain digital twins.

5.1.1 Data Driven Economy:

The rise of digital technologies and the internet has led to an explosion of data, and businesses and governments are increasingly turning to data analytics to gain a competitive edge (Ivanov et al., 2022). In recent years, the rapid development of advanced sensors and data acquisition technology has made data-driven models increasingly attractive in addition to simulation models. Data-driven models can be used to analyse large datasets, identify patterns and trends, and extract valuable insights that can be used to improve the performance of a system (Aheleroff et al., 2021).

Data-driven decision-making is being used in industries such as finance, healthcare, transportation, and retail to optimize operations, improve customer experiences, and develop new products and services (Y. Wang et al., 2015). Taking the examples from Siemens, the company has already succeeded in enabling companies to deploy digital twins in a number of applications accessible through Platform, *"such as continuously assessing and predicting the performance of manufacturing systems or supporting the optimization of production systems"*(Niu & Qin, 2021). It represents a fundamental shift in engineering and enables a transformation in the scale of human imagination.

Digital twin thus provides the structural back up of handling the larger data, *"by integrating the conception of live data from machines in the virtual image or digital model"*(Costa et al., 2022). Moreover, building performance simulations are typically based on historical or synthetic data rather than adapting the model to current or real-world conditions of the simulated environment.

Given that the Current simulation methods generally do not correlate with real-time environmental data i.e. Such offline simulations typically reduce the accuracy of predictions produced by simulation models compared to those produced by models based on real-time data (Aheleroff et al., 2021). Therefore, the utility of digital twins in the built environment is greatly enhanced by automated decision-making and feedback loops, enabling real-time automated control, and increasing the number of scenarios analysed to improve control system efficiency and reliability (Harapko & Affinito, 2022). The gathering of updated data throughout time is essential for many industrial applications, but the data must have the property of always being up to date (Brintrup et al., 2021).

In the Supply chain scenario, Data flows are central to the functioning of all activities. Moreover, the primary and important task is to capture the data in the first place. The various sensors, *"denser and wide-scale monitoring and control of sensors and actuator"* (Khan et al., 2021) through IIOT connectivity creating a smart value chain.

One of the key benefits of a data-driven approach to the supply chain is that it allows companies to make better decisions based on real-time data. For example, by using data analytics tools, companies can analyse customer behaviour, predict demand, and adjust their inventory levels accordingly (Kamble et al., 2022). Another key aspect of a data-driven supply chain is the use of technologies such as the Internet of Things (IoT) and machine learning. IoT devices can be used to collect data from various points along the supply chain, such as sensors that monitor temperature and humidity levels in warehouses and trucks. This data can then be used to optimize the supply chain in real-time, improving efficiency and reducing costs (Bhandal et al., 2022).

Machine learning algorithms can also be used to analyse large amounts of data and identify patterns and trends. This can help companies to make more accurate predictions about demand, identify areas of inefficiency in the supply chain, and optimize processes for maximum efficiency (Nguyen et al., 2022).

5.1.2 Open Innovation

Open innovation is a rather new notion, that is built and supported by the concepts of platform, partnership, and collaboration (Rahmanzadeh et al., 2022). Organizations develop value chain that addresses the important problem for society, such as the use of natural resources, human health, working conditions, and safety, thus changing the vision in the value chain. Open supply chain and open business models have synonymous objectives, value creation *"from the outside - through the use of external ideas, or from the inside – by providing third-party partners with ideas or assets not required by the firm"* (Palkina, 2022).

One way that open innovation can be applied to the supply chain is through the use of collaborative platforms. These platforms allow different partners to share information and collaborate on various aspects of the supply chain, such as product design, manufacturing, and logistics. By working together in this way, partners can share knowledge and resources, and identify opportunities for optimization and innovation (Bertoni & Bertoni, 2022).

The generation of knowledge within the supply chain is important for successfully combining and coordinating diverse knowledge resources among partners for better competition, thus the interaction between tacit and explicit knowledge in the organizational environment is important for developing new ideas (Pereira & Frazzon, 2021). Although a changing business environment is modifying the expectations of all our supply chain partners and requires strong management skills and processes to quickly adapt to these changing demands (De Souza et al., 2020). Effective knowledge generation arises from the integration of unique knowledge inputs from partners, like collaborative partner relationships brought in through data-exchange within Digital twin modules (Rozhkov et al., 2022). Inter-organizational relations are a key determinant of knowledge creation in the supply chain.

Another approach to open innovation in the supply chain is to involve customers and end-users in the product development process. By soliciting feedback and ideas from customers, companies can create products that better meet their needs and preferences (Rahmanzadeh et al., 2022). This can lead to increased customer satisfaction and loyalty, as well as new product and service opportunities.

Open innovation in the supply chain clearly facilitates companies to create new opportunities for growth and innovation, while also improving efficiency, reducing costs, and enhancing sustainability (Rahmanzadeh et al., 2022). As more companies embrace this approach, it can be expected to see further innovation and growth in the supply chain.

5.1.3 Mass customisation practices – Balancing SC and Personalisation:

Emerging IT Technologies inclusive of Industrial Internet of Things, cloud computing, and data analytics, as well as manufacturing systems like robotics, human-machine interfaces, and industrial information systems, have made it much easier for manufacturers to make better decisions (Rad et al., 2022). The paradigm of customizing that makes use of big data to gain a deeper comprehension of the requirements of customers and boost design productivity is referred to as *"smart customization"* (X. Wang et al., 2021).

The customization strategies leverage a vast amount of data from various sources, such as social media, online search behaviour, and purchase history, to gain insight into customers' preferences and behaviour (Manca et al., 2021). This data can then be used to tailor products and services to individual customers, creating a more personalized experience (Kohtamäki et al., 2022). This is made possible with the data handling capabilities of Supply chain digital twins.

For instance, having access to more customer data can help identify customer needs more accurately. The inter-connected shopfloor makes it possible to coordinate the supply chain more effectively during the manufacturing phase (Aarikka-Stenroos et al., 2022; F. Li, 2020). Manufacturers are able to better predict customer requirements and fluctuations in demand as a result of the increasing availability of data, which also results in a supply chain that is more collaborative (Rahmanzadeh et al., 2022).

In this scenario, manufacturers are able to actively modify production plans and manufacturing systems in order to meet emerging customer requirements and capitalize on market opportunities as soon as they arise (ABDELKAFI et al., 2013). The digital twin systems across the supply network makes it easier for manufacturers and customers to monitor each other and closely involves customers in the customization process (Zeb et al., 2022). In addition to increasing customer engagement in customization activities, customer participation has proven to be a promising method for establishing mutual trust between manufacturers and customers (X. Wang et al., 2021; Y. Wang et al., 2020).

5.2 Challenges

Digital Twin concept offers many great opportunities; however, a number of challenges must be properly addressed to attain the benefits that such technology brings.

5.2.1 Establishing a Digital Twin:

The process of creating a digital twin is complex and involves more than simply technology; it also symbolizes an ongoing effort to transform how an organization function (Julien & Martin, 2021). It requires both foundational investments in skills, projects, infrastructure, and, often, in cleaning up existing digital systems, and the mixing of people, machines, and organizational processes. The development involves several intersections as the digital twin *"represents a fusion of the informational and physical domains"* (Glatt et al., 2021) among *"data engineers, data scientist and system owners/controllers"* (Sleiti et al., 2022).

Few key competencies are required for the successful adoption of a digital twin within an organization during the large-scale data-based digital transformation.

- To gather innovative methods for collecting data, such as brand-new sensors and processes, and to know where data is located both inside and outside the company (Pereira & Frazzon, 2021).
- To express the digital value in languages that many domains within the business understand, and as they are frequently heavily involved in generating new digital opportunities (Le et al., 2022), to be able to draw knowledge from numerous domains to identify new, cross-cutting digital opportunities (Srai et al., 2019).
- Knowing the limitations and the meaning of the digital artifacts, such as data, analytical models, and software, that the company has access to, would be supportive in maintaining and developing digital twin (Abideen, Sundram, et al., 2021).

- Producing reliable and trustworthy data, analytical models, and delivery mechanisms for the digital twin (Costa et al., 2022). Developing concepts into reality with all the data roles (van der Valk et al., 2022).
- Identifying practical, feasible, and sensible as well as potential confidentiality issues to familiarize with the legal, ethical, and privacy implications of both the underlying data and analytical models and the digital twin (Chen & Huang, 2021).

5.2.2 Connectivity:

Providing real-time connectivity to assets that are constantly on the move or in remote locations is challenging. These technologies are not yet sufficiently developed technologically to offer industrial-grade connection (Kohtamäki et al., 2022). Additionally, always-on connections require significant bandwidth and processing power to provide non-trivial value (Maddikunta et al., 2022). To display the operational status, monitoring system conditions, and collaborating locations, the Digital Twin system of a single system or the entire physical environment of a value chain continuously updates and changes in real-time with its physical counterpart. The real-time monitoring process necessitates full-time connectivity (M. Deng et al., 2021).

5.2.3 Data consistency:

Considering a supply chain network, there are many virtual data sources interspersed along the value chain. The data is received from databases, business, and enterprise software, but it can also come from data mining or deep learning algorithms and other digital twins in the system (Marmolejo-Saucedo, 2020). The main challenge is the ability to maintain relevant, reliable, and secure data with reasonable accuracy to keep only the data and models that serve the intended use.

