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The Challenges of Modern Supply Chains

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BUSINESS AND DIGITAL TRANSFORMATION

Chapter 1

Digital Transformation of Supply Chains

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1.1 Origin and Development of Digital Technologies in Supply Chains

The concept of the supply chain was first introduced in Kransdorff's article, "Booz Allen's Rather Grandly Titled Supply Chain Management Concept", published on June 4, 1982, in the *Financial Times* (Szozda & Świerczek, 2016), thus marking the beginning of efforts to integrate product flows, starting with the development of Integrated Inventory Management (I2M). The article presented the viewpoint of Oliver from the consulting firm Booz Allen Hamilton, who emphasised the need to blur the artificial boundaries between production, marketing, sales, distribution, and finance, advocating for their treatment as an interconnected whole rather than as separate, independent functions (Szozda & Świerczek, 2016). This approach aligns with the Sales and Operations Planning (S&OP) framework but extends beyond departmental integration to encompass the organisational structures of entire companies. The supply chain concept's emergence signified its growing importance in management sciences (Lalonde, 1997). Indeed, scholars have argued that it has transformed the competitive landscape of business management, shifting the focus from individual companies competing against each other to competition between entire supply chains (Christopher, 1998; Drucker, 2007). The term "supply chain" originally denoted the coordination of material, raw material, and product flows among various entities within the chain, with its early development primarily occurring in manufacturing companies (Chopra & Meindl, 2007).

The evolution of the supply chain concept has been a subject of significant amount of academic debate. The concept has expanded over time to encompass the management of all functions related to flows between companies within a network composed of suppliers, manufacturers, and buyers. This network also includes distributors, retailers, and customers (Choi et al., 2001). As a result, supply chain management has expanded beyond achieving only operational goals to also include strategic objectives. This expansion is illustrated in Figure 1.1, which presents the classical understanding of this concept.

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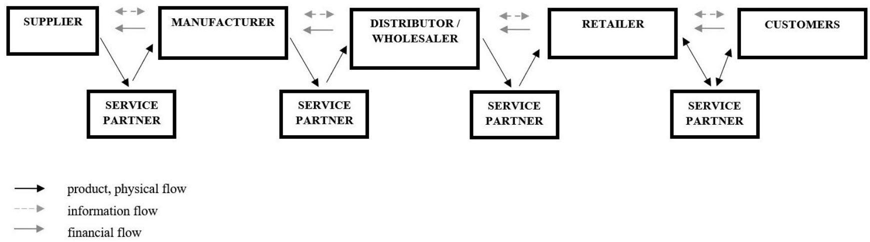

Figure 1.1 Supply chain structure.

Source: Own study

In one of the first significant articles on the subject, titled "Integrating the Supply Chain", Stevens (1989) stated that the primary goal of the supply chain is to synchronise customer demands with the flow of materials and products to maintain a balance between conflicting objectives: a high level of customer service, low inventory levels, and low unit costs. In this context, the supply chain began to be perceived as a single, cohesive process.

The management of such a large and complex system, which has expanded to a global scale over the years, necessitates technological support, particularly with regard to enhancing communication between its components. Consequently, when discussing the supply chain, Information and Communication Technologies (ICT) play a pivotal role. The evolution of ICT within the supply chain is illustrated in Figure 1.2.

The development of ICT in supply chains can be traced back to operations management and the emergence of the Material Requirements Planning (MRP) system (Ptak & Smith, 2011). The primary objective of MRP was to enhance production planning and inventory management. The MRP system was first implemented and computerised in the early 1950s by aero-engine manufacturers Rolls-Royce and General Electric. However, at that time, it was neither formally named nor commercialised. In 1964, in response to the requirements of the Toyota Manufacturing Programme, Orlicky and his team developed a system that was subsequently named MRP. The first company to adopt this system in 1964 was Black & Decker. A significant breakthrough occurred in 1975 with the publication of "Material Requirements Planning: The New Way of Life in Production and Inventory Management" (Orlicky, 1975), which facilitated the widespread adoption of MRP systems across manufacturing companies. This represented a major advancement in the organisation of production flows, as MRP was the first methodology to integrate procurement with distribution, enabling the calculation of material requirements based on product demand (Ptak & Smith, 2011).

Building upon the MRP methodology, a distribution inventory management system known as Distribution Requirements Planning (DRP) was

