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Postgraduate Dissertation

«A Study of Communication Technologies for Smart Supply Chain and Warehousing»

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Preface

The main reason for choosing this dissertation topic was my interest in Supply Chain Management and Logistics. I wanted to further explore how modern supply chains operate and how digital technologies are transforming this field.

In addition, I was particularly interested in studying 5G technology, as it is closely related to my professional field and current technological developments. The combination of supply chain management and advanced communication technologies provided an opportunity to examine a topic that is both academically interesting and practically relevant.

Through this dissertation, I expanded my knowledge of digital supply chains, smart logistics and next-generation communication networks, while also gaining a better understanding of their applications and future potential.

« A Study of Communication Technologies for Smart Supply Chain and Warehousing»

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Abstract

The rapid development of digital technologies has significantly transformed modern supply chain and logistics operations. Increasing globalization, growing customer expectations and the need for greater efficiency, resilience and sustainability have encouraged organizations to adopt advanced digital solutions capable of improving supply chain performance and operational effectiveness. Technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning, Blockchain, Cloud Computing and Digital Twins have become essential components of modern digital supply chains, enabling real-time monitoring, data-driven decision-making and enhanced collaboration among supply chain partners.

At the same time, the evolution of communication technologies has created new opportunities for the development of smart supply chain ecosystems. In particular, fifth-generation (5G) mobile networks provide high-speed connectivity, low latency and reliable communication capabilities that support intelligent logistics systems, smart warehousing, autonomous operations and large-scale IoT deployments. Furthermore, emerging sixth-generation (6G) technologies are expected to extend these capabilities by enabling more advanced levels of automation, intelligence and integration between physical and digital environments.

This dissertation investigates the role of digital technologies and advanced communication networks in modern supply chain and logistics systems. Particular emphasis is placed on the impact of 5G and 6G technologies on supply chain transformation, operational performance, resilience and intelligent logistics applications. The study also examines the integration of Artificial Intelligence, Digital Twins and Unmanned Aerial Vehicles (UAVs) within 5G- and 6G-enabled environments. A qualitative research methodology based on an extensive literature review is adopted to analyze current developments, challenges, opportunities and future trends.

The findings indicate that advanced communication technologies play a critical role in the development of intelligent, connected and resilient supply chain ecosystems. The convergence of 5G, 6G, Artificial Intelligence and emerging digital technologies is expected to significantly influence the future of supply chain management and logistics, creating new opportunities for innovation, automation and sustainable growth.

Keywords: Supply Chain, Logistics, UAV, Artificial Intelligence, 5G, 6G.

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List of Abbreviations & Acronyms

Abbreviation	Full Meaning
3GPP	3rd Generation Partnership Project
4G	Fourth Generation Cellular Technology
5G	Fifth Generation Cellular Technology
6G	Sixth Generation Cellular Technology
AI	Artificial Intelligence
AI-BDAC	Artificial Intelligence-Driven Big Data Analytics Culture
AIGC	Artificial Intelligence Generated Content
AIIoT	Artificial Intelligence of Things
AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface
AR	Augmented Reality
ARIMA	AutoRegressive Integrated Moving Average
B5G	Beyond Fifth Generation
BDA	Big Data Analytics
BLE	Bluetooth Low Energy
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CNN	Convolutional Neural Network
COVID-19	Coronavirus Disease 2019
CPS	Cyber-Physical Systems
CPPS	Cyber-Physical Production Systems
CSC	Cold Supply Chain

Abbreviation	Full Meaning
C-V2X	Cellular Vehicle-to-Everything
DNN	Deep Neural Network
DSC	Digital Supply Chain
DSRC	Dedicated Short Range Communications
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
ERP	Enterprise Resource Planning
GC	Green Communication
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HD	High Definition
HSCA	Humanitarian Supply Chain Agility
HSCP	Humanitarian Supply Chain Performance
HSCR	Humanitarian Supply Chain Resilience
HVAC	Heating, Ventilation and Air Conditioning
IC	Information Complexity
ICT	Information and Communication Technologies
IIoT	Industrial Internet of Things
IoT	Internet of Things
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LAN	Local Area Network
Li-Fi	Light Fidelity
LLM	Large Language Model

Abbreviation	**Full Meaning**
LPWAN	Low-Power Wide-Area Network
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MAC	Medium Access Control
MES	Manufacturing Execution System
mMTC	Massive Machine-Type Communications
MQTT	Message Queuing Telemetry Transport
NFC	Near Field Communication
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
PLC	Programmable Logic Controller
QoS	Quality of Service
QR	Quick Response
RAN	Radio Access Network
RFID	Radio Frequency Identification
RQ	Research Question
SC	Supply Chain
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SCRes	Supply Chain Resilience
SDN	Software-Defined Networking
SME	Small and Medium-sized Enterprise
TCP/IP	Transmission Control Protocol / Internet Protocol
TSN	Time-Sensitive Networking
UAV	Unmanned Aerial Vehicle
UAVs	Unmanned Aerial Vehicles

Abbreviation	**Full Meaning**
URL	Uniform Resource Locator
URLLC	Ultra-Reliable Low-Latency Communications
USB	Universal Serial Bus
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VLC	Visible Light Communication
VR	Virtual Reality
Wi-Fi	Wireless Fidelity
WMS	Warehouse Management System

1. Introduction

Supply Chain Management (SCM) has become one of the most important functions in modern organizations, as it supports the flow of products, services, information and resources from suppliers to final customers. Over the last few decades, globalization, increasing customer expectations, technological advances and growing market competition have significantly increased the complexity of supply chain operations. Organizations are now required to manage extensive networks of suppliers, manufacturers, logistics providers, warehouses and distribution channels while maintaining efficiency, flexibility, resilience and sustainability.

To address these challenges, supply chains have undergone a significant digital transformation. The emergence of digital technologies has changed the way supply chain activities are planned, monitored and managed. Traditional supply chains relied heavily on manual processes, fragmented information systems and limited visibility across operations. In contrast, modern digital supply chains utilize advanced technologies to improve connectivity, information sharing, automation and decision-making. Technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Blockchain, Cloud Computing, RFID systems, Digital Twins and Machine Learning have become key enablers of intelligent and data-driven supply chain operations.

At the same time, organizations face increasing risks and disruptions that can affect supply chain performance. Recent events such as global pandemics, geopolitical instability, natural disasters, cybersecurity threats and market uncertainty have highlighted the importance of supply chain resilience and risk management. As a result, companies are increasingly investing in digital technologies that improve visibility, support predictive decision-making, enhance operational flexibility and strengthen resilience across supply chain networks.

The development of Industry 4.0 has accelerated the integration of digital technologies into supply chain and logistics operations. Industry 4.0 promotes the use of connected devices, cyber-physical systems, automation technologies, real-time data analyticsand intelligent decision-support systems. These technologies enable organizations to improve operational performance, optimize resource utilization, increase responsivenessand support more sustainable business practices. More recently, the concept of Industry 5.0 has extended this approach by emphasizing human-centered innovation, sustainability, collaboration between humans and intelligent systems and the development of resilient industrial ecosystems.

Among the various technologies supporting digital transformation, communication technologies have emerged as a critical component of smart supply chains. Modern logistics and supply chain systems require reliable, high-speedand low-latency communication networks capable of supporting real-time monitoring, automation, intelligent transportation systems, smart warehousing and large-scale IoT deployments. In this context, the introduction of fifth-generation (5G) mobile networks has created new opportunities for digital supply chain development. Compared to previous communication technologies, 5G offers significantly improved data transmission speeds, lower latency, enhanced reliability and support for massive machine-type communications. These capabilities enable more efficient supply chain operations and facilitate the deployment of advanced technologies such as Artificial Intelligence, Digital Twins, autonomous systems and unmanned aerial vehicles (UAVs).

While 5G is currently driving digital transformation across multiple industries, researchers and technology providers are already exploring the capabilities of sixth-generation (6G) networks. 6G is expected to further enhance communication performance through ultra-low latency, higher data rates, advanced intelligence and seamless integration between digital and physical environments. These capabilities are expected to support the next generation of smart supply chains, intelligent logistics systems, industrial automation and future Industry 5.0 applications. Furthermore, the convergence of

5G, 6G, Artificial Intelligence, UAV technologies and intelligent logistics systems may significantly transform the way supply chains operate in the future.

The aim of this dissertation is to investigate the role of advanced communication technologies in modern supply chain and logistics systems, with particular emphasis on 5G and emerging 6G networks. The study examines how these technologies contribute to supply chain transformation, operational performance, intelligent logistics, automation and future digital ecosystems. In addition, the dissertation explores the interaction between communication technologies and emerging digital solutions such as Artificial Intelligence, UAV systems, Digital Twins and smart warehousing technologies.

To achieve this objective, the study addresses four main research questions. The first research question investigates how 5G technology contributes to supply chain transformation and operational performance. The second examines the integration of 5G with emerging smart technologies, including Artificial Intelligence, Digital Twins and UAV-based systems. The third research question focuses on the role of 6G technologies in future smart supply chains and logistics environments. Finally, the fourth research question explores the convergence of Artificial Intelligence with 5G and 6G technologies and its contribution to intelligent logistics, smart warehousing and future industrial ecosystems.

This dissertation adopts a qualitative research approach based on a comprehensive literature review. Academic journal articles, conference papers, scientific publications, industry reports and other relevant sources are systematically reviewed in order to identify current developments, technological trends, applications, challenges and future opportunities associated with digital supply chains and advanced communication technologies.

The structure of the dissertation is organized as follows. Chapter 2 presents the theoretical background of supply chains, including supply chain resilience, challenges, risk management and sustainability. Chapter 3 examines digitalization in supply chains and discusses the main digital technologies supporting modern supply chain operations. Chapter 4 describes the research methodology and presents the research questions and literature review process. Chapter 5 focuses on 5G technology, its characteristics, applications, architecture and interaction with Artificial Intelligence and UAV systems within supply chain and logistics environments. Chapter 6 examines 6G technology and explores its future role in intelligent supply chains, logistics systems and industrial applications. Finally, the dissertation concludes by summarizing the main findings, discussing practical implications and identifying future research directions.