To create the Supply chain Digital Twin, it is necessary to improve raw data pre-processing and to use the most recent, computation-efficient data analytics and learning approaches (Kolomoyets & Dickinger, 2023). This is due to the large influx of incurred machine data from the multi-dynamic structure in the Supply chain utilizing communication infrastructure. However, many businesses are still unable to capitalise on this data-driven opportunity due to numerous obstacles. Many businesses, for example, are not yet ready to use data because they lack the internal capabilities for obtaining, processing, and analysing large amounts of information to support business decisions.

5.2.4 Security:

Digital twins store data and intellectual capital that become increasingly valuable over time. To avoid data loss or other damage, it is important to ensure the security of your data management system (Badakhshan et al., 2022). At every level of the factory communications stack, there is a strong need to defend against security and privacy issues arising from attackers, unauthorized machine access, remote attacks, and rival intruders. Securing this machine communication with high-value data is difficult (M. Deng et al., 2021).

5.2.5 System Integration and Information Exchange:

In the event of establishing a Supply Chain Digital Twin, one system provides information to one or more systems keeping each other in sync. Therefore, the following are few aspects that are considered in establishing the network:

- **Information control – system:** to exercise control over quantitative and qualitative information from others (Ivanov et al., 2022).
- **Negotiation** - Multiple systems negotiate to determine how to exchange information to achieve their goals (Rahmanzadeh et al., 2022).

However, the information exchange and system integration, in turn impacts the other factor so much as the case of vertically integration the data flow is not affected as the information is subsumed within the organization and accomplishing the same would be a task in case of different organizations.

5.2.6 Energy consumption:

To achieve the goals of industrial Digital Twin, various components such as sensors, communications, and data processing must follow a holistic approach of energy-efficient and green infrastructure. As density measurements lead to large-scale, battery-powered energy harvesting devices, new hardware, communication infrastructure, and algorithmic approaches are required (Julien & Martin, 2021). Data centres, in particular, consume a significant amount of energy to operate, and this consumption is only expected to rise as the number of data centres increases.

The energy source must be considered, and ideally, the energy should come from sustainable sources (Esfahbodi et al., 2023). This is not currently the case, as combustible fossil fuels continue to be the world's primary source of electricity. As a result, the use of digital twins has the potential to consume enormous amounts of energy. If not addressed, this will exacerbate the current climate crisis (Paiola & Gebauer, 2020). Promoting sustainable energy sources is thus critical to ensuring that the growing use of electricity to enable digital technologies does not result in increased greenhouse gas emissions. Radio access, core network, and computing resources must therefore be optimized together, balancing the trade-offs for energy efficiency (Le et al., 2022; Marmolejo-Saucedo, 2020).

5.3 Features of Supply Chain digital twin

Upcoming technologies are playing a crucial role in supporting the implementation of a supply chain digital twin. Ideally, a Supply chain Digital twin made feasible by these several technological advancements and innovations (Busse et al., 2021), that have only recently reached maturity or will do so soon. This will make it possible to combine and modify these technologies in the development and implementation of a supply chain digital twin .

Prior to the discussion of the features of supply chain digital twin, this array of enabling technologies is given in the table as follows:

Table 5.1: Enabling Technologies of Supply chain Digital Twin

Criteria	Enabled by
Dynamic Modelling capabilities	Model module in SCDT Scenario construction module in SCDT Predictive simulation and analysis
Decision support capabilities (Simulation & Optimisation)	Reporting module in SCDT Scenario planning module in SCDT
Visibility and transparency	Cloud computing connectivity (5G & 6G)
Data Collection	Iot and IIoT Technology Cloud computing (Storage) Secure computation
Data Analysis	Cloud computing (Computation) Artificial Intelligence
Monitoring (Update frequency)	Iot Technology Connectivity (5G & 6G)

5.3.1 Simulation and Optimisation capabilities:

Supply Chain enterprise environments tend to be more complex, placing greater demands on planning, management, and control at each level of the Supply Chain. An integrated Supply chain could facilitate deep business integration (Hallavo, 2015) and value chain transformation at all levels of the Supply Chain (Koilo, 2022).

Supply chain Digital twins *"enable real-time transparency"* (Dolgui et al., 2020) as the data flow of crucial logistics (Abideen, Sundram, et al., 2021), financial key performance indicators (KPIs) (Zimmermann et al., 2020), inventory level, stock level (Badakhshan et al., 2022), service level, capacity, and transportation data (Burgos & Ivanov, 2021), are all monitored and made available at all time. They are effective control centres for businesses and data-driven tools. By simulating and creating **what-if scenarios** (Putz et al., 2021) that predict the impact in the future, performance-based simulation models assist in the creation of effective contingency plans to prevent or recover from disruptions.

5.3.1.1 Simulation modelling to facilitate process proficiency:

Products, as well as entire machines and factories, can be represented by a digital twin (Julien & Martin, 2021), which can simulate the structure and activity of the real-world counterpart while also acquiring real-time data from it to compare to the digital simulation of the digital twin in order to **eliminate inefficiencies** and **correct faulty processes** (Neto et al., 2020). Digital twins not only show Supply chains and the risks that go along with them, but they also provide supplier performance and risk analysis, as well as predictions for Supply chain interruptions and risks (Grieves, 2015).

Digital Twins have distinctive users at diverse parts and thus cover more extensive points of view (Sleiti et al., 2022). Simulation modelling addresses the expository and decision support prerequisites by demonstrating point by point (Bertoni & Bertoni, 2022) and exact replication of the framework or handle state in any possible situation being either in past or future. "*Digital Twin not only provides this functionality but also can suggest possible courses of action and execute them depending on the nature of the necessary steps*"(Manca et al., 2021).

5.3.1.2 Integrating simulation modelling and Business systems to formulating action plan:

In most cases, simulation modelling is done offline, which allows the model to be built after the required logistics and data have been gathered. While the Digital Twin, on the other hand, is designed to gather data continuously while processing it online, giving the user access to the most up-to-date predictions and analyses (Burgos & Ivanov, 2021). By demonstrating a thorough and accurate replication (Srai et al., 2019) of the system or process state in an imagined scenario that could be in the past or the future, simulation modelling meets the needs for analytical and decision support.

Depending on the nature of the required steps, SCDT not only offers this functionality but also has the ability to propose and carry out various possible courses of action. Moreover, Simulation modelling in SCDT is equipped with the ability of importing the simulation data or simulation results into an "*ERP system or a **business intelligence (BI) tool***" (Ivanov & Dolgui, 2021). This integration at the system level accelerates the response time and also, with the appropriate and precise action plan. Taking the instance of lower service level observation, the digital twin may trigger a BI algorithm to look for the root cause of the issue and update the required data (Harapko & Affinito, 2022; Y. Wang et al., 2015) to fix such challenges at a very early stage.

5.3.1.3 Simulation modelling for multiple and continuous computation:

Because different users in different roles are involved with digital twins, they can address a broader range of viewpoints, including those that are pertinent to operations, strategy, and sales (Zeb et al., 2022). The goal of simulation modelling is to provide the actors and stakeholders in the supply chain with solutions and responses at the encounter of problems (Bertoni & Bertoni, 2022) and/or unfavourable situations (Y. Wang et al., 2020).

Furthermore, the Digital Twin takes a more *holistic approach* (Manca et al., 2021). This is evident, as one major objective of Supply Chain Digital Twin is to understand intolerable differences from ideal conditions along any of the different dimensions. Such a deviation is an indication of business optimization (Abideen, Sundram, et al., 2021) and presents a chance for cost savings, quality improvement, or increased efficiency.

Supply chain digital twin, thus, runs behind every industrial activity and can help to identify inefficiencies and bottlenecks throughout the chain. Improvements in efficiency achieved through manufacturing system optimization (Kamble et al., 2022) can significantly reduce environmental impact while also resulting in better understanding of customer requirements and organize customization work (Chen & Huang, 2021). Therefore, it would be beneficial to integrate the digital twin into existing paradigms for greater customization capabilities.

5.3.1.4 Real time Dynamic modelling to facilitate logistics integrated production management:

Real-time dynamic modelling is the process of creating a model that simulates a system or process in real-time. It involves representing the behaviour of the system or process over time and updating the model as new data becomes available . Recent academic contributions have stressed using ***built-in models*** (Abideen, Sundram, et al., 2021) in the Supply chain digital twin to increase process automation. An essential feature of employing this method in Supply chain,

- is that the data that describes the characteristics of the actors and activities along the supply chain (Le et al., 2022), and
- the data is made easily accessible so that it can be used immediately by a modelling software to generate the required models (Putz et al., 2021).

This feature of – Real time modelling particularly finds application in the **logistics front** (Assumpção et al., 2022) out of all the other supply chain operations. As with the notion that businesses aim to sustain the market share, in a market that is becoming more and more competitive by taking advantage of the synergies between production management and logistics (Abideen, Pyeman, et al., 2021). As the supply chain divergence is likely to be a significant component of long-term resilience strategies for many businesses. This diversification supports the use of **multiple production** (Bodenbenner et al., 2020) facilities and distribution locations, giving businesses more options when issues arise by sourcing essential products and services from multiple vendors in various regions.