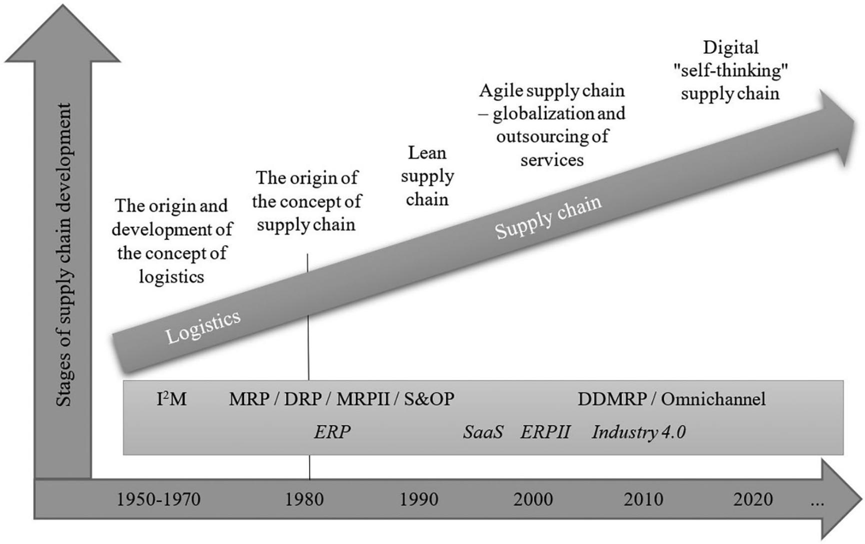

Figure 1.2 Timeline of concepts, methods, techniques, and tools in the ICT domain used in the supply chain.

Source: Own study

developed. DRP represents the application of MRP principles to the distribution phase of the supply chain, enabling the planning of product distribution within distribution channels based on demand forecasts. The system calculates the optimal quantity of goods that should be held at various transhipment points and warehouses to minimise transportation and storage costs while simultaneously meeting customer demand. The first academic publication on DRP appeared in 1978, and, by 1981, it had been implemented in a commercial company for the first time.

During the 1980s, the MRP system underwent an evolution that led to the emergence of MRP II (Manufacturing Resource Planning). This development marked a significant expansion of the system's scope, transcending the boundaries of material inventory planning to encompass the comprehensive planning of all resources within manufacturing companies. Often referred to as manufacturing resource planning, MRP II integrated not only inventory management but also operational and financial planning. This included the development of operational plans, such as production scheduling, production control, and workforce management, as well as financial planning (Ptak & Smith, 2011).

In the context of an examination of the development of ICT within the domain of supply chains, it is imperative to give due consideration to the S&OP system. This system was first established in 1983 and is widely regarded as a seminal moment in the evolution of operations management.

S&OP can be defined as an integrated business management process that ensures alignment, synchronisation, and coordination across all organisational functions, including logistics, marketing, sales, finance, and production. The S&OP process encompasses a number of key aspects, including demand planning, production planning, inventory management, customer order lead times, new product development, strategic initiatives, and the corresponding financial plans (Bozarth & Handfield, 2019).

It is evident that both MRP and MRP II systems, as well as DRP and S&OP, address certain aspects of a company or supply chain. However, they lack a comprehensive approach to the interdependencies between departments or between collaborating companies within the supply chain. In the 1990s, with the increasing availability of personal computers and the development of computer networks, the need emerged to integrate all departments within a company into a single, cohesive system. This development gave rise to the emergence of Enterprise Resource Planning (ERP) systems, which began to consolidate functions previously managed separately by MRP, MRP II, and other applications or systems. By creating a unified database, ERP systems enabled a seamless flow of information across departments, from procurement and production to distribution (Jacobs, 2007). Early providers, such as SAP, Oracle, and JD Edwards, offered solutions that facilitated comprehensive management of resources, production, finance, and logistics.

Following the year 2000, the development of the Internet and cloud technologies gave rise to further changes, thus representing a significant step in the evolution of ICT within the supply chain. The shift to Software as a Service (SaaS) models resulted in lower implementation costs, whilst simultaneously enhancing system flexibility and scalability. The emergence of ERP II was a response to the growing need to integrate internal company systems with the external environment, encompassing business partners, suppliers, and customers, whilst leveraging internet technologies. This evolution commenced in the early 21st century, approximately between 2000 and 2005, with traditional ERP systems being augmented with functionalities that facilitated inter-organisational collaboration and enhanced support for e-commerce processes. Modern ERP systems integrate additional features, such as Customer Relationship Management (CRM), Supply Chain Management (SCM), Business Analytics (BA), and technologies such as big data (BD), Internet of Things (IoT), and artificial intelligence (AI).

In the 21st century, a further concept has gained significance: Demand-Driven Material Requirements Planning (DDMRP), an innovative SCM methodology developed in response to the limitations of traditional MRP systems. DDMRP is referred to as demand-driven MRP, integrating well-established elements of MRP, DRP, lean management, and Six Sigma (Ptak & Smith, 2016). The DDMRP operates as a pull-based system, where inventory levels are determined by real-time, dynamically changing demand.

This approach enables companies to respond not only to fluctuations across the entire supply chain but also within individual entities of the network.