Overall, the continuous evolution of communication and digital technologies is reshaping the future of supply chain management. Understanding the opportunities, challenges and implications associated with 5G and 6G technologies is essential for organizations seeking to improve operational performance, increase resilience, support innovation and develop the next generation of smart supply chain ecosystems.

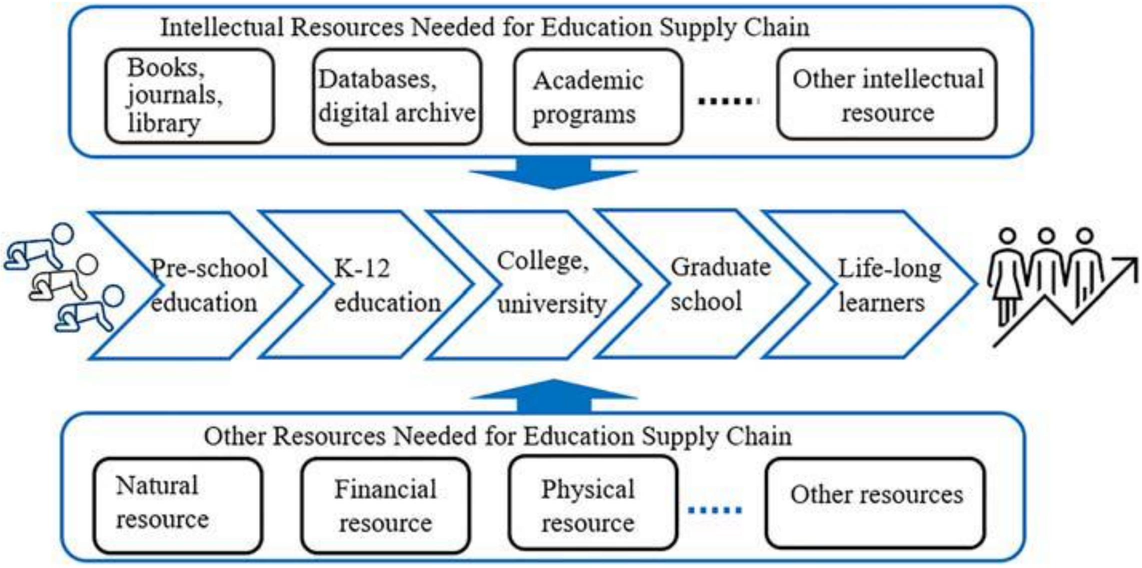
2. Supply Chain

2.1 Theoritical background of Supply Chain

2.1.1 Basic Concepts and Supply Chain Definition

Supply chain management is a fundamental concept in modern business operations, as it describes the coordinated flow of products, services, information and resources from the initial source of supply to the final customer. A supply chain is not limited to transportation or product delivery, but instead represents a broader system of interconnected activities that work together to create and deliver value. These activities include planning, sourcing raw materials, production, storage, distribution and customer service. The main objective of supply chain management is to ensure that products and services are delivered efficiently, at the right time, in the required quantity and at an acceptable cost [166].

From a theoretical perspective, a supply chain can be understood as an integrated network of organizations, processes and stakeholders that interact continuously to achieve common operational goals. This systems-based understanding is clearly reflected in the conceptual model presented in the paper [144], where supply chain logic is described through the interaction of multiple interconnected elements rather than isolated activities. Although the paper focuses on education as a specific application of supply chain thinking, the visual framework demonstrates an important theoretical principle: supply chains operate through coordinated flows of resources, information and participants across multiple stages. This systems perspective helps explain why supply chains should be studied as dynamic and interconnected structures rather than simple linear delivery mechanisms.



1Figure : Interactions in an education supply chain [144].

A traditional supply chain typically includes suppliers, manufacturers, distributors, retailers, logistics providers and final customers. Each participant has a specific role, but the performance of the entire supply chain depends on the effectiveness of coordination between all actors. Material flows move products from suppliers to customers, while information flows move in both directions, enabling communication, forecasting, inventory control and decision-making. Financial flows also form an essential part of the supply chain, supporting purchasing, payments, investments and contractual relationships. Because these flows are interconnected, delays or disruptions in one part of the network can affect the performance of the entire system [166].

The systems approach shown in the conceptual figure of also emphasizes that supply chains involve not only physical goods, but also knowledge, infrastructure, human participation and operational support mechanisms. This broader understanding is important because modern supply chains are increasingly complex and depend on coordination between both physical and digital resources. In practice, supply chain management requires balancing operational efficiency with flexibility, resilience and responsiveness to changing market conditions. As global business environments become more uncertain, supply chains are expected to adapt rapidly while maintaining continuity of operations [144].

A widely accepted theoretical framework for understanding supply chain operations is the Supply Chain Operations Reference (SCOR) model. The SCOR framework provides a structured and standardized way to describe supply chain processes across industries. The visual structure of the SCOR model presents supply chain management as a sequence of interconnected management functions rather than isolated business activities. This framework is particularly useful because it offers a common language for analyzing supply chain performance, identifying operational inefficiencies and designing improvement strategies [166].

According to the SCOR model, supply chain activities are organized around six primary processes: Plan, Source, Make, Deliver, Return and Enable. Planning refers to balancing demand and available resources in order to establish operational strategies and production schedules. Sourcing involves the procurement of materials, products and services from suppliers. Making represents the production or transformation stage, where raw materials are converted into finished goods. Delivery includes warehousing, transportation, order management and customer fulfillment activities. Return refers to reverse logistics processes, including defective products, excess inventory and product recovery. Finally, the Enable function supports all other supply chain activities through management of data, technology, performance measurement, human resources, compliance and risk control [166].

The inclusion of the Enable process is particularly important in modern supply chain theory because it reflects the increasing importance of supporting infrastructure and managerial coordination. Traditional supply chain models often focused only on material movement, but modern frameworks recognize that effective supply chains require technological integration, data visibility, workforce management and continuous performance monitoring. This broader perspective is especially relevant in digital supply chains, where operational success depends heavily on information systems and intelligent coordination mechanisms [166].

Another important theoretical concept within supply chain management is performance measurement. The SCOR model highlights key dimensions such as responsiveness, agility, reliability, cost efficiency and asset management. These dimensions help organizations evaluate how effectively their supply chains perform under normal operating conditions as well as during disruptions. Responsiveness reflects how quickly customer demands can be fulfilled, while agility measures the ability of the supply chain to adapt to unexpected changes. Reliability focuses on consistent operational performance, whereas cost and asset efficiency relate to financial sustainability and resource utilization [166].

The Digital Supply Chain (DSC) represents the evolution of the traditional supply chain through the integration of advanced digital technologies and enhanced connectivity across its operational functions. Key characteristics of a DSC include rapid responsiveness to demand fluctuations, flexibility in adapting to changes in market conditions and supply chain operations and the ability to achieve global connectivity and real-time coordination among stakeholders. Furthermore, the DSC supports continuous innovation and process improvement by enabling the early identification of potential issues and reducing the risk of operational disruptions. Intelligent technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI) and smart sensors, play a critical role within this environment by generating and utilizing large volumes of data. These technologies enhance decision-making processes, improve visibility across the supply chain and contribute to the optimization of planning, sourcing, production, delivery and return activities, ultimately increasing the overall efficiency and performance of the supply chain network [12].

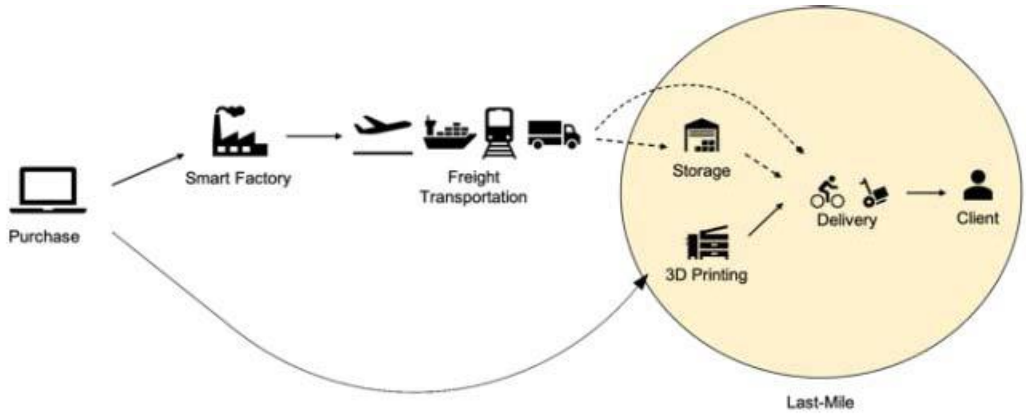
Understanding these theoretical foundations is essential for analyzing the evolution of supply chains in the context of digital transformation. Modern supply chains are no longer static operational systems, but intelligent ecosystems that combine physical logistics processes with information technologies, automation and real-time decision-making. The theoretical models presented in the selected literature provide the conceptual basis for understanding how supply chains evolve toward more connected, adaptive and technology-driven systems. This foundation is particularly important for the following chapters, where advanced technologies such as 5G, 6G, Artificial Intelligence and UAV systems are examined in relation to supply chain transformation.

2.1.2 Supply Chain Models and Theoretical Frameworks

Supply chain models and theoretical frameworks are important because they provide a structured way to understand how supply chain systems operate. Instead of viewing supply chains as simple product movement processes, these frameworks present them as organized systems where different activities, participants and decisions are connected. Visual models are particularly useful because they simplify complex operational relationships and show how supply chain processes interact with each other. This helps create a clearer theoretical understanding of supply chain management before examining advanced digital technologies in later chapters.

One of the most recognized supply chain frameworks is the SCOR model, which presents supply chain operations as a structured sequence of interconnected activities. The visual design of this framework shows that supply chain management is not based on a single operational task, but on multiple coordinated processes that support the movement of products and information. The model clearly separates activities such as planning, sourcing, production, delivery and returns, while also introducing supporting functions that enable the entire system to operate effectively. From a theoretical perspective, this visual structure demonstrates that supply chains function as integrated operational systems rather than isolated business activities [166].