With millions of data points about customer orders, shipment movements, and the location and state of assets, logistics operate in an especially data-rich environment (Palkina, 2022). Furthering, this analysis yielded a speculation that by altering the buyer-supplier roles in connected or even competing supply chains, value webs will develop that are ***characterized by structural dynamics*** (Dolgui et al., 2020) that include a variety of behaviours. The intersection of various actors in this logistics perspective, thus brings with it a spectrum of variables that determine and alter the functioning of Supply chain. *A long-term, timely, bidirectional* (Busse et al., 2021; Ivanov et al., 2010) data link to an actual logistics system is featured in a digital simulation model of that system.

Ideally, any **pertinent data** (Putz et al., 2021) discovered through observation of the entire supply chain transportation could be discovered through observation from the digital model. Thus, The Supply chain digital twin commands dynamic modelling in such events, through presenting the best-case scenario along with the time frame of action plan (Pan et al., 2021).

5.3.2 Supply Chain Visibility & Monitoring:

A digital twin is a virtual mapping of real-world links, and the creation of a digital twin platform network can result in numerous coupling points. It can not only produce greater benefits across various dimensions of the supply chain, but it can also realise the coupling between dimensions through platform integration, resulting in more efficient information sharing and resource allocation (Liotine, 2020). In the context of visibility and monitoring, a supply chain digital twin can provide real-time insights into the status of the supply chain, including the location of products (M. Deng et al., 2021), inventory levels, and the performance of suppliers and carriers.

A digital supply chain twin is a representation of the network state at any given time that enables full end-to-end visibility of the supply chain to increase resilience. *"End-to-end visibility is the number one factor cited in creating a successful supply chain"* (Ivanov et al., 2021). A digital Supply Chain twin—a computerized digital Supply Chain model that depicts the network state for any given moment in real time, allowing for complete end to end Supply Chain visibility to improve resilience and test contingency plans (De Souza et al., 2020)—can be produced by enhancing the existing decision-support tools with data analytics.

A digital twin can provide a comprehensive view of the supply chain from end to end (Putz et al., 2021). For example, if a delay occurs in the shipment of a product, the digital twin can help identify the root cause of the delay and provide insights into how to address it. This can help reduce the risk of disruptions (Ivanov & Dolgui, 2021) in the supply chain and ensure that products are delivered on time and to the right location.

Monitoring is another important aspect of supply chain management, and a digital twin can provide real-time monitoring of the supply chain (X. Wang et al., 2021). By using sensors and other monitoring tools, companies can track the status of products and materials throughout the supply chain and identify potential issues before they occur (Cirullies & Schwede, 2021). For example, if a product is exposed to unfavourable environmental conditions during shipment, the digital twin can help identify the issue and provide insights into how to address it.

The Supply chain Digital twin has the capability to handle enormous complexity that can quickly be modelled an automatically generate and assess hundreds of scenarios, not just two or three (Bodenbenner et al., 2020). Based on actual transportation, inventory, demand, and capacity data, a digital twin simulates the physical Supply Chain (Ivanov & Dolgui, 2021) and can be utilized for planning and real-time control choices (Neto et al., 2020).

5.3.3 Prediction and disruption management – To the future of risk mitigation capabilities:

5.3.3.1 *The future of risk mitigation strategies to System level integration:*

Supply chain is becoming more integrated each moment, *by the increasing number of involved participants and the growing service level expectations* (Pereira & Frazzon, 2021). Especially with the growing and dynamic nature (Ghosh et al., 2021), digitalization necessitates research that can assess, comprehend, and evaluate its facilitators, drivers, and performance outcomes. These performance outcomes could include anything from resilience and time competitiveness to risk management.

Many organizations are reconsidering their strategy to supply chain risk as a result of the *frequency and severity* (Bodenbenner et al., 2020) of recent disruptions. Leading businesses are currently developing pre-emptive risk management systems (Ivanov & Dolgui, 2021) with an emphasis on digital tools and tested mitigation techniques.

The supply network necessitates a higher level of data flow between and among the participants that enable better synchronisation of information. Furthermore, this improving level of integration in the supply network has a direct (MacCarthy et al., 2016) and positive impact on dealing with the changing consumer behaviour and market conditions. With the intention of increasing the efficacy, the goal is to examine its performance or, in some circumstances the *behavioural patterns* (Marmolejo-Saucedo, 2020) of supply chain network. This predictive analysis modules of Supply Chain Digital Twin could be applied on products, machines, and even entire business ecosystems to disclose information from the past, improve the present, and even forecast the *future performance* (Marmolejo-Saucedo, 2020) of the various areas examined.

5.3.3.2 Adaptive research capabilities in disruption management:

Supply chain operations centre the predicting mechanism, from demand planning to inventory management. The Supply Chain Digital Twin characterises dynamic research capabilities, employing advanced *data analytics and trace and tracking systems* (Ivanov & Dolgui, 2019). This technology aids in developing actions plans to address disruptions with a better understanding beginning with the origins of the disruption to impacts to the spread in supply network. This is necessary to formulate:

- Several risk factors such as supplier bankruptcy, natural disasters, and transportation disruptions could be mapped with the advanced predictive analysis in Supply Chain Digital Twin. This information can be used to **develop contingency plans** (Bertoni & Bertoni, 2022) and mitigate the risks.
- Thorough data analysis and interpretations would be used to gain insight and forecast accuracy, **reduce** the risk of **information disruption** (Karagiannis et al., 2022; Srai et al., 2019), and improve contingency plan activation, all of which can reduce risk in the Supply Chain.
- **T**his method could be employed also, to develop an **early warning system** to alert on the events that has attributes that might develop into a potential disruption. Moreover, this system can be used to trigger appropriate actions to prevent or minimize the impact of disruptions (Preut et al., 2021).
- **Scenario planning:** Predictive analysis can be used to develop various scenarios of potential disruptions (Busse et al., 2021; Santos et al., 2020) and their

impact on the supply chain. This information can be used to develop a robust disruption management plan that can be quickly implemented when a disruption occurs.

- Predictive analysis can be used to **monitor the supply chain in real-time** (Ivanov & Dolgui, 2021) and identify potential disruptions as they occur, which comes in handy to devise immediate action to mitigate the impact of the disruption.

5.3.4 A tool to Decision making:

A Supply chain digital twin is a model that always accurately depicts the status of the network in real-time and is created by combining all the features - simulation, optimization, and data analytics (Brintrup et al., 2021). A digital twin depicts the physical Supply chain with the *real transportation, inventory, demand, and capacity data* (Ivanov & Dolgui, 2019) at each moment in time. As established – A supply chain Digital twin should be thorough enough to evaluate the interactions of the supply chain, from large-scale changes in demand to what happens inside facilities (Cirullies & Schwede, 2021), to be able to perform tasks like analyse the demand patterns, flow of revenue and SKU observation, and scenario testing.

5.3.4.1 Decision support system to coincide variable timeframe:

For the purpose of supporting prescriptive decision-making, the digital twin facilitates to run a parallel version of the supply network with the same supply entities, parameters, and financial targets (Grieves, 2015; Kohtamäki et al., 2022). Thus, the technology empowers the organisations with a high degree of confidence in the outcomes, enabling management to make quick decisions (Harapko & Affinito, 2022).

A Supply Chain Digital Twin is a *"detailed simulation model of an actual supply chain"* (De Souza et al., 2020) which uses real-time data/snapshots to forecast supply chain dynamics (Burgos & Ivanov, 2021; Putz et al., 2021). The analysis is to understand the supply chain's behaviour, to forecast if case of any abnormal situations and to derive out an action plan (Koilo, 2022; Lee & Lee, 2021).

Furthermore, the real value that a supply chain digital twin offers organizations is a way to make better short-term and mid-term decisions:

- *"Mid-term decisions are mostly related to how a supply chain should work, such as design, optimization and master planning"* (De Souza et al., 2020). A digital twin helps to review and improve supply chain and all its underlying processes, resources, and logic. These tasks may require simulation of a few months of operations.

- *"Short-term decisions are mostly related to the identification of potential problems and the analysis of solutions"* (De Souza et al., 2020). Usually, this kind of decision making will only require the simulation of a few days or weeks.

5.3.4.2 Decision making systems capable of cognitive response:

The Supply Chain Digital Twin encompasses modules that provide for advanced modelling technique such as **model based learning** (Yan et al., 2022). This technique refers to the experimental learning that includes human interactions within a system, to help develop cognitive abilities. Due to its intuitive organizational skills and use of **evidence-based decision making** (Liotine, 2020; Yan et al., 2022), it can play a crucial role in the process of instituting a complete digital twin of systems.

Supply chain digital twins are capable of incorporating large amounts of data from various sources, such as sensors, production systems, and transportation systems. This data is used to train machine learning models (Pan et al., 2021; Zeb et al., 2022). In addition to the system data, this methodology creates an environment for interactive simulation with human intervention (Niu & Qin, 2021) to test out hypotheses using simulation methods.

Having a data-driven decision-making culture (Harapko & Affinito, 2022) and access to quality data has great potential for supporting both operational and strategic value creation in supply chain management (Esfahbodi et al., 2023). This is because such an approach generates actionable insights that can lead to sustainable business performance (Ivanov et al., 2022) and competitive advantage.

Information processing and analytical skills are crucial for supporting organisational responsiveness and performance in today's highly dynamic business climate, in addition to intuitive judgements made during the decision-making process (Badakhshan et al., 2022). Combination of this type of technique in Supply Chain Digital Twin provide a powerful tool for supply chain optimization with the possibilities to test out and implement **tested-out changes** (Grieves, 2015; Manca et al., 2021) in the physical system.