Following 2010, a shift in the development of ICT within the supply chain was observed, marking the onset of the Fourth Industrial Revolution, otherwise referred to as Industry 4.0 (Kagermann et al., 2013). The concept of the smart factory, in which production processes operate automatically, is the genesis of Industry 4.0 (Hermann et al., 2016). This development is characterised by the communication of centrally controlled devices in a manner analogous to social networks. The integration of machines and production materials into networks enables the autonomous organisation of manufacturing beyond company and national boundaries, thereby achieving optimal efficiency (Szozda, 2017a). This paradigm shift has given rise to a novel approach, which integrates systems and establishes networks that connect people with digitally controlled machines through ICT and the Internet. Consequently, this results in the centralisation of functions within the supply chain, with companies establishing global SCM centres and platforms. This change has been made possible by moving information into the virtual space, also known as the cloud (Szozda, 2017a). The arrival of Industry 4.0 has caused a major change in SCM through the introduction of new technologies that fundamentally change how it works. The fundamental principles of Industry 4.0 encompass automation, integration of information systems, data analytics, and real-time communication among all participants in the process, from raw material suppliers and manufacturers to end consumers (Pfohl, 2015). The overarching objective of Industry 4.0 is to revolutionise SCM by transforming traditional, often fragmented processes into highly efficient and flexible integrated systems.

The development of new technologies was accelerated by the emergence of the COVID-19 pandemic in late 2019 and subsequent global spread in 2020 (Choi et al., 2020). This period has been characterised by significant disruptions in the functioning of global supply chains, particularly in supplier collaboration. At the same time, it has defined the trajectory of their further evolution – towards operations that emphasise rapid adaptation to environmental changes. The pandemic has necessitated the reorganisation of supply flows, changes in raw material sourcing models, and adjustments in distribution strategies (Haren & Simchi-Levi, 2020; Linton & Vakil, 2020), which in turn have driven the rapid evolution of digital technologies in SCM. The integration of contemporary solutions, encompassing cloud-based systems, IoT, blockchain, AI, and BD, has been instrumental in facilitating enhanced integration and optimisation of processes. This, in turn, has resulted in enhanced responsiveness to disruptions and greater operational transparency. Supply chain disruptions led to a shift in focus towards customers, resulting in solutions that align with the principles of customer-centric supply chains. The pandemic also triggered a significant breakthrough in product distribution, with sales moving into the virtual space and product deliveries becoming increasingly personalised, relying on dedicated transport models commonly referred to as door-to-door delivery. This shift has driven transformations in distribution channels, evolving from multichannel models to omnichannel strategies aimed at delivering a seamless customer experience.

In the period following the pandemic, lasting changes have reinforced digital transformation as the foundation of modern supply chain operations, emphasising flexibility, security, and innovation. The pandemic necessitated fundamental shifts in many supply chains, and these changes continue to evolve. Specific technologies have gained broader application in optimising business processes, improving SCM, and enhancing data analytics, further driving the digital transformation of supply chains.

1.2 Current Trends in ICT in the Context of Supply Chains

The implementation of new, advanced technologies is a fundamental requirement for the digital transformation of supply chains. Digital transformation, accelerated by Industry 4.0, consists of a set of over 60 technologies and concepts related to the application of Industry 4.0 in supply chains, which can be analysed through the following dimensions: (1) mobility, (2) network collaboration, (3) automation, (4) socialising, (5) transparency, and (6) modularisation (Pfohl, 2015). Lee et al. (2014) present a slightly different perspective, categorising digital transformation technologies and concepts in supply chains into four groups: (1) data and connectivity, (2) analytics and AI, (3) human-machine interaction, and (4) automated machinery. Similarly, Berger and BDI identified four key technology groups in their report "The Digital Transformation of Industry" (Roland Berger, 2015): (1) digital data, (2) automation, (3) connectivity, and (4) remote customer access. A common denominator across these classifications is data, connectivity, and communication, and it is these ICT-related areas that are considered to have the greatest impact on supply chains. The integration of ICT technologies facilitates the establishment of interconnected networks among various entities, including supply chain companies, customers, machines, devices, products, and services, thereby enabling the transition of supply chain process management into the virtual domain. This transition is facilitated via software, systems, applications, and technology-enhanced products that enable remote connectivity.

The ICT technologies most frequently cited in the literature as significant and influential in supply chains (Choi et al., 2022; Zhang et al., 2024; Nowicka & Szymczak, 2020), as well as those that have been the focus of academic research in recent years (Zhang et al., 2023), include BD, cloud computing, IoT, 5G, automatic identification and data capture (AIDC), cyber-physical systems (CPS), 3D printing, blockchain, and AI. Additionally, increasing attention is being given to emerging solutions such as digital twins and augmented reality (AR), wearable computing, and control towers. The subsequent section provides a concise synopsis of these technologies, accompanied by their implementation within supply chains.

BD technology enables the collection of electronic information flowing into the SCM system. These systems are capable of handling diverse and dynamic data types, including both structured and unstructured data, as well as real-time streams and batch-processed information (Dygaszewicz, 2014). The analysis of substantial datasets facilitates the storage, retrieval, processing, and analysis of extensive databases, thereby generating novel insights and knowledge within the supply chain. This process also enables the identification of trends and correlations (Raman et al., 2018; Lee et al., 2014). A notable application of this technology in supply chains encompasses the development of dynamic pricing personalisation models and the analysis of waste generated within a closed-loop supply chain to minimise its volume.