Another important characteristic shown in supply chain frameworks is the role of coordination between different participants. In more modern conceptual models, supply chains are presented as collaborative environments where suppliers, service providers, manufacturers and customers are connected through continuous interaction. The visual representation of these systems emphasizes the importance of communication, information exchange and shared decision-making. Instead of following a rigid linear process, supply chain activities appear as dynamic relationships between multiple people, showing that modern supply chains are increasingly flexible and interconnected systems [27].



2Figure : Product journey [27].

Agribusiness supply chains provide an illustrative example of the complexity and diversity of modern supply chain structures. Unlike traditional manufacturing supply chains, agribusiness systems incorporate multiple interconnected actors, including input suppliers, farmers, processors, distributors, retailers and consumers. These supply chains often operate across national and international markets and are influenced by economic, environmental, social and regulatory factors. The literature highlights that agribusiness supply chains increasingly function as complex ecosystems where collaboration, coordination and value creation occur across multiple stages of production and distribution. This broader perspective reinforces the view that supply chains should be understood as interconnected networks rather than simple linear flows of products and information [69].

The smart supply chain framework further expands this perspective by visually presenting supply chain management as an intelligent and adaptive ecosystem. The structure of this model illustrates how operational decisions are influenced by data, digital technologies and collaboration between stakeholders. Rather than focusing only on physical logistics activities, the framework demonstrates that supply chain performance depends on continuous information flow, strategic decision-making and the ability to respond quickly to changing conditions. This visual approach reflects the transition from traditional operational models toward more responsive and technology-supported supply chain structures [27].

Another useful theoretical model is the conceptual framework linking digital transformation, smart technologies and business performance. The visual structure of this framework shows that supply chain performance is no longer influenced only by operational efficiency, but also by the integration of digital systems and intelligent technologies. The diagram presents a relationship where technological adoption supports stronger operational performance through improved coordination and smarter processes. This perspective is important because it introduces supply chain theory as something that evolves with technology rather than remaining fixed in traditional logistics structures [135].

Cloud-based theoretical models provide another perspective on supply chain design. In the visual architecture presented in cloud manufacturing frameworks, supply chain operations are represented as distributed networks of resources, services and decision layers. Instead of showing production as a centralized activity, the diagrams illustrate multiple service nodes connected through digital platforms, where tasks are assigned, scheduled and coordinated dynamically. These visual models demonstrate how modern supply chain theory increasingly includes flexibility, distributed resource management and digital service orchestration as core operational principles [143].

An especially important feature in these visual cloud-based frameworks is the integration of transportation and service coordination into a single operational model. The diagrams show that supply chain decisions are not limited to production or inventory management, but also involve routing choices, service availability and network-level optimization. This broader visual representation supports the idea that modern supply chains operate as coordinated ecosystems where logistics, manufacturing and information systems interact continuously. Such frameworks are particularly useful when examining advanced digital logistics environments [143].

When comparing these theoretical frameworks, a clear evolution can be observed. Traditional models focus on process structure and operational sequencing, while more recent visual frameworks emphasize collaboration, intelligence, distributed systems and digital coordination. This progression reflects the broader transformation of supply chain management from static operational systems into adaptive and interconnected ecosystems. Understanding these frameworks is important because they provide the theoretical foundation for analyzing how technologies such as 5G, 6G, Artificial Intelligence and UAV systems can transform supply chain operations in the following chapters.

2.1.3 Industry 4.0 and Smart Supply Chain

Industry 4.0 represents a major transformation in industrial operations, where traditional manufacturing and logistics systems evolve into more connected, automated and intelligent environments. The visual representation of industrial transformation in the selected literature presents this transition as a movement from conventional production models toward digitally integrated systems where communication, automation and data-driven decision-making become central operational elements. This perspective shows that Industry 4.0 is not simply the adoption of new technologies, but a broader structural change in how industrial and supply chain systems operate [18].

One of the most useful conceptual visuals presents Industry 4.0 as a combination of interconnected technological components that work together to improve operational efficiency. The framework includes technologies that support automation, data processing, system connectivity and intelligent operational control. Rather than functioning independently, these components are visually shown as parts of an integrated ecosystem. This helps explain why Industry 4.0 should be understood as a systems-based industrial model, where multiple digital technologies interact to support more responsive and adaptive supply chain operations [18].

A complementary perspective on Industry 4.0 emphasizes the importance of integration and connectivity across manufacturing and logistics environments. According to Strandhagen et al. [102], Industry 4.0 is built upon three fundamental forms of integration: vertical integration, horizontal integration and end-to-end engineering integration. Vertical integration enables seamless communication between operational technologies, production systems and enterprise-level information systems such as ERP and MES platforms. Horizontal integration extends connectivity across organizational boundaries, facilitating collaboration among suppliers, manufacturers and logistics partners. End-to-end integration supports information exchange throughout the entire product lifecycle, from product design and production to distribution and after-sales services. Furthermore, the authors identify Cyber-Physical Systems (CPS), the Internet of Things (IoT) and Smart Factories as core components of Industry 4.0. Through these technologies, physical assets, machines, products and information systems become interconnected, enabling real-time data collection, automated decision-making, improved operational visibility and more responsive manufacturing logistics. This integrated perspective highlights how Industry 4.0 provides the technological foundation for the development of smart supply chains characterized by higher levels of connectivity, flexibility and operational intelligence [102].

The relationship between Industry 4.0 and supply chain management becomes clearer when examining process-based visual models of supply chain operations. Traditional supply chains are often represented as sequential processes involving raw materials, production, transportation, warehousing, distribution and customer delivery. This type of visual structure reflects a linear operational model where activities follow predefined stages. However, the introduction of Industry 4.0 changes this structure by making these stages more connected, visible and responsive through digital coordination. As a result, supply chains evolve from static operational chains into intelligent and interactive systems [18].

Another important visual perspective highlights the operational challenges faced by conventional supply chain systems. These include issues related to traceability, quality control, security, operational cost and performance efficiency. The graphical presentation of these challenges demonstrates that supply chain complexity increases as operations become larger and more interconnected. Industry 4.0 addresses these limitations by introducing technologies that improve visibility, coordination and faster decision-making across supply chain activities. This visual interpretation supports the idea that digital transformation is not only an innovation opportunity, but also a response to operational limitations in traditional logistics systems [18].

The concept of the smart supply chain becomes more visible in logistics-focused frameworks such as smart warehouse models. These visual structures present logistics environments as interconnected systems where operational activities are continuously linked through digital communication and automated coordination. Instead of isolated warehouse operations, the diagrams show synchronized flows between inventory control, goods movement, information exchange and distribution processes. This visual logic reflects the shift from conventional logistics management toward intelligent supply chain ecosystems capable of responding more quickly to operational demands [42].

Another useful visual concept is the idea of information mutual connection, where different supply chain elements continuously exchange operational information. In this type of framework, products, warehouse systems, logistics processes and management functions are visually connected rather than separated. This demonstrates that smart supply chains depend heavily on real-time coordination and continuous operational awareness. The theoretical importance of this perspective lies in showing that supply chain intelligence is created through system-wide connectivity rather than isolated technological upgrades [42].

Industry 4.0 also introduces stronger interaction between human operators and intelligent systems. Visual models related to advanced industrial environments show that modern production and logistics are increasingly based on collaboration between people, automated systems and intelligent interfaces. Rather than removing human participation completely, these frameworks suggest a more collaborative operational structure where digital technologies support human decision-making, safety and efficiency. This is an important aspect of smart supply chain development, as intelligent systems must remain operationally practical and manageable within real industrial environments [68].

The broader conceptual framework of smart supply chain transformation further strengthens this perspective by visually linking digital transformation with supply chain performance through the use of smart technologies. The structure of this framework suggests that supply chain improvement does not occur only through automation, but through the integration of technologies that improve coordination, responsiveness and decision-making capabilities. This reflects a more strategic understanding of Industry 4.0, where supply chain intelligence becomes an organizational capability rather than a simple technological feature [135].

The importance of Industry 4.0 for smart supply chains is also reflected in digital maturity assessment frameworks that evaluate the readiness and transformation progress of organizations. A systematic comparison of thirteen digital maturity models identified a broad set of dimensions associated with Industry 4.0 adoption, including business strategy, digital technologies, data management, human resources, innovation, cybersecurity, smart manufacturing, supply chain integration and customer-oriented digital services. The analysis demonstrates that successful Industry 4.0 implementation requires not only technological investments but also organizational, strategic and operational capabilities that support digital transformation across the entire enterprise. This perspective reinforces the view of Industry 4.0 as a holistic transformation framework that integrates technological, managerial and supply chain dimensions into a unified digital ecosystem [78].

Overall, the visual frameworks examined in the selected studies present a clear evolution from traditional supply chain structures toward smart and digitally integrated operational ecosystems. Industry 4.0 acts as the foundation of this transformation by enabling stronger connectivity, improved process visibility, intelligent coordination and more adaptive logistics operations. This theoretical understanding is particularly important because it establishes the basis for the more advanced digital technologies discussed in later chapters, including 5G, 6G, Artificial Intelligence and autonomous logistics systems.

2.1.4 Industry 5.0 and Future Supply Chain Trends

Industry 5.0 represents the next stage in industrial and supply chain evolution, building on the digital transformation introduced by Industry 4.0 while placing greater emphasis on human involvement, resilience and sustainability. Visual comparisons between Industry 4.0 and Industry 5.0 show a clear shift in industrial priorities. While Industry 4.0 focuses mainly on automation, system optimization and smart production, Industry 5.0 expands this perspective by introducing a more balanced model where technology works together with human decision-making and broader social goals. This evolution suggests that future supply chains will not only become smarter, but also more adaptive and human-centered [90].

A key idea shown in the comparative framework is the stronger role of human participation in Industry 5.0 environments. Unlike previous industrial models, where automation was often designed to reduce human involvement in operational processes, Industry 5.0 promotes collaboration between humans and intelligent systems. The visual representation highlights human-machine interaction, employee well-being, learning and safer working environments as important structural elements. For supply chain management, this suggests that future logistics and operational systems will combine automation with human expertise rather than replacing human roles completely [90].