5.3.5 Bridging Data Diversity: Standardizing Information:

Supply chain Digital twin mimic the behaviour, performance, and characteristics of the physical twin that include physical assets, products, or processes, in a digital environment. In a way, Supply chain Digital twin enables *"homogenization of data"*(Wolters, 2019). This decoupling of information from its physical form is made possible by the digitization of data (Hallavo, 2015; Perianes-Rodriguez et al., 2016) and the use of advanced analytics and modelling techniques (Rad et al., 2022).

With the ability to create standardized digital models (Björkdahl, 2020) of physical assets, products, or processes across the supply chain network, this allows companies to standardize data and processes (Sleiti et al., 2022), and use these standardized models to optimize performance and improve quality control. The Digital Twin System caters to the requirements of involved supply chain actors by integrating manufacturing data (Grieves, 2015) with contextual information and comprehensively homogenising semantic data (Liotine, 2020).

The Supply chain Digital twin organises the information generated by each asset into groups that are usually understandable based on characteristics, i.e., data sets of machine faults or logistics re-routes (Battistoni et al., 2023). Additionally, this gives outside actors, along the from supply network, access to the pertinent output data. Thus, the Supply chain Digital Twin System serves as the foundation for a thorough digitization of logistics and manufacturing (Ghosh et al., 2021; Sleiti et al., 2022).

With the feasibility to share contextualised information (Lee & Lee, 2021) about the status of entire system, from production lines to the logistics using the Supply chain Digital twin System. Thereby, the outside programme or machine manufacturer provides innovative services or create new solutions, without having to be present (Karagiannis et al., 2022; Santos et al., 2020). As the data is sufficient enough to be associated and used by various systems because the necessary context is always provided, and each recipient gets the needed information. Thus, The Supply chain Digital twin System fosters cross-plant synergies along the value chain.

Table 5.2: Summary of Supply chain Digital twin Features

	Simulation and Optimisation capabilities
Simulation modelling to facilitate process proficiency	Digital twins can simulate the structure and activity of the real-world counterpart while also acquiring real-time data from it to eliminate inefficiencies and correct faulty processes. They provide supplier performance and risk analysis, as well as predictions for Supply chain interruptions and risks. Simulation modelling addresses expository and decision support prerequisites.
Integrating simulation modelling and Business systems to formulating action plan	Simulation modelling is done offline, while the Digital Twin is designed to gather data continuously and provide up-to-date predictions and analyses. Supply chain Digital twin offers analytical and decision support, as well as the ability to propose and carry out various possible courses of action. It is also equipped with the ability to import the simulation data or simulation results into an ERP system or a business intelligence tool, which accelerates response time and provides an action plan.
Simulation modelling for multiple and continuous computation	Digital twins are used to provide actors and stakeholders in the supply chain with solutions and responses at the encounter of problems. They take a holistic approach and can help identify inefficiencies and bottlenecks throughout the chain, leading to cost savings, quality improvement, or increased efficiency. Integrating the digital twin into existing paradigms for greater customization capabilities.
Real time Dynamic modelling to facilitate logistics integrated production management	Real-time dynamic modelling is the process of creating a model that simulates a system or process in real-time. It involves representing the behaviour of the system or process over time and updating the model as new data becomes available. Recent academic contributions have stressed using built-in models to increase process automation. Real time modelling particularly finds application in the logistics front, as businesses aim to sustain the market share. This diversification supports the use of multiple production facilities and distribution locations, giving businesses more options when issues arise.

Supply Chain Visibility & Monitoring	
End-to-End visibility	A digital twin is a virtual mapping of real-world links that can provide real-time insights into the status of the supply chain, including the location of products, inventory levels, and performance of suppliers and carriers. It is a representation of the network state at any given time that enables full end-to-end visibility to increase resilience and test contingency plans.
Real-time monitoring	A digital twin can help identify the root cause of a delay and provide insights into how to address it, reducing the risk of disruptions. It can also provide real-time monitoring of the supply chain and identify potential issues before they occur. It simulates the physical Supply Chain and can be used for planning and real-time control choices.
Prediction and disruption management – To the future of risk mitigation capabilities	
The future of risk mitigation strategies to System level integration	Supply chain is becoming more integrated each moment, requiring research to assess, comprehend, and evaluate its facilitators, drivers, and performance outcomes. Many organizations are reconsidering their strategy to supply chain risk due to the frequency and severity of recent disruptions, and leading businesses are developing pre-emptive risk management systems with digital tools and tested mitigation techniques. Supply chain Digital twin can be applied to products, machines, and even entire business ecosystems to disclose information from the past, improve the present, and forecast the future performance of the various areas examined.
Adaptive research capabilities in disruption management	The Supply chain Digital twin is a dynamic research capability that uses advanced data analytics and trace and tracking systems to develop actions plans to address disruptions. It can be used to map risk factors such as supplier bankruptcy, natural disasters, and transportation disruptions, develop contingency plans, gain insights, and forecast accuracy, reduce the risk of information disruption, and improvise contingency plans accordingly. Predictive analysis can also be used to monitor the supply chain in real-time and identify potential disruptions as they occur, allowing for immediate action to mitigate the impact of the disruption.

A tool to Decision making	
Decision support system to coincide variable timeframe	A Supply Chain Digital Twin is a detailed simulation model of an actual supply chain which uses real-time data/snapshots to forecast supply chain dynamics. It empowers organisations with a high degree of confidence in the outcomes, enabling management to make quick decisions. It also helps to make better short-term and mid-term decisions, such as design, optimization, and master planning.
Decision making systems capable of cognitive response	The Supply Chain Digital Twin is an advanced modelling technique that uses human interactions to develop cognitive abilities. It can be used to train machine learning models and create an environment for interactive simulation with human intervention.
Bridging Data Diversity: Standardizing Information	
Homogenization of data	Supply Chain Digital Twin enables "homogenization of data" by digitizing data and using advanced analytics and modelling techniques. The Digital Twin System integrates manufacturing data with contextual information and semantic data to standardize data and processes to optimize performance and improve quality control. The Supply Chain Digital Twin System provides contextualised information to enable cross-plant synergies along the value chain.

6. Implication of Supply Chain Digital Twin in Business Model Innovation

6.1 Fundamentals of Business Model Innovation

The standard definition of a business model innovation is *"the way firms create and capture value, that is new to the product market space"*(Björkdahl et al., 2022; Paiola & Gebauer, 2020). Starting from Large conglomerates to small scale enterprises, the *'value creation'* (Yi et al., 2022) takes new shapes through alteration and transformation of production, management, and structural modes. Often times leading to a *'new way'* (Kolomoyets & Dickinger, 2023; Sjödin et al., 2020) with these new capabilities.

Business models are a complicated, multifaceted idea. A statement, a description, a representation, an architectural, a conceptual tool or model, a structural template, a method, a framework, or a pattern are some of the ways that it has been described in earlier works (Haftor & Climent Costa, 2023). Business models are frequently described as models, or cognitive configurations that may be presented, shown, and altered as representations of a class of organizations in how they work as opposed to something real (Gasparin et al., 2022). Accordingly, a business model is a *"stripped-down characterization that captures the essence of the cause-and-effect interactions between consumers, the organization, and money"* (X. Li et al., 2020), rather than a comprehensive account of what a firm does.

There are many advocated frameworks for business models that include various business model components. A business model is frequently defined as a collection of elements with connections and interactions between them (Teece, 2018; Zott et al., 2011); these components that work together in an interdependent way to define how a company creates, delivers, and captures value. The components that make up the business model include:

- **Value Proposition:** Organisations and Enterprises, strive through different processes and constructs to provide to its customer or target audience through a variety of product, service, or solution. It highlights the exclusive features, benefits, and advantages of the product or service, and distinguishes it from competitors in the market (Teece, 2010). It should be customer-centric, and communicate the value that the customer will receive, rather than just listing features or functionalities.
- **Key Partnerships** describes the relationships that a company has with other businesses or organizations, along the value chain, that are critical to its success, such as suppliers, distributors, or strategic alliances (Assumpção et al., 2022). The key partnerships are one way to push the convergence two or more technological advancements to adapt to the changing circumstances. Taking inspiration from "Stakeholder theory", value creation is a **cooperative effort through partnerships** that, in a perfect world, benefits both the focus firm and all of its stakeholders (Koilo, 2022).
- **Key Resources** refers to the critical assets that a company needs in order to create and deliver its products or services, such as technology, manufacturing facilities, intellectual property, or skilled employees (Ghezzi & Cavallo, 2020). But with the search for competitiveness, the focus has turned from the products and services themselves to the value they produce for customers, as myriad substitutes are now only a click away thanks to global supply chains. A key component of contemporary *"enterprise is value (co-)creation, which depends on the perspectives of various players in the value-creating system"* (Khan et al., 2021; Pereira & Frazzon, 2021), thus the arena for **open innovation** and **involving customers** (Abdelkafi Nizar, 2012) have become one of the key resources upon the so many other factors influencing supremacy.
- **Key Activities** outlines the most important tasks and processes that a company must undertake in order to execute its business model successfully, such as product development, marketing, distribution, or customer service (Ghezzi & Cavallo, 2020).
- **Cost Structure** details the various costs that a company incurs in order to operate its business, such as production costs, marketing expenses, employee salaries, or rent (Christensen et al., 2016).
- **Revenue Streams** outlines the ways in which a company earns revenue from its products or services, such as through direct sales, subscription fees, advertising, or licensing (Ghezzi et al., 2022).