Large datasets are typically stored and processed in the cloud, which enables uninterrupted access to supply chain system resources, particularly online data (Wu et al., 2013). The cloud is a term used to describe data centres accessible to multiple users and supply chain entities via the Internet. It is associated with the virtualisation of data access, as information is transferred into the digital space and hosted on servers. This facilitates concurrent access and utilisation of data and information by disparate supply chain entities. Cloud computing technology in supply chains encompasses platforms for managing customer orders and real-time inventory tracking (Ivanov et al., 2022). Supply chain entities with access to cloud-based data can synchronise information pertaining to demand forecasts, orders, inventory levels, warehousing, transportation, and production.

The advent of fog computing represents a significant development in the realm of cloud computing. This emerging concept functions as a form of mini-cloud, serving as an intermediary in the transmission of data between devices and the central cloud infrastructure. The proliferation of devices connected directly to the cloud can impede the efficient transmission of real-time data. To address this, an intermediary layer, termed fog computing, has been developed to collect and process data from devices, objects, and supply chain entities, thereby enhancing autonomy and mitigating potential risks associated with data access delays (Nowicka & Szymczak, 2020). This technology is particularly beneficial in supply chains with a large number of distributed, network-connected entities.

The term 'IoT' was first introduced in 1999 by British technology pioneer Kevin Ashton in the context of utilising radiofrequency identification (RFID) technology within Procter & Gamble's supply chain (Ashton, 2009; Szozda, 2017b). The term refers to the integration of physical objects within information systems to create a unified system for data exchange (Weber & Weber, 2010). IoT technology pertains to the direct or indirect capacity of objects and devices to collect, process, share, or exchange data through network connections (Shimizu & Hitt, 2004; Yu et al., 2016). The application of IoT is evident across all functional areas of the supply chain. It enhances visibility by providing real-time access to the attributes of connected objects, ensuring that all supply chain participants can access relevant information at any time (Haddud & Khare, 2018). Robots and drones are used for inventory inspections and tracking the location of items, products, or hazardous materials across different supply chain companies. The collected information is transmitted in real-time to other entities or cloud computing systems via IoT technology.

One of the examples of IoT and AR implementation is wearable technology. The nomenclature of this technology is deliberate, as it refers to its mode of use, which is to be worn on the body. It is embedded in products worn by individuals, such as smartwatches or devices that monitor vital signs. These wearables constitute a network of physical objects equipped with electronics, sensors, and software, thereby enabling connectivity with each other, as well as with other devices, objects, and supply chain entities, without the need for human intervention (Shafique et al., 2019). An example of a widely adopted wearable technology in the supply chain is Google Glass, which supports warehouse workers in order picking, among other applications (Knight et al., 2015).

IoT is only feasible in the context of mobile communication technology, which has now reached its fifth generation (5G mobile networks) (Zhang et al., 2024). 5G has the potential to achieve data transmission speeds of up to 10 Gb/s, latency below 1 ms, increased network capacity to support billions of devices, as well as enhanced security, reliability, and significant energy savings. The advent of 5G technology has paved the way for the digitalisation of numerous local processes within the supply chain, encompassing domains such as manufacturing, warehousing, and transportation. This digitalisation, in turn, can usher in a new era of fully digitised supply chains, thereby enabling digital processes at the network level (Zhang et al., 2024).

Another emerging technology that is becoming increasingly important in SCM is the digital twin. This technology enables the creation of a digital replica – a virtual ecosystem of business processes – that mirrors real-world operations (Haag & Anderl, 2018). It represents a digital, virtual reality model that is as dynamic and evolving over time as its physical counterpart. Digital twins allow for testing and simulation, including scheduling, queuing, and prioritising tasks within the network of interdependent supply chain processes. This enables risk-free decision-making while reducing uncertainty. For example, an automotive manufacturer is developing a digital twin to monitor the flow of components and finished products along the production line, helping to identify and eliminate bottlenecks in manufacturing.

One of the most important groups of technologies supporting the digital supply chain, widely implemented in various structures and closely linked to connectivity, is AIDC. This includes barcodes, QR codes, RFID, biometrics (such as iris and facial recognition systems), optical character recognition (OCR), smart cards, and voice recognition (Pfohl et al., 2015). Within the supply chain, AIDC technology allows products to be tracked at every stage of their flow, regardless of their location. It collects product data and integrates it directly into computer systems. Each time a product is removed from a store shelf or warehouse shelf, it is recorded in the system and then stored in the cloud, making this information accessible to all entities in the supply chain. An example of an AIDC application in the supply chain is a virtual inventory control system that operates in real time. When stock levels approach critical thresholds, the devices automatically send notifications that trigger a replenishment process. The embedded software in these systems identifies and determines the exact amount of goods to be reordered, ensuring that stock levels remain sufficient. Such solutions move inventory management into the virtual domain, minimising the risk of material or product shortages.