This human-centered perspective is also supported by ElFar et al. (2021), who argue that Industry 5.0 represents a paradigm shift from fully automated production toward collaborative manufacturing environments where humans and intelligent technologies operate together. According to the authors, Industry 5.0 combines Artificial Intelligence (AI), the Internet of Things (IoT), cloud-based systems and collaborative robots (cobots) to enhance productivity while preserving the role of human creativity, intuition and decision-making. Rather than replacing employees, advanced technologies are intended to support human capabilities, improve workplace safety and create more flexible production and supply chain systems [142].

Another important trend visible in the Industry 5.0 framework is the growing importance of sustainability and resilience. The visual model presents these concepts as central industrial objectives rather than secondary operational concerns. This reflects an important change in supply chain thinking, where future systems are expected not only to deliver efficiency, but also to remain stable during disruptions and operate with stronger environmental awareness. Modern supply chains increasingly face uncertainty caused by global disruptions, changing demand patterns and operational risks. The Industry 5.0 perspective suggests that future supply chains must be designed to adapt more effectively to these conditions [90].

A second useful conceptual model presents the relationship between Industry 5.0 and supply chain performance through a structured framework. In this visual representation, Industry 5.0 acts as the main driving force influencing important supply chain dimensions such as visibility, efficiency and responsiveness. Rather than treating performance as a single operational outcome, the model shows that supply chain improvement is created through interaction between multiple performance factors. This perspective helps explain how future supply chain systems may evolve through coordinated technological and organizational transformation [114].

The position of visibility within this conceptual framework is particularly important. The visual structure suggests that better supply chain visibility improves the ability of organizations to monitor operations, understand disruptions and make faster decisions. Improved visibility also appears connected with stronger operational efficiency and responsiveness, showing that access to timely information plays a central role in future supply chain management. This reflects the broader trend toward more transparent and data-aware logistics ecosystems where operational awareness supports stronger performance [118].

Efficiency remains an important supply chain objective, but the visual framework suggests that future efficiency will depend less on isolated cost reduction and more on intelligent coordination between processes. In this context, operational performance is influenced by how effectively systems communicate, adapt and respond to changing conditions. This reflects a broader transformation in supply chain thinking, where efficiency is increasingly linked to flexibility, digital coordination and strategic responsiveness rather than traditional productivity measures alone [118].

Responsiveness is another major future trend highlighted by the conceptual model. Supply chains are becoming more dynamic due to rapid market changes, global disruptions and increasing customer expectations. The visual framework suggests that organizations with stronger visibility and operational coordination are better positioned to respond quickly to unexpected events. This aligns with the future vision of supply chains as adaptive systems capable of reacting rapidly while maintaining operational continuity and service performance [118].

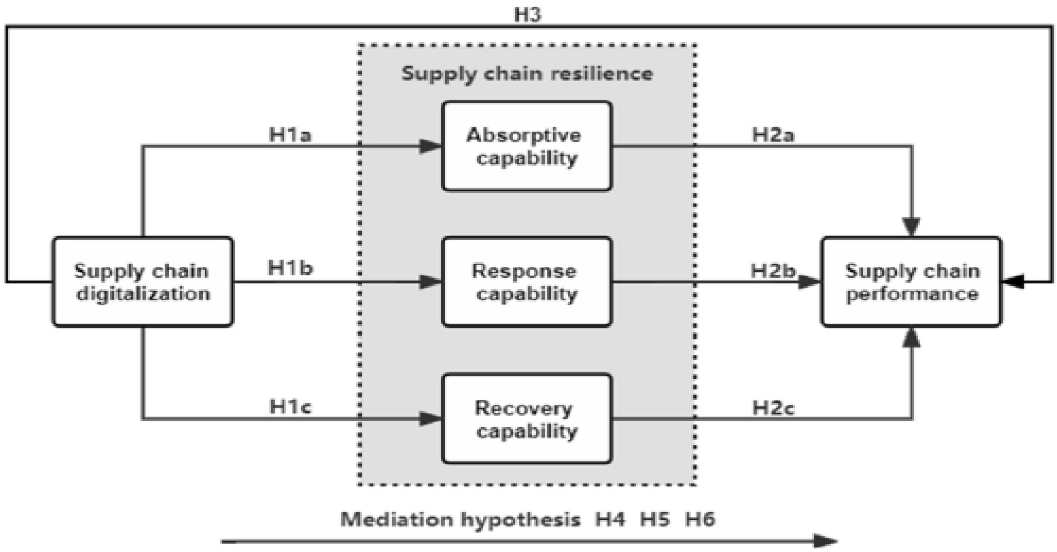
Overall, the visual frameworks from the selected studies suggest that future supply chain trends will move toward more intelligent, resilient, sustainable and human-centered systems. Industry 5.0 does not simply represent a technological upgrade, but a broader transformation in supply chain design and management philosophy. Future supply chains are expected to combine digital intelligence, operational flexibility, human collaboration and stronger resilience to create systems that are more capable of handling uncertainty and supporting long-term performance improvement.

2.2 Supply Chain Resilience

2.2.1 Concept and Dimensions of Supply Chain Resilience

Supply chain resilience refers to the ability of the Supply Chain to continue operating, respond effectively to disruptions and recover from unexpected events while maintaining acceptable performance. Modern supply chains operate in complex and uncertain environments where disruptions may result from natural disasters, geopolitical events, operational failures, pandemics, or market instability. Because supply chains involve many interconnected participants and processes, a disruption in one part of the network can quickly affect the entire system. For this reason, resilience has become an important concept in supply chain management, focusing not only on risk prevention but also on the ability to adapt and recover when disruptions occur [118].

A useful conceptual perspective presented in the selected literature describes supply chain resilience as an open system property rather than a closed operational function. The visual framework in this study shows supply chains as systems that continuously interact with their external environment rather than operating in isolation. This means that resilience depends on how effectively the supply chain responds to environmental changes, external pressures and unpredictable disturbances. This systems-based view helps explain why resilience should be understood as a dynamic capability rather than a fixed operational characteristic [94].



3Figure : Depiction of resilience capacities with respect to system performance [118].

Another important idea presented visually in the resilience framework is the relationship between vulnerability and recoverability. The conceptual model suggests that resilience is not simply the absence of risk, but the balance between exposure to disruption and the ability to restore operations. A supply chain may face vulnerabilities such as supplier dependence, limited visibility, or transportation constraints, but resilience increases when strong recovery capabilities exist. This visual interpretation presents resilience as a balance between weakness and response capacity, which provides a more realistic understanding of how supply chains behave during disruptions.

The process-oriented perspective of resilience also becomes clearer when examining models that present resilience through different disruption phases. The visual structure of these frameworks suggests that resilience should not be evaluated only after a disruption occurs, but across multiple stages. Before disruption, supply chains focus on preparation, monitoring and preventive capabilities. During disruption, operational flexibility, fast response and coordination become critical. After disruption, recovery, restoration and organizational learning become essential. This staged visual logic presents resilience as a continuous management capability rather than a single reactive action [118].

Adaptation is another central dimension of supply chain resilience. The conceptual frameworks suggest that resilient supply chains are not designed only to return to their previous operational state, but also to adjust to new conditions when necessary. This means that resilience includes learning, reconfiguration and operational flexibility. If environmental conditions change significantly, simply restoring previous operations may not be sufficient. Instead, supply chains may need to redesign sourcing strategies, modify transportation routes, or introduce alternative operational practices. This adaptive dimension makes resilience a strategic capability rather than a short-term recovery mechanism [94].

The network perspective presented in resilience mapping studies further expands this understanding. Visual knowledge maps show supply chains as interconnected ecosystems rather than linear operational chains. In this structure, resilience becomes a network-level characteristic because disruptions can spread across suppliers, logistics providers, manufacturers and distribution systems. This ripple effect perspective is particularly important because it demonstrates that resilience depends not only on the strength of individual organizations, but also on the coordination and robustness of the broader supply chain network [80].

An additional perspective on supply chain resilience is provided by the open-system approach proposed by Hosseini et al. [94]. Unlike traditional views that examine resilience primarily as a recovery outcome, the open-system perspective considers supply chains as dynamic systems that continuously interact with their external environment. Within this framework, resilience emerges from the balance between vulnerability and recoverability over time. The authors identify three fundamental resilience capacities: absorptive capacity, which reflects the ability to withstand disruptions with minimal performance loss; adaptive capacity, which enables operational adjustment and reconfiguration during disruption; and restorative capacity, which supports the recovery and restoration of normal operations. This perspective highlights that resilience is not a static characteristic but a dynamic capability that evolves through continuous interaction with environmental conditions, risk factors and recovery mechanisms. As a result, resilient supply chains are better positioned to maintain operational continuity, adapt to unexpected changes and recover more effectively from disruptive events [93].

The literature further distinguishes resilience capabilities into operational and strategic dimensions. Operational resilience focuses primarily on reactive actions and recovery activities that enable organizations to restore operations following disruption events. In contrast, strategic resilience emphasizes long-term preparedness, adaptation and renewal capabilities that allow supply chains to anticipate future risks and adjust to changing environmental conditions. To strengthen resilience, organizations increasingly adopt practices such as flexibility, redundancy, alternative sourcing, agility, collaboration and information sharing across supply chain partners. Recent studies also highlight the importance of proactive resilience strategies that focus on disruption prevention and preparedness, alongside reactive strategies that support recovery and business continuity after disruptions occur. These capabilities have become particularly important in response to large-scale disruption events such as the COVID-19 pandemic, which demonstrated the need for adaptable, digitally connected and resilient supply chain networks [55].

Another important dimension highlighted in the visual mapping of resilience is connectivity between resilience and digital transformation. The conceptual structures suggest that resilience is increasingly influenced by visibility, information sharing and operational awareness across supply chain networks. Better information access improves disruption detection, coordination and faster decision-making. This means that resilience is no longer based only on physical redundancy or backup resources, but also on stronger information capabilities and digital coordination mechanisms. As supply chains become more technologically connected, resilience increasingly depends on intelligent system awareness [80].

Performance measurement also plays an important role in resilience management. Conceptual resilience models show that resilience is closely related to operational performance indicators such as delivery reliability, lead times, service continuity and response efficiency. This perspective suggests that resilience should be understood not only as a theoretical capability, but also as something that can be observed through operational performance behavior before, during and after disruption events. This practical dimension makes resilience relevant not only for strategic planning, but also for day-to-day supply chain management [118].