- **Customer Segments** defines the specific groups of customers that a company is targeting with its products or services. A company may have multiple customer segments with different needs and preferences (Martins et al., 2015).
- **Distribution Channels** describes the ways in which a company reaches and interacts with its customers, such as through physical stores, online marketplaces, social media, or direct sales (Koilo, 2022).

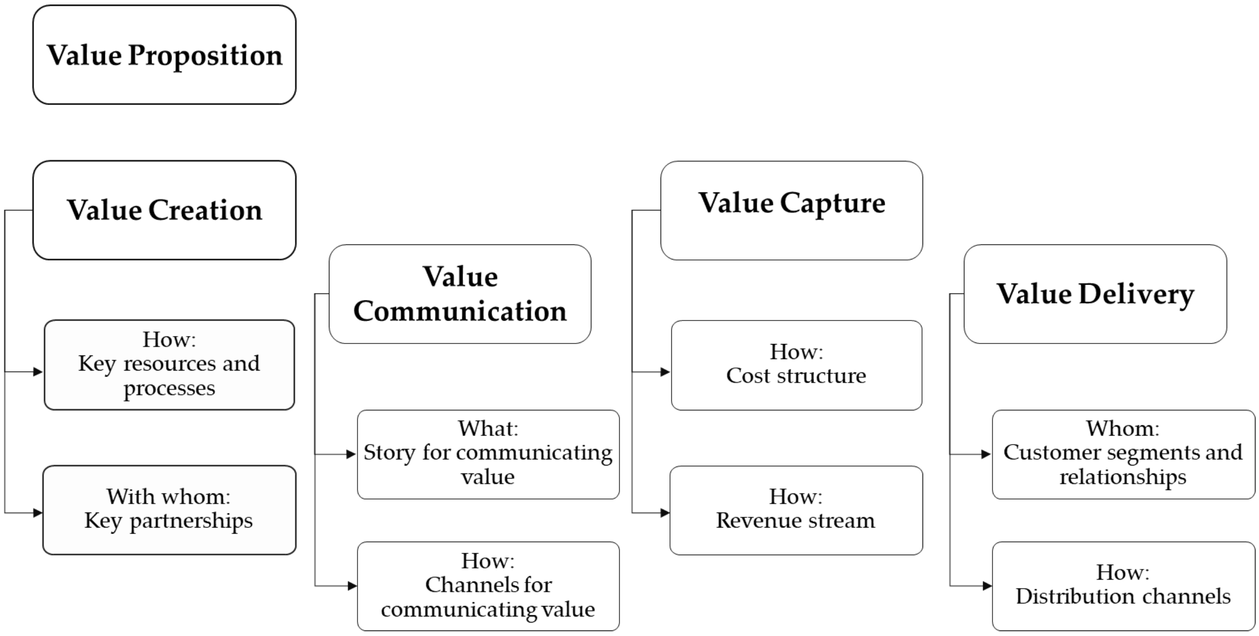

Figure 6.1: Business model Framework (According to Abdelkafi et al. 2013)

In conjecture with business model innovation, the study show that it is a step-by-step process that are performed in conjunction with the customers: *"value proposition definition, value provision design, and value-in-use delivery"* (Martins et al., 2015). Although Businesses may need to adapt their business models to stay competitive or capitalize on new technologies, these with a condition that, these business model innovations are *"costly, uncertain, difficult, and prone to failure"*(Christensen et al., 2016). Nevertheless, A number of research recognizes the processes that are involved at different stages of the business model innovation. Furthermore, based on the theory of showing how generative cognitive processes, aided by methods of *"analogical reasoning and conceptual"*(Assumpção et al., 2022; White et al., 2022) combining, can be used to achieve business model innovation.

Business model innovation from a supply chain perspective involves identifying new ways to create and capture value throughout the supply chain. This can involve

rethinking how products are designed, produced, distributed, and consumed, as well as exploring new revenue streams and cost-saving measures (Nasir et al., 2022). Moreover, the traditional supply chain management focuses on interorganizational interactions involving supplies, manufacturing, retailers, logistics operators, and customers from the perspective of operational and, as a result, economic improvement; but whereas the future of supply chain management looks at the interactions from the perspective of the drivers of economic results and **sustainable competitive advantages:** minimization of greenhouse gas emissions, environmental waste, and optimal resource utilization (Yan et al., 2022).

The introduction of new activities, new structures and/or new forms of governance of corporate activities are built on the context with respect to achieving social and environmental benefits, effectively changing the creation, delivery and recording of value (Niemeyer et al., 2022). From the example of Dell Inc. and Wal-Mart - ***to demonstrate value associated with the business models*** (Teece, 2018).

Walmart's business model is based on offering a wide range of products at low prices to attract price-sensitive customers. Walmart leverages its massive buying power to negotiate lower prices from suppliers, implementing **efficient supply chain** (Abdelkafi & Pero, 2018) and logistics management systems to reduce costs, and using economies of scale to keep prices low.

Dell, on the other hand, is a technology company that designs, develops, and sells personal computers, servers, storage devices, and other related products and services. Dell's business model is based on direct selling, which means that it sells its products **directly to customers** (Abdelkafi & Pero, 2018) through its website, phone, or mail. Dell has eliminated intermediaries such as retailers and distributors from its supply chain, which enables it to reduce costs and offer **competitive prices to customers**. Dell also offers customization options, which allow customers to configure their own computers according to their specific needs.

Dell and Walmart's business models *"were different, superior, and required supporting processes that were hard for competitors to replicate"*(McDonald & Eisenhardt, 2020). Thus, efficient, and effective business model design is crucial to creating a competitive advantage for an organization. The many components must be complementary to one another and effectively function as a system (Parmar et al., 2020).

6.2 Navigating the Implications for Business Model Innovation:

New goods or services and organisational changes have been among the most common internal factors that have helped companies innovate their *business models over the last two decades* (Koilo, 2022). Major external factors include technological advancements, environmental laws, and consumer preferences. In almost all industry systems and products are linked in a network, thereby any change along the supply chain impacts the entire network. Taking into account the innovation process in the forthcoming framework, the digital intellectual supply chain network grid enables the formulation of a theory about the immanence of innovation throughout the entire supply chain network (Rad et al., 2022).

The business model, which captures the fundamental processes by which business is conducted without getting into the specifics of operations, abstracts the complexity of operations and serves as a representation of that reality (Abdelkafi Nizar, 2012). The technology-oriented Supply chain Digital twin brings in a shift in data management, data flow and functionalities associated within the actors in supply chain.

Additionally, the size of the supply network will continue to decrease in the future thanks to the use of *"interactive data and information"*(Chen & Huang, 2021) throughout the supply chain, the feature makes it feasible for medium and short-term strategies to take precedence over long-term contracting strategies in a competitive environment. A few of the implications on Business model is discussed below:

6.2.1 Structural changes with the oncoming of SCDT:

Value creation has traditionally been classified as either *endogenous* (Bhandal et al., 2022; Liotine, 2020), focusing on internal initiatives to enhance supply chain performance, or *exogenous* (Bhandal et al., 2022; MacCarthy et al., 2016), spanning companies. However, it is also important to keep in mind that the supply chain functions as a sort of organisation where interdependencies, time, and shifting boundaries force firms to manage the relationships with supply chain actors effectively in order to successfully achieve the value goals of the focus firm.

The research conceded that one or many of the following factors have been strongly influencing the value creation all along:

- a **supplier relationship management (SRM) capability**: critical aspect of supply chain management that focuses on building and maintaining strong relationships with suppliers to ensure the reliable (Taeuscher & Abdelkafi, 2016) and timely delivery of goods and services at competitive prices.

- the **supply-side collaboration** (Koilo, 2022) enhances the performance of the supply chain in terms of a better stabilising effect and service level.
- higher levels of **customer cooperation** (Ghosh et al., 2021; Sjödin et al., 2020) have a significant effect on the rate of adoption of lean manufacturing, which is regarded as a key lever for value creation.

With the advent of digitisation, IT capabilities facilitate supply chains in sustaining **relational capital** (Bhandal et al., 2022). This Technological capability in Supply Chain Digital Twin, is used to acquire, process, and send information to support organisational decision-making as well as to enable communication, coordination, and collaboration between various parties along the supply chain (Marikyan et al., 2022). With digital twin technology, businesses are capable of quicker tests and implement changes in the supply chain operations without disrupting physical operations. This **agility** (Karagiannis et al., 2022) can lead to structural changes in the supply chain, such as the adoption of new processes, the introduction of new products, and the development of new business models.

In extension, Supply Chain Digital Twin offers dynamic capabilities that combines businesses, develop, and ***reconfigure internal and external competencies*** (ABDELKAFI et al., 2013; Rozhkov et al., 2022) to respond to quickly shifting and unpredictable environments. It is evident from the research study the Supply Chain Digital Twin's dynamic capacity in improvising organisational capability for strategic decision-making (Haftor & Climent Costa, 2023) while also reducing uncertainty through generating insights.

Moreover, with this collection of insights, Digital twin technology allows businesses to **collaborate more effectively** (McDonald & Eisenhardt, 2020; Teece, 2010) with suppliers, customers, and other stakeholders in the supply chain. This collaboration can lead to structural changes in the supply chain, such as the development of new partnerships, the creation of new supply chain models, and the optimization of supply chain networks.