CPS, also referred to as intelligent systems, are defined as the integration of computational layers with physical processes that communicate over a data infrastructure (Lee, 2008). This means that these systems facilitate the connection between the virtual and physical worlds, ensuring coordination between computational and physical components. CPS are used to monitor and control devices, as well as the processes in which these devices operate (Lee et al., 2015). Within the supply chain, CPS enable both vertical and horizontal integration between supply chain entities. They facilitate the real-time transfer of data and information between physical and virtual environments, ensuring high levels of synchronisation, control, visibility, and efficiency across supply chain links. This, in turn, improves overall productivity and performance (Oztemel & Gursev, 2020). An example of CPS in the supply chain is ensuring that raw materials and components come from the intended source and have not been altered or substituted in transit from supplier to recipient. This contributes to the cybersecurity of the supply chain, helping to detect and prevent illicit activities.

An important ICT-based technology in the development of the digital supply chain is the control tower. This advanced software solution functions as a central hub for overseeing, monitoring, and coordinating supply chain processes, ensuring real-time visibility (Zhang & Xiao, 2023). Control towers have been designed to manage and regulate decision-making processes and their execution across various functional areas and between companies, optimising the entire network in alignment with strategic goals as well as short- and long-term decisions. The primary objective of a control tower is to enhance supply chain performance and improve efficiency (Salah El Din et al., 2023). Such technologies are essential for maintaining operational fluidity, enabling rapid responses to emerging issues, and optimising processes. An example of a control tower solution is provided by Blue Yonder, a system powered by AI and machine learning. This system facilitates both automation and optimisation across the entire supply chain, thereby enabling businesses to respond more swiftly to market changes, detect disruptions, forecast trends, and make effective operational decisions.

Another technology that has been identified as aiding the digital transformation of the supply chain is blockchain technology. This is a system that is used for storing and transmitting information about transactions conducted over the Internet. The information is structured in sequential blocks of data, with each block containing records of a specific number of transactions. Once a block reaches capacity, a new block is created, followed by another, forming a continuous chain of data (Biedrzycki, 2016). In supply chains, blockchain technology is primarily utilised for processing buying and selling transactions. It enables the elimination of intermediaries, allowing for real-time settlement between supply chain participants at the moment of goods receipt, which can also be automated through product registration, such as via RFID gateways. An example of the use of blockchain in the supply chain is the collaboration between Walmart and IBM. In this case, blockchain is used within the food supply ecosystem to ensure greater control over the flow of food products. It is applied to processes such as monitoring product quality and verifying the origin of goods, including tracing the supply chain of mangoes sold in the United States and pork distributed in China. The use of blockchain technology has significantly reduced the time required to verify the origin of products, cutting the process from seven days to just 2.2 seconds (Hoffman, 2021).

AI, as opposed to the natural intelligence exhibited by animals, including humans, refers to intelligence demonstrated by machines. It involves the creation of models and programs that simulate, at least partially, intelligent behaviour. AI is defined as an "intelligent agent", which observes its environment, learns from it, and adopts behaviours necessary to achieve a specific goal or solve a problem (Russell & Norvig, 2009). AI technology forms the foundation for self-learning computer systems, enabling machine learning – a branch of AI dedicated to algorithms that improve and refine themselves automatically through exposure to data or, in other words, experience (Cichosz, 2000). An example of AI application in supply chains includes autonomous vehicles and the automation of production and resource extraction systems. Furthermore, AI-driven systems are utilised for data analysis and classification, such as the categorisation of products based on specific criteria, including thematic groups, consumption patterns, or pricing.

3D printing, otherwise referred to as additive manufacturing, is a process that facilitates the production of three-dimensional objects and products based on computer models (computer-aided design – CAD or digital 3D models) (Liaw & Guvendiren, 2017). The 3D printing process encompasses various processes in which material is deposited or fused under computer control to create a three-dimensional object. In the context of the supply chain, 3D printing is primarily utilised for customised production. This technology enhances supply chain flexibility, reduces order fulfilment time, and minimises inventory levels. For instance, Adidas has been working for several years on integrating 3D printing into its running shoe production, with the technology currently being used for manufacturing midsoles. Looking ahead, Adidas has announced its goal of creating perfectly customised footwear. In the future, customers visiting a store will be required to run on a treadmill for a few minutes. The collected data and foot scan will then serve as the basis for producing a personalised shoe using 3D printing technology.

1.3 An Attempt to Define the Digital Supply Chain

The large-scale adoption of advanced ICT technologies is driving the transformation of supply chain structures. These technologies enable real-time monitoring and analysis of flows, support product customisation, and facilitate the development of value-added services (Colin et al., 2015). Supply chain structures that extensively leverage ICT are commonly referred to as digital, smart, or cloud supply chains. However, these terms are not synonymous. Among them, the cloud supply chain represents the most narrowly defined concept, situated within the broader framework of the digital supply chain.