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Overall, the selected conceptual frameworks present supply chain resilience as a multidimensional capability that combines preparedness, adaptability, recovery, coordination and performance stability. Rather than representing a single operational feature, resilience emerges as a strategic property of modern supply chain systems operating in uncertain and interconnected environments. This theoretical understanding is particularly important because resilience increasingly forms the foundation for future digital, intelligent and technology-driven supply chain systems discussed in later chapters.

2.2.2 Industry 4.0 and Digital Technologies for Resilience

Industry 4.0 has changed the way supply chains respond to disruptions by introducing digital technologies that improve visibility, communication and decision-making. Traditional supply chains often struggle when unexpected disruptions occur because information is delayed, operations are less connected and decision-making is slower. The conceptual frameworks in the selected studies show that Industry 4.0 helps create more resilient supply chains by improving the ability to monitor operations, predict risks, respond quickly and recover more effectively after disruptions.

One important idea shown in the Industry 4.0 resilience frameworks is that resilience depends strongly on visibility and information awareness. Digital technologies allow organizations to monitor supply chain activities in real time instead of reacting only after problems become visible. The conceptual models show that better monitoring improves the ability to detect disruptions early, understand operational risks and make faster decisions. This is especially important in modern supply chains where delays in one part of the network can quickly affect the entire system [60].

Connected technologies such as smart sensors and digital monitoring systems also play an important role in resilience. The selected frameworks present supply chains as connected environments where products, transportation systems, warehouses and operational processes continuously exchange information. This stronger connectivity improves operational awareness and allows companies to react more quickly when disruptions occur. Instead of depending on manual reporting or delayed information exchange, digital technologies create a more responsive supply chain environment [152].

Another important contribution of Industry 4.0 is the improvement of adaptability. The resilience models suggest that supply chains need not only to survive disruptions, but also to adjust their operations when conditions change. Digital technologies support this by improving communication between supply chain partners and enabling faster operational coordination. Better connectivity makes it easier to reorganize processes, change supply routes, or adjust inventory decisions when normal operations are affected [60].

A useful conceptual architecture in the selected studies is the Digital Twin model, which supports resilience through digital representation of physical operations. The framework shows a connection between the physical operational environment and its digital counterpart, supported by monitoring, simulation and optimization functions. This structure allows organizations to test possible responses, evaluate operational changes and improve decision-making without directly affecting physical operations. This makes Digital Twin technology an important resilience tool because it supports both prevention and faster recovery [63].

Another important perspective presented in the selected literature is that digital resilience is not only based on technology adoption, but also on the ability of supply chain systems to continuously learn and improve through data-driven decision-making. The conceptual approach of this study suggests that resilient supply chains become stronger when digital technologies support operational learning, faster adaptation and more informed strategic responses to disruptions. This highlights that resilience is not only about recovery, but also about long-term improvement and preparedness [60].

Information technology also strengthens resilience by improving collaboration between supply chain partners. The conceptual frameworks show that resilience depends not only on internal company capabilities, but also on communication between suppliers, logistics providers, distributors and customers. Better information sharing reduces uncertainty and improves coordination across the supply chain. When organizations exchange accurate and timely information, disruptions can be managed more effectively and recovery becomes faster [136].

Recent literature further highlights the growing role of Industry 4.0 technologies in strengthening supply chain resilience. Studies indicate that technologies such as Artificial Intelligence, Big Data Analytics, Blockchain, Cloud Computing and Digital Twins contribute significantly to resilience by improving visibility, risk monitoring, information sharing and disruption management capabilities. These technologies enable organizations to better anticipate supply chain disruptions, enhance operational coordination and support faster recovery processes. Furthermore, digital transformation facilitates greater agility and adaptability, allowing supply chain networks to respond more effectively to uncertain and rapidly changing environments. This perspective reinforces the view that resilience increasingly depends on the integration of advanced digital technologies across supply chain operations [79].

Recent research further suggests that the transition from Industry 4.0 to Industry 5.0 further strengthens supply chain resilience by combining advanced digital technologies with human-centered collaboration and sustainability. While Industry 4.0 primarily focuses on automation and intelligent manufacturing, Industry 5.0 integrates human expertise with technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twins, Blockchain, Edge Computing, Cyber-Physical Systems, collaborative robots (cobots) and Augmented and Virtual Reality. These technologies enable organizations to improve real-time visibility, predictive risk assessment, operational coordination and adaptive decision-making during major disruptions such as pandemics, wars and climate change. Furthermore, Industry 5.0 emphasizes not only operational efficiency but also resilience, employee well-being, sustainability and long-term value creation, allowing supply chains to absorb disruptions, adapt to changing conditions and recover more effectively from unexpected events [119].

Another important resilience factor shown in the selected studies is trust and integration between supply chain participants. In more complex supply chains, especially cross-border operations, disruptions often become worse when participants work with disconnected information systems. Digital technologies improve resilience by creating shared operational visibility and stronger coordination between different stakeholders. This reduces communication gaps and improves collective response capabilities during operational disruptions [61].

Overall, the selected conceptual models show that Industry 4.0 improves supply chain resilience by combining visibility, connectivity, adaptability, collaboration and intelligent digital support. Rather than treating resilience only as recovery after disruption, these frameworks present resilience as a continuous operational capability supported by digital technologies. This makes Industry 4.0 an important foundation for the development of more adaptive and resilient supply chain systems.

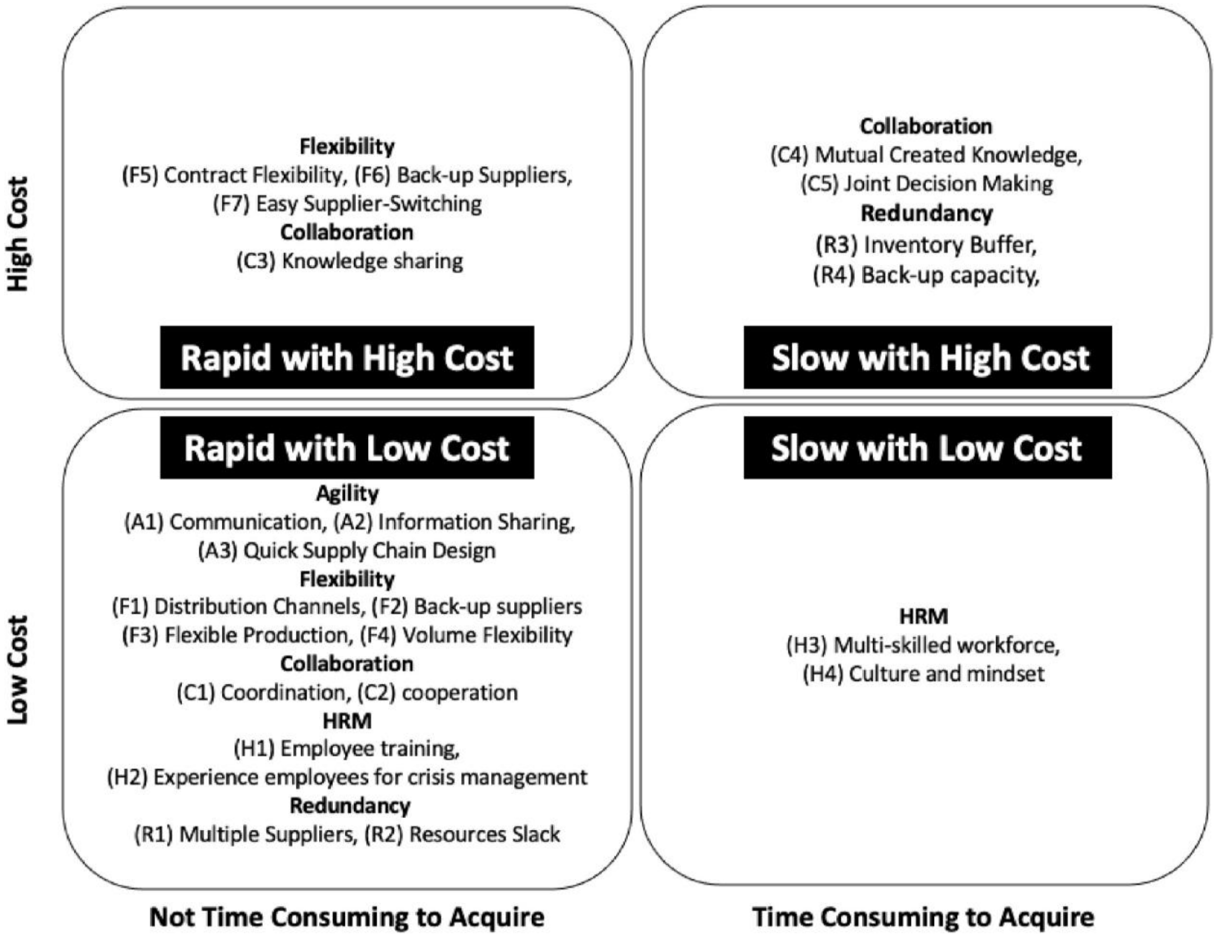
2.2.3 Strategies and Practices for Enhancing Resilience

Improving supply chain resilience requires practical strategies that help organizations respond effectively to disruptions and maintain operational continuity. The conceptual frameworks in the selected studies show that resilience is not based on a single action, but on a combination of practices that support prevention, response, recovery and long-term adaptation. Modern supply chains face many uncertainties, so resilience must be supported by operational strategies that improve flexibility, coordination and faster decision-making.

One important resilience strategy shown in the selected frameworks is agility. The visual strategy matrix presents agility as one of the fastest and most practical responses during disruptions, especially when organizations need to react quickly with limited resources. Agility improves the ability to make fast operational decisions, adjust supply chain activities and respond to changing demand conditions. In supply chain environments where delays can quickly create wider disruption, fast response capability becomes a major resilience advantage.

Flexibility is another important resilience practice. The conceptual strategy model suggests that resilient supply chains need alternative operational options when normal processes are disrupted. This may include changing suppliers, modifying transportation routes, adjusting production capacity, or using alternative delivery methods. Flexibility allows organizations to continue operating even when planned processes are no longer possible. This makes supply chain operations more adaptable and reduces dependence on fixed operational structures.