6.2.2 SCDT leverages data management to help build Supply chain control tower:

The Supply chain control tower is a centralized platform that provides end-to-end visibility from monitoring all the process, modules, data flows in and among the various nodes and actors in the Supply chain of the organization (Ivanov et al., 2010).

The Supply chain control tower serves as a nerve centre for the supply chain, providing a single source of truth for all stakeholders, including suppliers, manufacturers, logistics providers, and customers (Yi et al., 2022). It collects and integrates data from various sources, such as sensors, ERP systems, and transportation management systems, and uses advanced analytics and visualization tools to provide insights and actionable intelligence (Marikyan et al., 2022).

A control tower is a central point which gives enhanced visibility on the activities that take place in the supply chain network (Aarikka-Stenroos et al., 2022). In this case, the control tower digital twin interacts and exchanges data between production, storage, and distribution (operational digital twin). The tower includes location models, linear mixed-integer optimization models (Bertoni & Bertoni, 2022), dynamic simulation techniques, multi-scenario what-if analysis to drive clear communication (Ivanov & Dolgui, 2021), and predictive analytics to predict supply chain changes and disruptions and enable better collaboration between stakeholders (Marmolejo-Saucedo, 2020).

A supply chain control tower can have a significant influence on a company's business model by enabling more effective supply chain management and improving the overall performance of the business.

- A supply chain digital twin can provide more accurate and precise information about the supply chain, and with this real-time data from the digital twin, the control tower can provide more **up-to-date insights into the supply chain** (Palkina, 2022) which is used to optimize the control tower's decision-making processes. This aids in reducing errors and in improving the efficiency of the supply chain.
- A supply chain control tower can help **identify bottlenecks and inefficiencies** in the supply chain (Kohtamäki et al., 2022), allowing companies to optimize their operations and reduce costs. This can help companies to remain competitive and increase profitability.
- A supply chain digital twin can simulate different scenarios and predict outcomes, allowing the control tower to plan and prepare for potential disruptions (Battistoni et al., 2023) or changes in demand. This can help improve **the resilience and agility of the supply chain**.
- By providing end-to-end visibility of the supply chain, a control tower can help ensure that products are delivered on time and in the desired condition. This can improve customer satisfaction and loyalty, which can be a key driver of business growth (Neto et al., 2020).

Recognizing and mitigating disruption risks is a major concern all over the world. In this scenario, the actors involved will benefit from the advantages of the real Supply Chain via the digital replica provided by Supply Chain digital twins. The digital twins will be a game changer in the implementation of an interconnected Supply Chain structure (M. Deng et al., 2021), to digitally link all members to reap the benefits of increased Supply Chain visibility, develop contingency plans (Ivanov et al., 2017), and identify and manage threads in networked Supply Chain.

6.2.3 SCDT formulating the futuristic collaborative business models:

One of the significant variables in overseeing a supply chain is having collaborative partners (Ghezzi et al., 2022). Digital twins are transforming the way supply networks conduct business by offering a variety of options to support collaborative settings, data-based decision making, and strengthening business procedures (Marmolejo-Saucedo, 2020). When combined with a supply chain digital twin, collaborative business models can lead to significant benefits for the entire supply chain. Setting up a sound relationship comes from a solid establishment of communication, common objectives, increased transparency, and mutual collaboration (Ghosh et al., 2021).

Observing on the supply chain operations, the partnership establishes a system that is perfectly balancing efficiency and effectiveness. Effective in handling all the pre-order operations digitally, a much better fit for the hyper-connected, web-driven economy of today, where customers demand instant gratification, customization, variety, and, often, personalization. And Efficient in operations such as adopting make-to-order or design-to-order, according to the scale of the order. This system alters the notion of supply chain as it centrally evolves around establishing the working models and business decisions based on the requirement driven from the customer.

Companies in the same supply chain are orienting towards how to reorganize their value chains with additional stakeholders to enable **resource sharing** (Grieves, 2015). Companies in various supply chains can begin to consider potential synergies that would allow waste, by-products, and other resources to be shared as inputs for their operating activities (Taeuscher & Abdelkafi, 2016). This can also be done with external industrial actors from a variety of industries. These synergies can take the form of industrial symbiosis.

In a similar fashion, the need for cohesion among different companies, even if they do not operate in the same supply chain stems to promote the sustainable objectives (Le et al., 2022), that are beginning to play prominent roles in our society. And resource management can be supported by information systems or the previously mentioned digital technologies that enable data tracking and analytics (Esfahbodi et al., 2023).

The digital twin is accomplished enough to examine any physical product at any stage on the factory floor and overlay the virtual product on top of it. This virtual product capability can be extended across multiple factories (Chen & Huang, 2021). This means that people all over the world can not only look at the performance of their own factory, but also compare it to factories in other parts of the world . A problem in one factory can be identified and controlled not only in that factory, but the solution can be immediately transferred and implemented in all other factories worldwide (Sleiti et al., 2022).

6.2.4 SCDT and adaptations to the Servitization

End users are at the centre of strategies and interactions thanks to the shift of conventional product-based business models into outcome-as-a-service (Christensen et al., 2016) models, which also offers useful data into product usage. Companies intend to implement condition-monitoring technologies and service billing structures in order to fully enable Servitization notions (Paiola & Gebauer, 2020). Within the decade, Servitization will play a big role in the logistics industry's new normal, with the shift to digitalization and reasonably priced IoT technology across industries. Companies can choose to pay for equipment utilization, typically per hour of operation or every item successfully picked, rather than spending a lot of money on expensive equipment like airplanes and robots.

In a 2019 poll of more than 400 worldwide manufacturers, 82% were *"actively researching or moving to servitize their businesses"*(Bodenbenner et al., 2020), according to an IDC white paper. There are valid causes behind this significant change. Servitized businesses outperform non-servitized rivals in terms of service revenue by 30% and have five times more room to grow their top line over 5% (Bodenbenner et al., 2020) annually. Furthermore, according to a Synchron Research analysis, 98% of the end customers polled prefer original equipment manufacturers to provide service agreements to increase product uptime.

Companies and governments can help by implementing socially responsible procurement policies. In the past, manufacturers sold assets to customers. However, in a world where waste is minimised, it is *far better for producers to retain ownership while selling a service to the customer* (Adel, 2022). Customers typically receive better overall service with maintenance and quality at the forefront. Manufacturers, in turn, can ensure that the product is serviced and maintained properly prior to its next cycle.

Over the past two decades, there have been more opportunities for working with other enterprises. Because of new digital technology, industrial enterprises have increasingly shifted downstream to offer services (Haftor & Climent Costa, 2023; Ivanov et al., 2021). Business model innovation could result from Servitization, a transition in the grounds for value creation and capture, even though the addition of services does not always result in this (Zott et al., 2011). The substitution of items with services, in which businesses make money by charging for a service rather than a commodity, is the most evident business model innovation in relation to services (Blecker & Abdelkafi, 2006).

By creating new value creation mechanisms through data-driven or product-as-a-service business models, Digital Twin not only strengthens conventional *business models and value chains but also expands them* (Manca et al., 2021).These are introduced into an ecosystem in an effort to reach out to new clients and collaborators in order to take advantage of fresh possibilities and revenue streams.

Service providers now have access to customers through more touchpoints, increasing the opportunity to strengthen customer loyalty and add value while also taking on additional risk and responsibility for parts (Ghezzi et al., 2022), technicians, and knowledge. Logistics stands at a critical position on this new equation due to the fact retaining the functioning of a servitized asset or fleet depends on the uninterrupted supply and delivery of parts (Rahmanzadeh et al., 2022). For instance, Fiat Chrysler Automobiles joined other automakers in offering automobiles as a service in 2019 and charging subscribers. A monthly subscription to access different car models without having to handle maintenance and repairs. Using applications and internet platforms, automakers can engage subscribers more regularly with personalized communications and extra offerings in settings other than aggravating auto repairs and dealership visits (Karagiannis et al., 2022).

6.2.5 SCDT to facilitate economically and ecologically viable businesses models:

New business models and services (Preut et al., 2021) can be created and provided based on the increased transparency provided by the digital twin along the complete product lifecycle. *Predictive maintenance and repair services* (Preut et al., 2021) are currently the most popular and talked-about solutions for this. By leveraging the data model of the physical object, design factors can be visualized, and its status data can be tracked (Wolters, 2019). Sensor data can be transmitted and analysed in near-real-time, allowing the virtual representation of the product to be instantly updated in response to any changes in its physical state. As a result, the digital twin enables direct and detailed monitoring of the physical counterpart.

The concept of ecological value creation, devised by the *"integration of technological and management* methodologies" (Koilo, 2022) has been the centre of various studies. In order to capture the value of innovation, a business model plays a significant part. Gathered from the literature analysis, there has been a strong connection with the evolution of technologies associating Supply chain Digital twins and sustainable value creation (Abdelkafi & Pero, 2018). These developments, furthermore, explain the importance and/or the methodologies that would be adopted for the exercising of ecological business transactions.

Supply chain Digital twins aid tremendously in tackling one of the biggest challenges in supply chain management - the lack of visibility and coordination (Abideen, Pyeman, et al., 2021) between supply chain partners. With Supply chain Digital twins, each supply chain partner can see the impact of their actions on the entire supply chain, enabling them to make informed decisions that benefit the entire system. Thus, With the availability of data from Supply chain Digital twins influences both **individual and organisational behaviour** (Taeuscher & Abdelkafi, 2016), which in turn impacts the other actors in the value chain.