The concept of a cloud supply chain, which is shown in Figure 1.3, can be defined as the integration of all operational processes (e.g. logistics, warehousing, manufacturing, procurement, sales, and returns) and all supply chain flows (i.e. material, informational, and financial) with all supply chain actors (i.e. suppliers, manufacturers, distributors, retailers and customers) within digital platforms and ecosystems. This structure is understood as an integration of advanced SCM concepts and digital technology based on a dynamic, situational composition of physical services into networks (Ivanov et al., 2022). The key determinant of whether a supply chain can be classified as a cloud supply chain is the use of cloud technology.

An intelligent or smart supply chain is a more advanced version of the cloud supply chain, where cutting-edge ICT technologies connect processes among different partners, forming a single, intelligent, and interconnected system (Zhang et al., 2023). This concept is often referred to as a "self-thinking" supply chain, emphasising the integration of all systems and entities into a unified ecosystem (Calatayud et al., 2019). The foundation of this supply chain is supported by three primary technology groups: IoT, cloud computing, and AI, which enable the development of product-service systems. These technologies generate vast amounts of data, which are stored and analysed in real-time through IoT and AI. This allows for continuous monitoring of supply chain performance, as well as early detection and management of potential risks. Additionally, this approach enhances demand forecasting for products and enables predictive maintenance of equipment and machinery, leading to continuous process optimisation. With AI, decision-making

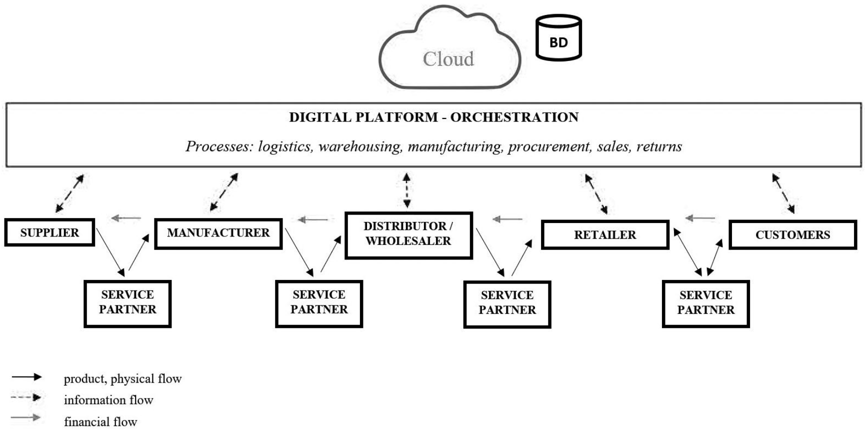

Figure 1.3 Cloud supply chain.

Source: Own study

can be automated, allowing for adjustments at both individual supply chain links and the entire system level. This adaptability enables the supply chain to quickly respond to an increasingly complex and uncertain environment. Cloud technology provides real-time access to data, facilitating the monitoring of both product demand and available production and distribution capacities. As a result, it becomes possible to regulate (accelerate or slow down) the flow of materials, raw materials, and products at various stages of the supply chain.

The configuration of a smart, self-thinking supply chain is illustrated in Figure 1.4.

The digital supply chain represents a further development in this field, integrating the cloud supply chain and the smart supply chain. In addition to key attributes such as real-time access to information through a unified system and intelligence – meaning the ability to obtain insights and knowledge that enable rapid and well-informed decision-making regarding the supply chain – the digital supply chain is characterised by automation, integration, agility, cyber-awareness, continuity, and sustainability (Szozda, 2022; Nowicka, 2019; Wu et al., 2016).

An example of the digital supply chain model (DSCM) within Industry 4.0 is presented by Garay-Rondero et al. (2020), who identified six key dimensions, as illustrated in Figure 1.5.

The first dimension forms the core of the model, utilising cloud computing and cloud robotics (Calatayud et al., 2019). It functions as the "brain" of the system, integrating AI to enhance the flexibility of digitalised supply chains, allowing them to respond rapidly to changing conditions.