Collaboration also plays a central role in resilience improvement. The resilience frameworks show that stronger coordination between suppliers, logistics providers, manufacturers and distributors improves the ability to manage disruptions more effectively. When supply chain participants share information and coordinate decisions, uncertainty can be reduced and response actions become faster. Collaboration is especially important in complex supply chains where disruptions in one area can quickly affect multiple partners across the network.



4Figure : Proposed SME SCRes reactive strategy time/cost matrix [151].

Another important resilience practice is redundancy. The strategy framework presents redundancy as a way to create backup capacity that can support operations during disruption events. This may involve maintaining additional inventory, alternative suppliers, reserve transportation capacity, or backup operational resources. Although redundancy may increase operational cost, it improves resilience by reducing vulnerability when primary systems fail. In uncertain environments, some level of redundancy can provide important operational protection.

Human resource management is also identified as an important resilience factor. The strategic resilience framework suggests that employee skills, preparedness and organizational culture strongly influence how effectively disruptions are managed. Technology and operational systems alone are not enough if employees cannot respond quickly or make effective decisions during emergencies. Training, crisis awareness and operational coordination improve the ability of organizations to react under pressure and support stronger resilience performance [151].

Another emerging practice for strengthening supply chain resilience is the use of gamification techniques within Supply Chain Management 4.0 environments. Recent studies suggest that game-based elements such as points, badges, leaderboards, rewards and progress indicators can improve employee engagement, training effectiveness and participation in operational activities. In logistics and warehouse environments, gamification has been proposed as a mechanism for supporting workforce adaptation to digital transformation initiatives and Industry 4.0 technologies. By increasing employee motivation and encouraging continuous learning, gamification can enhance organizational preparedness and improve the ability of supply chain personnel to respond effectively during disruptions. This highlights that resilience depends not only on technological capabilities and operational strategies, but also on human-centered approaches that strengthen workforce readiness and adaptability [21].

The resilience lifecycle framework provides another useful perspective by showing resilience as a sequence of operational stages. The conceptual model presents resilience through resistance and recovery phases. During the resistance stage, organizations focus on avoiding disruption when possible and containing its impact when disruption occurs. During the recovery stage, attention shifts toward stabilization of operations and gradual return to normal performance. This framework helps explain that resilience is not a single response event, but a structured operational process.

An important practical lesson from the selected studies is that resilience should be supported by continuous monitoring and strategic preparation rather than only reactive action. The resilience frameworks suggest that organizations with stronger visibility, better situational awareness and clearer operational planning are more capable of detecting risks early and responding effectively. This improves both resistance and recovery performance, making resilience a more proactive organizational capability.

Digital support also strengthens resilience practices. Although traditional resilience strategies remain important, the selected studies suggest that digital technologies improve execution through better information sharing, faster monitoring and stronger operational coordination. This helps organizations apply resilience strategies more effectively across complex supply chain networks. As supply chains become more digital, resilience increasingly depends on both operational practices and technological support [65].

Overall, the selected conceptual frameworks show that supply chain resilience is strengthened through a combination of agility, flexibility, collaboration, redundancy, human preparedness and structured recovery planning. These practices work together to reduce vulnerability, improve operational response and support faster recovery after disruptions. Effective resilience therefore depends on both strategic planning and practical operational capabilities.

2.3 Supply Chain Challenges

2.3.1 Supply Chain Risks and Disruptions

Supply chain risks and disruptions have become one of the most significant challenges facing modern Supply Chain Management (SCM). As supply chains become increasingly globalized and interconnected, organizations are exposed to a wide range of uncertainties that can interrupt the flow of materials, information and products. These disruptions can originate from both internal and external sources and may significantly affect operational performance, customer service and overall business continuity.

The literature highlights that supply chain disruptions can occur unexpectedly and often have consequences that extend beyond a single organization. According to Abeysekara et al., global supply chains have historically been affected by various disruptive events, including natural disasters, pandemics, economic crises, political instability, terrorist attacks, transportation failures and technological breakdowns. These events can interrupt production activities, delay deliveries, increase operational costs and reduce supply chain efficiency.

One of the most widely discussed examples of large-scale supply chain disruption is the COVID-19 pandemic. The report by Deloitte describes COVID-19 as a "black swan" event that exposed the vulnerability of global supply chains. The pandemic demonstrated how disruptions occurring in one geographical region can rapidly spread throughout global supply networks. Because many organizations rely on suppliers located in specific regions, factory shutdowns, transportation restrictions and labor shortages created significant supply shortages and operational delays across multiple industries [56].

The reviewed literature further explains that modern supply chains often suffer from limited visibility beyond first-tier suppliers. While organizations may closely monitor their direct suppliers, disruptions frequently originate from second-tier or third-tier suppliers that remain largely invisible. As a result, companies may underestimate their exposure to risk until operational problems emerge. This lack of transparency can increase the impact of disruptions and make recovery more difficult.

Supply chain risks can generally be classified into different categories. The literature identifies risks related to suppliers, transportation, production processes, market demand, financial conditions, environmental factors and geopolitical events. Each category can affect supply chain performance in different ways, requiring organizations to develop appropriate risk management strategies. The increasing complexity of global supply networks has made the identification and assessment of these risks a critical managerial responsibility.

The consequences of supply chain disruptions are often substantial. Disruptions may lead to production stoppages, inventory shortages, delayed customer deliveries, increased logistics costs, loss of revenue and damage to organizational reputation. In highly competitive markets, even short-term interruptions can negatively affect customer satisfaction and long-term business performance. For this reason, organizations are increasingly investing in risk management practices designed to reduce their vulnerability to unexpected events.

The literature also emphasizes that supply chain risk management extends beyond simply reacting to disruptions after they occur. Modern approaches focus on proactive risk identification, assessment and mitigation. Organizations are encouraged to continuously monitor potential threats, evaluate their likelihood and impact and develop contingency plans before disruptions occur. This shift from reactive to proactive risk management has become increasingly important in modern supply chains.

Recent research further highlights the role of digital technologies in managing supply chain risks. The increasing adoption of data analytics, digital monitoring systems, artificial intelligence and real-time information sharing enables organizations to identify emerging risks more quickly and improve decision-making during disruption events. These technologies enhance supply chain visibility and support faster responses to unexpected situations [164].

The reviewed studies indicate that risk management has become an essential component of supply chain strategy. Organizations that fail to understand and manage risks effectively may experience significant operational and financial consequences when disruptions occur. Conversely, companies that actively identify risks and develop mitigation strategies are generally better positioned to maintain continuity and adapt to changing conditions [149].

Overall, the literature demonstrates that supply chain risks and disruptions are unavoidable elements of modern business environments. Natural disasters, pandemics, supplier failures, economic crises and geopolitical uncertainties can all threaten supply chain operations. As supply chains continue to expand globally, the ability to identify, assess and manage risks effectively will remain a critical factor in achieving operational stability and long-term organizational success.

2.3.2 Technological Challenges and Integration Issues

The rapid digital transformation of supply chains has created significant opportunities for improving operational efficiency, visibility and decision-making. Technologies such as the Internet of Things (IoT), Radio Frequency Identification (RFID), cloud computing, artificial intelligence and real-time data analytics are increasingly integrated into Supply Chain Management (SCM) systems. Despite their potential benefits, organizations face numerous technological challenges and integration issues that can hinder successful implementation and reduce the expected value of digital transformation initiatives.

One of the most significant technological challenges is the complexity of integrating new digital technologies with existing supply chain systems. Many organizations continue to operate legacy information systems that were not originally designed to communicate with modern IoT-enabled platforms. As a result, integrating sensors, RFID devices, data management platforms and enterprise systems often requires substantial modifications to infrastructure, software and business processes. This complexity increases implementation costs and may delay the realization of expected benefits.

The literature emphasizes that interoperability remains a critical concern in technology-enabled supply chains. Effective supply chain integration requires seamless communication between suppliers, manufacturers, distributors, retailers and customers. However, different organizations frequently use incompatible technologies, software platforms and data standards. The absence of universally accepted standards limits information sharing and creates barriers to collaboration across supply chain networks. Consequently, organizations may struggle to fully exploit the visibility and transparency advantages offered by digital technologies.

Another major challenge relates to data management and system connectivity. IoT-based supply chains generate vast volumes of real-time data from sensors, RFID tags, transportation systems, warehouses and production facilities. While this data can improve forecasting and operational control, organizations often face difficulties in collecting, processing, storing and analyzing such large quantities of information. Poor data quality, inconsistent data formats and inadequate analytical capabilities may reduce the reliability of decision-making processes and limit the effectiveness of technology investments.

Security and cybersecurity risks represent another critical technological challenge. IoT devices continuously exchange information across interconnected networks, creating multiple points of vulnerability. The literature identifies concerns related to unauthorized access, data theft, information leakage, cyberattacks and system manipulation. Because supply chain operations increasingly depend on digital connectivity, cybersecurity failures can disrupt operations, compromise sensitive business information and damage organizational reputation. As a result, securing interconnected systems has become a strategic priority for supply chain managers.

Hardware and software limitations also create integration difficulties. IoT devices often face constraints related to battery life, processing power, storage capacity and network connectivity. Similarly, software systems may lack the scalability and maturity required to support large-scale supply chain applications. These technical limitations can reduce system reliability, increase maintenance requirements and affect overall operational performance. Organizations must therefore carefully evaluate the technological capabilities of their infrastructure before implementing advanced digital solutions [153].

The implementation of intelligent logistics systems further requires substantial organizational and technical expertise. According to Hou and Chen, successful deployment of IoT-based logistics systems depends on the integration of multiple technologies, including RFID, wireless communication systems, cloud computing, artificial intelligence and logistics information platforms. Managing the interaction between these technologies requires specialized knowledge and significant technical resources, which may not always be available within organizations.

In addition, technological transformation often requires extensive organizational changes. Employees must adapt to new digital tools, modified workflows and data-driven decision-making processes. Resistance to change, lack of technical skills and insufficient training can slow technology adoption and reduce implementation success. The literature suggests that organizations must invest not only in technology but also in employee development and change management initiatives to ensure successful integration.