Table 6.1: Summary of Business model Implications

Structural changes with the oncoming of Supply chain Digital twins	Value creation has traditionally been classified as endogenous or exogenous, but the research revealed that one or many factors have been influencing it. Digital twin technology enables businesses to acquire, process, and send information to support organisational decision-making and enable communication, coordination, and collaboration between various parties along the supply chain.
	Supply chain Digital twins also allows businesses to collaborate more effectively with suppliers, customers, and other stakeholders, leading to structural changes in the supply chain such as the development of new partnerships, the creation of new supply chain models, and the optimization of supply chain networks.
SCDT leverages data management to help build Supply chain control tower	The Supply chain control tower is a centralized platform that provides end-to-end visibility of the supply chain. Supply chain Digital twins enables Supply chain control tower to collect and integrate data from various sources, such as sensors, ERP systems, and transportation management systems, and uses advanced analytics and visualization tools to provide insights and actionable intelligence.
	A supply chain digital twin can provide accurate and precise information about the supply chain, allowing companies to optimize their operations and reduce costs. It can also simulate different scenarios and predict outcomes, improving the resilience and agility of the supply chain.
	Digital twins will be a game changer in the implementation of an interconnected Supply Chain structure, providing increased visibility, contingency plans, and management of threads.
SCDT formulating the futuristic collaborative business models	Collaborative partners are transforming the way supply networks conduct business by offering a variety of options to support collaborative settings, data-based decision making, and strengthening business procedures. This system balances efficiency and effectiveness, making it a better fit for the hyper-connected, web-driven economy.
	The Supply chain Digital twin can be used to examine any physical product at any stage on the factory floor and overlay the virtual product on top of it. This can be extended across multiple factories, allowing people to compare the performance of their own factory and also, to level up the performance metrics to global standards.

	End users are increasingly at the centre of strategies and interactions due to the shift of conventional product-based business models into outcome-as-a-service models. Companies are implementing condition-monitoring technologies and service billing structures to enable Servitization, which will play a big role in the logistics industry's new normal.
SCDT and adaptations to the Servitization	Business model innovation can result from Servitization, a change in the rationale for value creation and capture, and Digital Twin, which creates new value creation mechanisms through data-driven or product-as-a-service business models.
	Service providers now have access to customers through more touchpoints, increasing the opportunity to strengthen customer loyalty and add value while also taking on additional risk and responsibility for parts.
SCDT to facilitate economically and ecologically viable businesses models	Supply chain Digital twins provides visibility and coordination between supply chain partners, enabling them to make informed decisions that benefit the entire system. Data from Supply chain Digital twins influences both individual and organisational behaviour, which impacts the other actors in the value chain.
	The digital twin enables direct and detailed monitoring of the physical counterpart, enabling new business models and services.

7. Discussions and Managerial Implications

Starting from a conducive exploration of research that is covering the technicalities of Supply chain digital Twin. While such technology aids businesses in increasing the effectiveness, adaptability, and speed of the supply networks, the **societal, ethical, and economical** (Ghezzi et al., 2022) changes have continuously put those capabilities to the test, necessitating constant and quick adaptation.

The primary aspect is realising the supply chain network with the advent of digitalisation. Knowing the dynamic structure of Supply chain, Digital Twin agrees at all levels of integration spanning across all dimensions (Holopainen et al., 2022). In a way Digital twin established at all nodes of the supply chain interaction is similar in comprising several layers, including network structure, flows, process control algorithms, and operational parameters (Chen & Huang, 2021). The relationships between Digital twin and their use cases are numerous. However, the purpose of a Digital twin varies greatly depending on the use case.

From the research, the methodology derives out the factors interlinked with the upcoming digital transition. The analysis, in fact, yielded the most researched and discussed topics in the field of supply chain progressing with the said digitalisation.

Supply chain Operations impose a large amount data flow concerning a broad spectrum of applications, that necessitates Digital twins to have up to date by connecting to external systems and databases. Simulation and optimization models are critical components of the Supply Chain Digital Twin, which substantially states the use of Digital Twin has an immediate link to business profitability by providing visibility and automation that reduces supply chain costs (Kamble et al., 2022).

For instance, with integrating Supply Chain directly to customers' ERP systems, where selling and purchasing are automated and frictionless with the Digital Twin facilitated virtualisation on consignment stocks, not just at the inventory of suppliers and at the organisation, but rather at all the inventory level throughout the supply network could be optimised.

Not only do digital twins visualise Supply chain and associated risks, but they also provide overall supply network performance and forecasts of Supply chain interruptions and risks. Through the development of technologies (Battistoni et al., 2023) that provides assistance to firms in developing Supply chain resilience by providing **real-time and remote monitoring**. Although, Digital twin in Supply Chain Management, are not yet focused on autonomously controlling the system. The Supply chain digital twin covers an array of functions – from inventory management to order management, extending up to cash management (Badakhshan et al., 2022). With digital Supply Chain twins, important data such as financial key performance indicators (KPIs), inventory level, stock level, service level, capacity, and transportation data can be viewed in real time (Ivanov et al., 2010).

By simulating and creating what-if scenarios that predict the future impact, performance-based simulation models aid in the creation of efficient contingency plans to **prevent or recover from disruptions** (Ivanov & Dolgui, 2019, 2021). The dynamic potential of Digital twins is the capability it offers firms to completely reconfigure supply chain design in the light of anticipated disruptions. The findings show that businesses can use Digital twins to improve supply chain resilience (Khan et al., 2021; Kohtamäki et al., 2022).

Resilience has evolved to become an important supply chain characteristic, that can assist firms in surviving unexpected events, and it is especially important during a global health crisis such as Covid-19 (Burgos & Ivanov, 2021). The research findings provide a lens through which firms can instil survivability in their operations by utilising Digital twins' solutions to create dynamic capabilities (Teece, 2018). It is evident that the companies are already considering developing a Digital twin solution for supply chain resilience. Thus, the role of Supply chain Digital twins is paramount in developing supply chain resiliency in the **face of disruption risks** (Lee & Lee, 2021), as well as anticipated visibility in a large-scale and **dynamic business context** (Santos et al., 2020), allowing for the proactive generation of timely contingency and recovery plans.

Also, the studies provide new insights on how digital twin system support management decisions. Strategic modules enable continuous real-time data flow into the system and a physical or virtual constant connection, which allows the digital twin system to function as an integrated **multi-physics**, **multi-scale simulation** (Khan et al., 2021; Yan et al., 2022) of a dynamic management decision system. It systematically allows digital laboratories for commercial enterprise experiments of the ***"decision-***

making processes by incorporating feedback, delays, and non-linearities between variables" (Yan et al., 2022) that support executive decision-making environments rather than relying solely on subjective judgments in the decision-making process.

The findings from the academic study advocates that Digital twins describe the relationships between digitally instrumented assets and activities, modelling the interactions between an organization's various data sources. By enabling businesses to optimise their supply chain processes, supply chain digital twin technology has the potential to spur the development of new business models (White et al., 2022).

Digital twins can comprehensively traverse across different functional departments, continuously perceive customer needs, drive a **customer-centric operation model** (Ghezzi & Cavallo, 2020), and increase efficiency. Implementing a digital twin also necessitates close collaboration among various departments. Performance improvements generate value when the insights from the digital twin enable organisations to improve and expand the range of services and products. These performance enhancements are frequently the direct result of the search for **new digital opportunities** (Aheleroff et al., 2021). A simple example of how data collection leads to the creation of new goods and services that of would be - Netflix. On how Netflix collects extensive data on the movies that its customers enjoy and can create new shows to meet these demands.

A Digital Twin system essentially connects the product at all the stages, from manufacturing to customer-end, and supply chain stakeholders, allowing data from product operation, product application context, and user feedback to be collected. This data is the **most valuable asset** (Khan et al., 2021; X. Wang et al., 2021) in today's fiercely competitive society and can reveal a wide range of business possibilities.

With the Digital Twin system, extended to cover the entire product and service lifecycle, the system assists in creating a digital business ecosystem in which they can **co-create product-service offerings** (Bertoni & Bertoni, 2022) and values with customers and stakeholders. The ecosystem is generally defined by modular interfaces for different parties to provide products and services.

Thus, when IoT sensors and sophisticated analytics are integrated and considered holistically, it is determined to improve performance across four key dimensions: **'lowering operational costs, improving brand integrity and customer experience, identifying new revenue streams'** (Marmolejo-Saucedo, 2020; Sjödin et al., 2020), and providing competitive differentiation. Customers and end users can use these services and provide feedback to help improve them. With the level of data flow in and between the several digital twin in the supply chain network, the system along with supply-side actors, then use this feedback to improve their existing services or develop new ones (Paiola & Gebauer, 2020).

The literature review included in this research study indicates that prior research has widely recognised the value of Supply chain and digital twins for **enhancing dynamic capabilities** (Ivanov et al., 2021), which in turn reflects positively on the overall organisational performance. The Supply chain digital twin assists organisation's ability in capturing and administering large scale data in the process of value creation. Each and every decision in and across companies, resource accumulation from the entire supply network, and implementation strategies could be systematically explored with numerical data and the information available from the Digital Twin's (Harapko & Affinito, 2022). This will aid managers in making timely adjustments and good decisions while also enhancing knowledge management and organisational learning. A summary of the main findings coherent with this discussion is listed below:

1. **Improved supply planning:** The digital twin technology enables decision-makers to **visualize and analyse** the entire supply chain network, including suppliers, manufacturers, distributors, and customers. With the capability to **simulate different scenarios** (Pereira & Frazzon, 2021), Supply Chain Digital Twin enables decision-makers in optimizing the supply chain network to reduce costs, improve efficiency, and increase customer satisfaction.