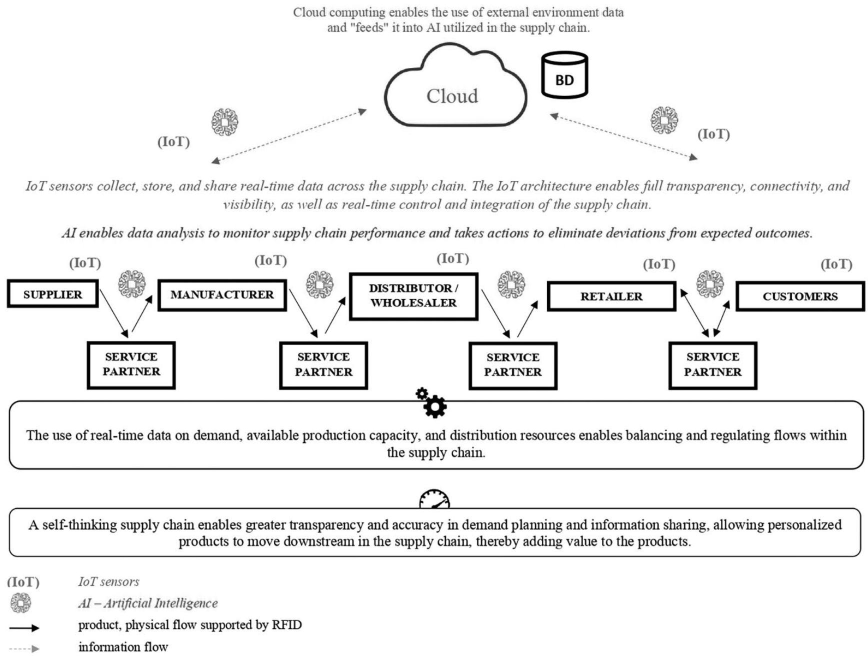

Figure 1.4 Smart supply chain.

Source: Own study

The second dimension describes the physical network structure, which is interconnected with Industry 4.0 technology enablers and features through CPS and control tower technology.

The third dimension focuses on the implementation of Industry 4.0 concepts, enablers, and features, ensuring seamless integration within the supply chain.

The fourth dimension revolves around key flows within the supply chain, including inbound material flow, outbound finished product/goods flow, service flow, information flow, knowledge flow, financial resources flow (money/profit), as well as risk and return flows of goods and services.

The fifth dimension is the virtual value chain, providing a holistic view of the entire supply chain while leveraging Industry 4.0 technology enablers. Its primary objective is to ensure transparency, communication, collaboration, flexibility, responsiveness, and accuracy throughout the entire structure.

The final, sixth dimension represents the convergence of the digital and physical worlds, forming a new system where real and digital environments merge and interact symbiotically.

In all of the presented concepts of cloud, smart, and digital supply chains, cloud technology has been placed at the centre of the supply chain. However,

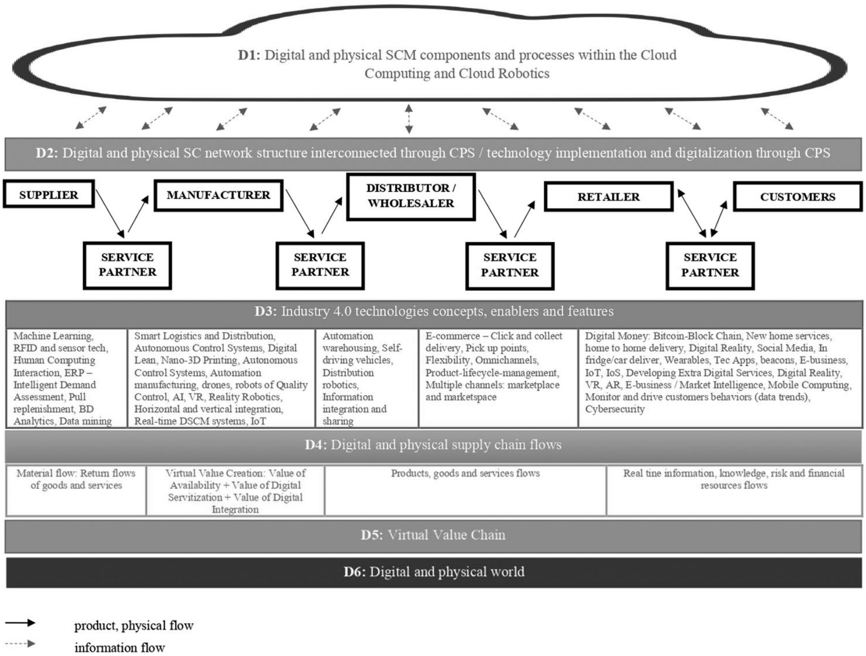

Figure 1.5 Digital supply chain model (DSCM) in Industry 4.0.

Source: Own study

it is crucial to acknowledge that these systems have been designed to facilitate a customer-centric approach, as illustrated in Figure 1.6.

The digital supply chain employs a range of technologies from the field of industrial digital transformation, otherwise referred to as Industry 4.0, at all points in its structure. These supply chains are distinguished by the integration of management and automation of decision-making processes. Significantly, automation is applied to supply chain processes that do not add value, while machine learning is employed in areas where AI can be implemented. The digital supply chain offers greater agility, responsiveness, and adaptability. Researchers from the Gartner group have identified a number of factors that contribute to agility in supply chains, including the use of multiple organisational models, known as modules. This modular approach enables agile business process design and management, facilitating the seamless switching between modules when necessary. Consequently, the digital supply chain is both flexible and highly integrated. Digital transformation facilitates the easy integration and removal of partners and supply chain links as needed. While significant attention is given to information flows in the digital supply chain, the security of financial transactions is equally important. To ensure secure transactions, blockchain technology is employed. Transparency in supply