The challenge of achieving end-to-end visibility across the supply chain is another important integration issue. Although IoT technologies enable real-time monitoring of products, transportation assets and inventory, visibility can only be achieved when all supply chain partners participate in data sharing. Differences in technological maturity, investment capabilities and strategic priorities among partners may limit information exchange and reduce the effectiveness of integrated digital systems.

Despite these challenges, the literature acknowledges the substantial benefits associated with successful technological integration. IoT-enabled supply chains can improve tracking accuracy, automate operational processes, enhance inventory management, reduce logistics costs and increase responsiveness to customer demands. For example, research on intelligent logistics systems demonstrates that optimized IoT-based logistics operations can generate measurable cost savings and improve supply chain efficiency through enhanced monitoring and coordination capabilities [20].

Overall, technological challenges and integration issues remain significant barriers to the digital transformation of supply chains. System interoperability problems, cybersecurity concerns, data management complexities, infrastructure limitations and organizational resistance can all affect implementation success. However, organizations that successfully address these challenges can achieve greater visibility, efficiency, flexibility and competitiveness within increasingly complex supply chain environments.

2.3.3 Managing Complexity through Digital Technologies

Modern supply chains operate in highly dynamic and complex environments characterized by globalized networks, multiple stakeholders, fluctuating demand and increasing exposure to disruptions. Traditional supply chain management approaches often struggle to cope with this complexity because decision-makers lack real-time visibility and predictive capabilities. Digital technologies such as the Internet of Things (IoT), Big Data analytics, Artificial Intelligence (AI), cloud computing and Digital Twins have emerged as powerful tools for managing this complexity and improving supply chain performance.

One of the most significant developments is the emergence of the Digital Twin concept. A Digital Twin is a virtual representation of a physical system that continuously receives real-time data from the actual environment and mirrors its current state. In supply chain management, Digital Twins create computerized models that represent supply network conditions, inventory levels, transportation flows, capacities and operational performance in real time. This enables organizations to monitor supply chain activities continuously, predict future disruptions and evaluate alternative response strategies before implementing them in practice.

The integration of IoT technologies plays a fundamental role in supporting Digital Twin applications. IoT devices, sensors, RFID systems and connected equipment continuously collect operational data throughout the supply chain. These technologies provide real-time information regarding product locations, inventory status, transportation conditions, equipment performance and environmental variables. Through automated data collection and transmission, organizations can achieve unprecedented levels of supply chain visibility and transparency.

Digital technologies also enhance supply chain resilience by improving risk management capabilities. According to Ivanov and Dolgui (2021), Digital Supply Chain Twins allow organizations to identify disruption scenarios, assess vulnerability, monitor disruptions as they occur and develop recovery strategies based on real-time information. By combining historical data analysis with predictive analytics and simulation models, managers can evaluate the potential impact of disruptions and implement proactive measures to reduce risks and maintain business continuity.

A key advantage of digitalization is the ability to transform large volumes of data into actionable insights. Modern supply chains generate enormous quantities of information from suppliers, manufacturers, logistics providers, retailers and customers. Big Data analytics and Artificial Intelligence tools enable organizations to process this information efficiently and support more accurate forecasting, inventory optimization, route planning and operational decision-making. As a result, companies can respond more rapidly to market changes and improve overall supply chain agility.

Digital technologies also facilitate end-to-end visibility across complex supply chain networks. Visibility is particularly important in global supply chains where disruptions can propagate rapidly across multiple tiers of suppliers and partners. Through real-time monitoring systems, tracking technologies and digital platforms, managers gain a comprehensive view of supply chain operations and can identify bottlenecks, delays, or emerging risks more effectively. This enhanced visibility supports faster and more informed decision-making during both routine operations and crisis situations.

Another important contribution of digital technologies is their ability to support simulation and scenario analysis. Digital Twins create virtual environments where organizations can test different supply chain configurations, evaluate contingency plans and analyze the consequences of various disruption scenarios without affecting actual operations. This capability enables managers to explore alternative strategies, optimize resource allocation and improve preparedness for unexpected events [57].

The application of Digital Twins extends beyond risk management to operational optimization. Research on refrigerated food supply chains demonstrates how Digital Twins can monitor product conditions, simulate quality changes, predict deterioration and support logistics decisions. By combining sensor data with mechanistic models, organizations can better understand product behavior throughout the supply chain, improve process control, reduce waste and enhance sustainability performance. These capabilities illustrate how Digital Twins can manage complexity not only at the network level but also at the individual product level [146].

Furthermore, digital technologies improve coordination and collaboration among supply chain partners. Shared digital platforms allow stakeholders to exchange information in near real time, synchronize activities and coordinate responses to operational challenges. Improved communication reduces uncertainty, enhances transparency and strengthens relationships between organizations operating within complex supply networks [148].

Despite these benefits, the implementation of Digital Twins and IoT-based systems requires significant investments in technology infrastructure, data integration, cybersecurity and employee capabilities. Organizations must ensure the quality and reliability of collected data, establish effective governance mechanisms and develop the analytical skills necessary to transform information into strategic value. The successful management of complexity through digital technologies therefore depends not only on technological adoption but also on organizational readiness and continuous innovation.

Overall, digital technologies provide powerful mechanisms for managing the increasing complexity of modern supply chains. Through real-time visibility, predictive analytics, simulation capabilities and enhanced collaboration, Digital Twins and IoT systems enable organizations to improve resilience, optimize operations, reduce uncertainty and make more effective decisions in increasingly complex and interconnected supply chain environments.

2.4 Risk Management in Supply Chain

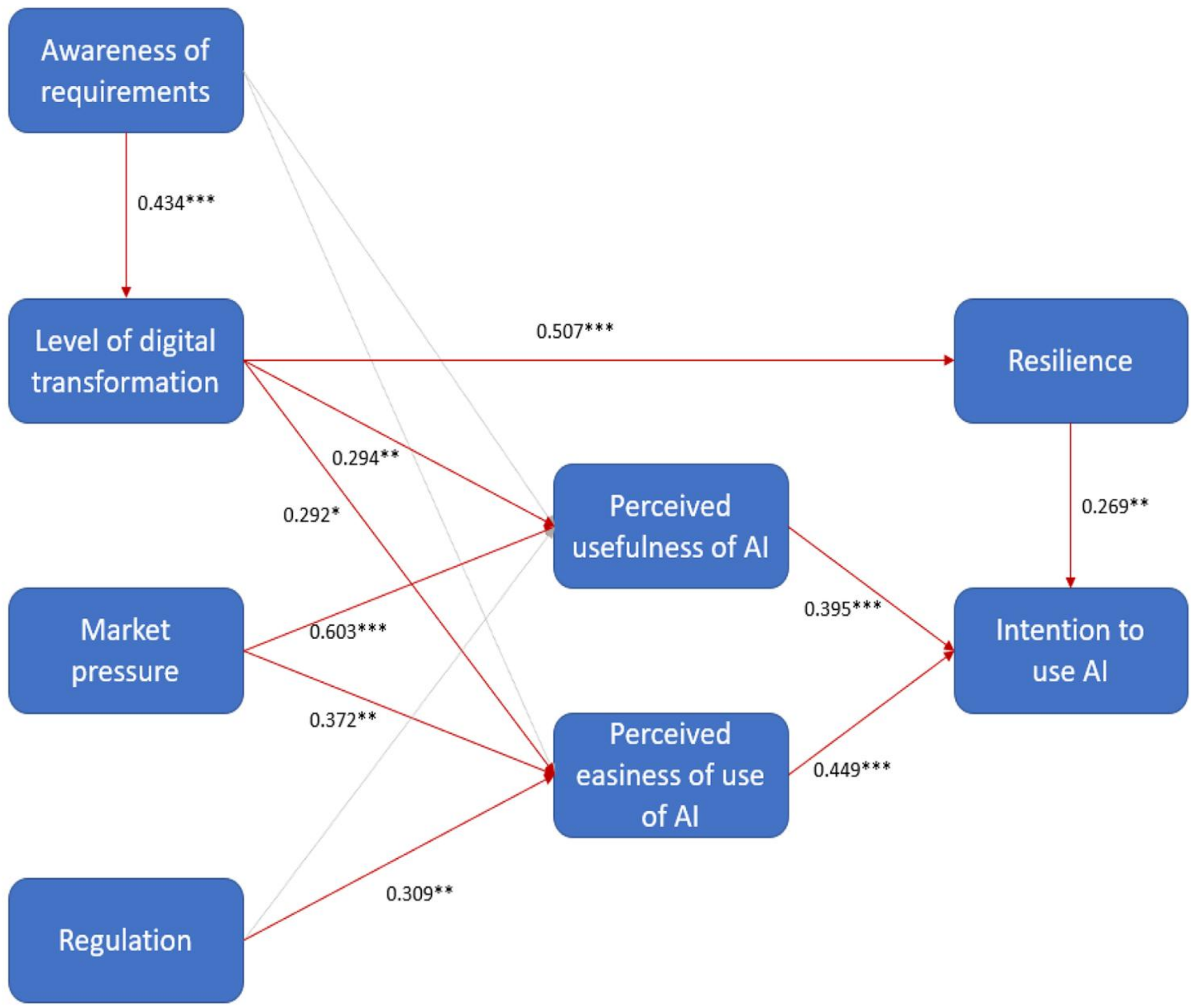
Digital technologies have become increasingly important in supporting supply chain risk management and resilience. As supply chains become more complex and interconnected, organizations face a growing number of risks originating from supplier failures, transportation disruptions, natural disasters, pandemics, geopolitical instability and market uncertainty. Traditional risk management approaches often focus on reacting to disruptions after they occur, whereas digital technologies enable organizations to identify, monitor and mitigate risks more proactively. Through improved visibility, real-time information sharing and advanced analytical capabilities, digital technologies help organizations strengthen their ability to withstand and recover from disruptions [78].

One of the most significant contributions of digital technologies is the improvement of supply chain visibility. Modern digital systems allow organizations to collect and exchange information across multiple stages of the supply chain, providing managers with a more comprehensive understanding of ongoing operations. Enhanced visibility supports the early identification of disruptions, improves monitoring capabilities and enables faster decision-making when unexpected events occur. Research highlights that visibility has become a critical factor in managing supply chain resilience, particularly in environments characterized by high uncertainty and frequent disruptions [134].