2. **Enhanced risk mitigating capabilities:** Natural catastrophes, cyberattacks, and supplier bankruptcy are only a few examples of supply chain disruptions that can have a big impact on a global scale (Y. Wang et al., 2015). Supply Chain Digital Twin's with the highest level of data analytics, assess potential risks and effects of supply chain disruption, this information is then, used in creating backup plans.

3. **Improved decision-making:** By evaluating different scenarios, decision-makers can make informed decisions that consider the impact on the entire supply chain network. Utilize technology for data analysis and computer simulation to assist diversified scenario planning that supports future business development (M. Deng et al., 2021), reduce decision errors due to subjectivity and mental bias, and enable cross-disciplinary communication.

4. **Recognise and replicate the nature of Supply-chain in business setup:** The development of value derived from supply and demand, even though this development does not adhere to a single form, is at the core of business dynamics, despite changes in the market environment, consumer behaviour (Barykin et al., 2020), technological advancements, the supply chain and

business model, competitor strategies (Kamble et al., 2022). The life cycle or stage of any industry or product provides a range of business opportunities and second curves with open innovations for the market's expansion.

5. **Increased collaboration:** Collaboration between various divisions and supply chain participants, including suppliers, manufacturers, logistics providers, and customers, can be facilitated by the use of digital twin technology. Organizations may be able to tailor their goods and services to meet the requirements of particular customers thanks to supply chain digital twin technology, organizations can create customised supply chain models (Kolomoyets & Dickinger, 2023) that address particular consumer needs by simulating various scenarios and studying customer data.
6. **New business models:** Supply chain digital twin technology can enable organizations to develop new business models that leverage their supply chain capabilities. By simulating different scenarios and analysing market data, organizations can identify new market opportunities and develop innovative supply chain models that create value for customers and stakeholders.

Besides, developing digital twins can integrate current, historical, and decentralised business data, as well as support for various application scenarios. Smart supply chain with a digital twin network not only have a more friendly human-computer interface, but also the function of "self-optimization," or automatically adjusting based on user habits and use characteristics, providing consumers with a better use experience. Consequently, the establishment of an entire Supply chain digital twin facilitates information communication between departments, reduces resource waste caused by information asymmetry, and can bring all stakeholders into the operation of enterprises, which is beneficial to the social benefits of entire organisation.

8. Conclusions and Directions for future research

This study addresses on the fundamentals of Supply chain digital Twin to generate the various advantages in the business setting. The key takeaways from the literature analysis, portray on by what means the digital twin, as an emerging technology, will significantly expand supply chain capabilities. The literature review further, elaborated on the horizons of how interconnected the various aspects of technological advancements are. In fact, the keyword network analysis aided in understanding the impacts of the many sub-systems that contribute to the massive changes such as Cyber-physical systems, Sustainability centred Industry 5.0 in the upcoming future.

The proceedings in the digitalization, has the potential to reshape every aspect of an enterprise's operations, as multi-varietal coordination, and division of labour among enterprises will bring benefits under the condition of resource sharing. With the advent of IoT devices and other digital technologies, there is an abundance of data available about every aspect of the supply chain. A digital twin can leverage this data to provide insights and optimize operations. Thus, the digital twin makes supply chain network more flexible and predictive, lowering risks associated with uncertainties.

Following the Literature analysis, the factors that drive Supply chain digital twin was explored. With the advent of growing technology, the complexity of handling and incorporating the systems also grows. The Supply chain digital twin is a system that is founded on these enabling technologies. A detailed study on how these various data analytics to simulation to modelling technique aid in shaping up the features of Supply chain digital twin is presented.

Supply chain Digital Twin is strongly associated with improving the supply-demand equilibrium, as it makes it possible to establish a synchronisation of data, material, and financial transactions. Real-time data from physical Supply Chain is used by digital twins, including data from RFID, track and trace devices, and online risk databases. With the help of a digital twin, Manufacturers, and other stake holders in the supply chain, can anticipate operational failures, and decrease downtime. The goal is to enhance the visibility of services and processes by disseminating information among supply chain stakeholders.

It is thus evident from the research that, high-tech manufacturing equipment that gives consumers access to customised products via digital twin technologies, interconnected networks, and smart devices would have an impact on the supply chain environment. Supply chain and factory-level digital twins are best suited to profit from capital-intensive industries with intricate and highly engineered production processes. The digital twin can be used to assess design options before making capital commitments during the design and investment period of expensive assets, which maximises efficiency and cost and reduces risk. The same digital twin can be used to manage highly complex, time-dependent processes that vary frequently due to variability in the availability of resources, such as people and equipment, through careful production scheduling.

The Supply Chain Digital Twin, in addition to changing the manufacturing process, also converges logistics integration in forming a supply network. This digital form of the supply networks' interconnected grid is discernible, with the digital core at its centre. Since every node in the network has the potential to interact with any other node therein, enabling increased connectivity in previously unconnected regions. In this Supply Chain Digital Twin arena, interactions are bidirectional, forming a connection between previously unrelated supply chain links. A Supply chain digital twin is built by integrating the data from each separate value link into a digital virtual entity. This interconnectedness greatly impacts enterprises, to realise benefits from increased resource efficiency, user experience optimization, etc.

Resilience remains vital in a supply chain functioning. Supply chains' resilience allow recovery and adaptation when the Supply chains are exposed to and impacted by changes in operational and environmental factors. Supply Chain Digital Twin is equipped with the technology to try hypothetical scenarios and calculate the effects of changes on the Digital twin supply chain network. The Supply Chain Digital Twin combines optimisation models, and dynamic simulation methods into performing what-if multi-scenario analysis, increasing Supply Chain resilience through quicker and more accurate identification of potential external and internal disruptions and disturbances as well as through the minimization or avoidance of their negative effects.

This further emphasises on how Supply Chain Digital Twin allows manufacturers to gain a better understanding of their supply chain network, resulting in a better business ecosystem creation by building a virtual model with real-world data sources. Customers can better participate in value-added activities in virtual space with the help of the digital twin, which will greatly expand increase the variety of products and services available and promote open innovation. In addressing business opportunities across their value chain, enterprises must take a systematic approach more importantly, businesses are on the outlook to shift from an enterprise-centred to a user-centred approach. This can significantly improve enterprise efficiency and effectiveness, as well as user experience.

In extension, However, few limitations are to be considered. To begin with, the research predominantly exhibits the foundations of the Supply chain based on expert studies and a few companies that are at the very beginning of developing this technology. Starting from ideation of digital twin knowledge to the integration of various coming of age technology that are essential for the operations of this Supply chain digital twin, are in fact found only from theoretical research studies.

In addition to the research based on theoretical studies, there is a catch here though, and it has to do with how these data are collected and data management is handled. As this system makes use of real-time data from operational processes, a large portion of the data is third-party data, which could be data that are held by private entities or public bodies both local and foreign. This raises concerns about data acquisition and data quality. These are issues beyond the control of firms, but they must be considered from the start of an investment project to develop a Digital twin for supply chain.

The analysing and quarrying the value of the massive data collected by the digital twin using only the enterprise itself is insufficient. As a result, the enterprise's internal departments, users, and external partners should collaborate to change the previous segmented process and split information state. Organisations at all levels, must share data with the other entities involved along the chain, to fully capitalise on the value of the digital twin, however, with the assistance of external partners and encourage partners to participate in innovation.

Furthermore, firms would need to ensure an effective internal data management system to support such an initiative, as well as the necessary technological infrastructure capabilities to house the technology. following up, the research covers the effect of these technological highlights in the face of upcoming business models.

These findings of this research could be further explored in the future, on the aspects concerning the downstream applications in the supply chain, such as sales and marketing and last-mile delivery. Applications such as a Digital Twin-enabled 3D model to layout a floor plan and a Digital Twin enabled interface in a last-mile delivery system where customers can directly see and interact with the operations and delivery process could consolidate transparency and add more value to retailers' products and services.

Actors of the supply chain are in a unique position to gain knowledge from properly constructed research on the advantages of a supply chain digital twin to inspire strong and flexible supply chain architecture. A digital twin approach to supply chain resilience and risk management offers many opportunities for empirical research, particularly in the form of case studies that could produce real knowledge about its particularities, difficulties, and advantages. Subsequently, previous research has focused on the digital twin at the shopfloor or unit level, rather than the entire supply chain or customisation organisation level. Digital twins are quickly moving beyond the manufacturing landscape.

Having said that, this paper is a preliminary investigation of the Supply chain digital twin-enabled applications and its potential business transitions. Future empirical research might adopt a more contextual approach in addition to the areas of study mentioned above with the goal of comprehending the Supply chain Digital twin system in various economic sectors.

Furthermore, Future studies could build on systems or creation of a scale that would allow the concept of "digital twin capabilities" to be measured. In addition to this, further research could examine the connection between digital twin capacity and value manifestations like business performance and customer happiness. This will also make it possible to closely investigate the precursors or facilitators of the digital twin capabilities. These innovations would advance the subject and draw in a wider range of academics.

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