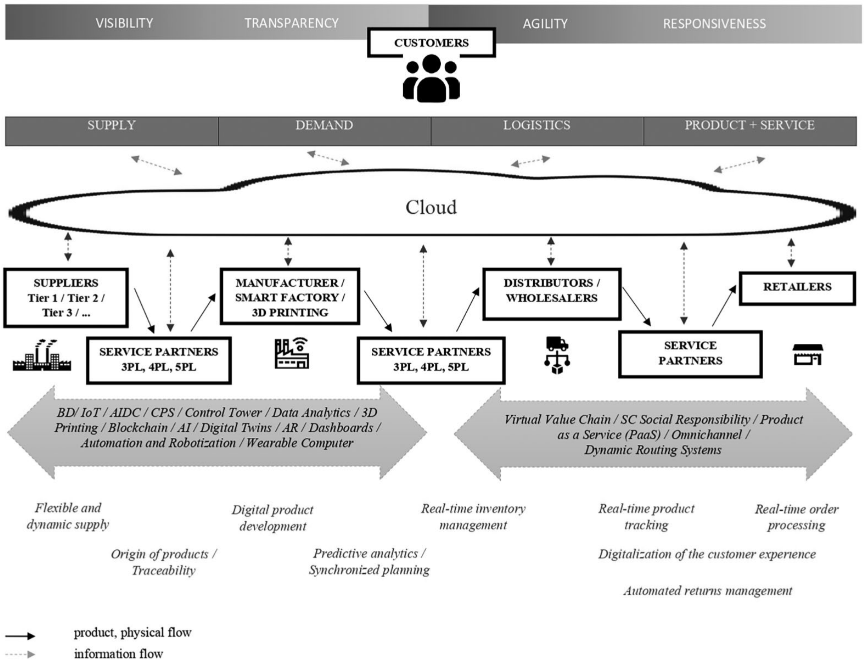

Figure 1.6 Digital supply chain: customer-centric approach.

Source: Own study

chain processes, resilience to disruptions, and proactive risk mitigation are critical factors. Enhanced transparency is essential for the supply chain to be truly customer-centric, enabling the production and delivery of personalised products and services. In a digital supply chain, the customer is placed at the centre. The integration of lean and agile concepts within such a structure is a key consideration. By taking into account production capabilities and the transparency of available information, the optimal point for product and service customisation can be determined, with customers playing an active role in the design and manufacturing of products. Through the use of additive manufacturing and 3D printing, products are increasingly personalised, and spare parts are becoming instantly available. The digital supply chain operates continuously, 24 hours a day, 365 days a year. It also supports sustainable operations, addressing the need to reduce the negative impact of human activity and industry on the environment. It serves as a tool for implementing sustainable supply chain concepts, enabling the creation of circular supply chains (Nowicka & Szymczak, 2020). Sustainability in this context goes beyond ecology to include the promotion of healthy ecosystems. It also includes taking care of employees and working with suppliers and customers by promoting partnership-based relationships and socially responsible practices. Supply chain leaders are setting ambitious environmental targets to reduce emissions, water, and energy consumption, use of natural resources, and elimination of hazardous waste, particularly in manufacturing facilities.

1.4 Challenges and Discussion Points

A study conducted by the Gartner group (Aronow et al., 2017) has revealed that changes in supply chain structures moving towards digital supply chains are most noticeable in Europe, North America, and Asia. However, the full implementation of a digital supply chain comes with numerous challenges. Digital supply chain transformation remains a work in progress, still in its developmental phase, and only a few organisations can claim to have structures that can, to some extent, be considered digital (Preindl et al., 2020). It is important to note that transforming a supply chain into a digital one is not a simple task – it is a highly complex process. The transformation process necessitates the presence of specific conditions, processes, and capabilities, particularly the expertise of experienced managers, to successfully reconfigure resources (Sousa-Zomer et al., 2020). The degree of readiness for digital transformation among companies varies extensively. While some organisations adhere to classical strategies grounded in mission-driven and long-term visions, others demonstrate a notable absence of long-term planning. Research conducted in 2017 and 2018 by Nowicka (2019) highlights that supply chains have begun the process of digital transformation in their operations and processes. However, this shift is not yet driven by a broader strategic planning perspective but rather by external environmental demands. The ongoing digital transformation of supply chains has been further accelerated by the global pandemic of the Coronavirus (SARS-CoV-2), which has acted as a catalyst for this trend. A study undertaken by Randstad-Ifo among the managerial staff of German companies found that for approximately 55% of firms, the pandemic marked a period of digital transformation. During the pandemic, 31% of surveyed companies introduced new digital solutions, while another 36% intensified the use of existing digital tools (Corona digitalisiert die deutsche Wirtschaft, 2020).

The implementation of new technologies within supply chain structures and the transition towards digital frameworks have the potential to engender a competitive advantage. However, this process is not without its challenges, including the availability, reliability, and cost of adopting new technologies; the need to integrate modern tools with traditional operating systems; information sharing and data security against cyber threats; and adapting to the increasing expectations of consumers (Zhang et al., 2023).

A significant limitation in implementing digital supply chain transformation is the lack of technological infrastructure in the manufacturing sector, particularly for small- and medium-sized companies. There is also a shortage of skilled personnel, resulting in a considerable gap between new job