The concept of Digital Twins has emerged as an important technological development for risk management and resilience. Digital Twins create virtual representations of physical supply chain systems that are continuously updated using real-time operational data. These digital models allow organizations to monitor supply chain performance, simulate disruption scenarios, evaluate alternative recovery strategies and assess the potential consequences of operational decisions before implementation. By combining real-time visibility with predictive and simulation capabilities, Digital Twins support more informed and proactive risk management practices [145].

The literature also highlights the growing role of Industry 4.0 technologies in resilience management. Technologies such as the Internet of Things (IoT), Big Data Analytics, Artificial Intelligence, cloud computing and blockchain facilitate data collection, information integration and analytical decision-making across supply chain networks. These technologies improve organizations' ability to detect emerging risks, evaluate vulnerabilities and coordinate responses among supply chain partners. As a result, digital transformation is increasingly viewed as a key enabler of resilient supply chain operations [77] [66].

The increasing adoption of e-commerce has further accelerated the digital transformation of supply chain management by improving the flow of information, capital and logistics activities across supply chain networks. Through internet-based connectivity, organizations can exchange information more rapidly and accurately with suppliers, customers, financial institutions and logistics providers, creating a more integrated and coordinated operating environment. This enhanced connectivity strengthens supply chain agility and resilience by supporting faster communication, improved visibility and more efficient coordination among supply chain partners. Furthermore, the integration of IoT technologies within warehousing and logistics operations enables intelligent inventory management, automated product identification and real-time monitoring capabilities, contributing to higher operational efficiency and improved responsiveness during disruption events [13].



*: p< 0.05; **: p<0.01; ***: p<0.001

5Figure : Standardised path coefficient estimates of the model for AI adoption [77].

Artificial Intelligence and Big Data Analytics further strengthen risk management capabilities by supporting predictive analysis and decision-making under uncertainty. Large volumes of supply chain data can be analyzed to identify patterns, anticipate potential disruptions and evaluate the effectiveness of different mitigation strategies. Predictive analytics allows organizations to move beyond reactive approaches and develop more proactive responses to potential risks. This capability is particularly important in highly dynamic environments where disruptions can evolve rapidly and affect multiple supply chain activities simultaneously.

Another important application of digital technologies is the development of early warning systems. These systems continuously monitor operational data, external events and supply chain conditions to identify potential threats before they escalate into major disruptions. Early warning mechanisms provide organizations with valuable time to activate contingency plans, adjust operational strategies and allocate resources more effectively. The literature suggests that timely detection significantly improves an organization's ability to minimize disruption impacts and accelerate recovery processes [134].

Research also demonstrates that digitalization contributes directly to supply chain resilience. Digital technologies improve collaboration, information sharing and coordination among supply chain partners, enabling organizations to respond more effectively to disruptions. Studies indicate that firms with stronger digital capabilities are generally better positioned to maintain operational continuity, adapt to changing circumstances and recover more rapidly from unexpected events. Consequently, digital transformation is increasingly recognized as a strategic investment that supports both resilience and long-term supply chain performance [118].

The importance of resilience capabilities is further emphasized in studies examining both commercial and humanitarian supply chains. Capabilities such as flexibility, adaptability, collaboration and rapid response are consistently identified as essential for effective disruption management. Organizations that develop these capabilities are more capable of absorbing shocks, maintaining service levels and restoring normal operations following disruption events. Digital technologies often serve as important enablers of these resilience capabilities by improving information availability and supporting more agile decision-making processes [129] [132].

The COVID-19 pandemic provided a clear example of the value of digital technologies in risk management. The pandemic generated simultaneous disruptions across supply, production, transportation and demand networks, creating unprecedented challenges for organizations worldwide. Studies examining the impact of COVID-19 show that digital tools played an important role in helping organizations monitor rapidly changing conditions, assess disruption impacts and implement appropriate response measures. The pandemic highlighted the importance of resilience-oriented supply chain strategies supported by real-time information and digital decision-support systems [125].

Effective risk management also requires systematic identification and assessment of potential risks. Research on supply chain risk management frameworks emphasizes the importance of continuously evaluating vulnerabilities, monitoring risk exposure and implementing mitigation strategies designed to reduce both the likelihood and consequences of disruptions. Digital technologies support these activities by providing organizations with more accurate information, analytical capabilities and monitoring tools that improve overall risk management effectiveness [109].

An additional challenge discussed in the literature is the ripple effect, which describes how disruptions spread through interconnected supply chain networks. A disruption affecting one supplier, manufacturer, or logistics provider may propagate across multiple stages of the supply chain, creating consequences far beyond the original source of the problem. Studies show that understanding disruption propagation is essential for effective resilience planning and risk mitigation. Digital technologies, particularly simulation models and Digital Twins, help organizations analyze ripple effects and evaluate potential intervention strategies before disruptions escalate further [146] [145].

Simulation-based approaches have also gained increasing attention in disruption management. During the COVID-19 pandemic, simulation models were widely used to predict disruption impacts, evaluate alternative response scenarios and support decision-making under uncertainty. These models allow organizations to explore different disruption situations, assess potential outcomes and improve preparedness for future crises. The integration of simulation tools with real-time data and digital technologies further enhances their value for supply chain risk management [94].

Overall, the reviewed literature demonstrates that digital technologies have become essential tools for managing supply chain risks and improving resilience. Through enhanced visibility, Digital Twins, predictive analytics, simulation models, early warning systems and collaborative digital platforms, organizations can strengthen their ability to anticipate disruptions, reduce vulnerability and recover more effectively from unexpected events. As supply chains continue to face increasing uncertainty and complexity, the role of digital technologies in risk management and resilience is expected to become even more important.

2.5 Sustainability and Modern Approaches

Sustainability has become a major priority in modern supply chain management as organizations face increasing pressure to balance economic performance with environmental and social responsibilities. Traditional supply chains were primarily focused on cost reduction and operational efficiency, whereas modern supply chains seek to create long-term value while minimizing negative environmental impacts. As a result, sustainability has become closely connected with digital transformation, resilience and the adoption of innovative supply chain practices [129].

The literature highlights that sustainable supply chains aim to improve resource utilization, reduce waste generation, lower energy consumption and minimize environmental impacts throughout the entire supply chain. These objectives are strongly aligned with the concept of cleaner production, which focuses on improving operational processes while reducing the use of materials, energy and other resources. Cleaner production strategies help organizations achieve both environmental and economic benefits by increasing efficiency and reducing unnecessary waste.

Industry 4.0 technologies are increasingly supporting sustainability initiatives across supply chain operations. Technologies such as the Internet of Things (IoT), Artificial Intelligence, Big Data Analytics, Cyber-Physical Systems and digital monitoring platforms enable organizations to collect and analyze real-time information regarding production, logistics, inventory and resource utilization. Through better monitoring and process control, firms can improve operational efficiency, reduce environmental impacts and support more sustainable business practices.

An important modern approach discussed in the literature is supply chain mapping. Supply chain mapping refers to the process of documenting and visualizing supply chain activities, relationships, flows and processes across suppliers, manufacturers, distributors and customers. By creating a comprehensive representation of the supply chain, organizations can improve visibility, identify vulnerabilities and better understand how products, information and resources move throughout the network. Supply chain mapping has gained increasing attention due to its contribution to both resilience and sustainability objectives [127].

The reviewed studies emphasize that supply chain mapping improves visibility across upstream, midstream and downstream activities. Enhanced visibility allows organizations to monitor suppliers, identify inefficiencies, detect potential disruptions and improve decision-making. In increasingly complex global supply chains, visibility has become a critical capability for improving both operational performance and sustainability outcomes. Organizations with greater visibility are better able to identify waste, optimize resource allocation and respond to environmental and operational challenges.

Supply chain mapping is also closely associated with resilience. Research indicates that organizations with a better understanding of their supply chain structures and relationships are more capable of responding to disruptions and maintaining operational continuity. Improved visibility supports preparedness, response and recovery activities, enabling firms to manage uncertainty more effectively. Some studies refer to the combined benefits of visibility and resilience as “visilience,” emphasizing the strong relationship between these two capabilities.

Modern sustainability approaches also include the development of green supply chains. Green supply chain management focuses on incorporating environmental considerations into supply chain activities, including procurement, manufacturing, transportation, distribution and reverse logistics. Organizations increasingly seek to reduce carbon emissions, improve energy efficiency, utilize environmentally friendly materials and adopt sustainable production processes. These initiatives help firms comply with environmental regulations while improving their environmental performance and public image.

Another important development is the adoption of closed-loop supply chains. Unlike traditional supply chains that focus only on forward product flows, closed-loop supply chains incorporate reverse logistics activities that allow products, materials and components to be recovered, reused, remanufactured, or recycled. This approach contributes to waste reduction, resource conservation and environmental sustainability by extending product lifecycles and reducing the need for new raw materials [130].

The literature also highlights the growing importance of responsiveness in sustainable supply chains. Responsiveness refers to the ability of a supply chain to satisfy customer demand quickly and effectively while adapting to changing market conditions. Modern supply chains must balance responsiveness with environmental objectives, creating systems that are both efficient and sustainable. Research demonstrates that organizations can improve competitiveness by simultaneously pursuing environmental performance and operational responsiveness [130].

Furthermore, sustainability is increasingly viewed as a strategic capability rather than simply an environmental initiative. Organizations that successfully integrate sustainability into their supply chain strategies can improve operational performance, strengthen resilience, enhance customer satisfaction and create long-term competitive advantages. The combination of digital technologies, supply chain visibility, resilience capabilities and sustainable practices is driving the development of more intelligent and adaptive supply chain systems.

Overall, the reviewed literature demonstrates that sustainability and modern supply chain approaches are closely interconnected. Cleaner production, Industry 4.0 technologies, supply chain mapping, visibility, resilience, green supply chain management and closed-loop supply chains all contribute to the creation of more sustainable and efficient supply chain systems. As environmental concerns and market uncertainties continue to grow, these approaches are expected to play an increasingly important role in the future development of supply chain management.

3. Digitalization of Supply Chain & Technologies

3.1 Introduction to Digital Supply Chain

The concept of the Digital Supply Chain (DSC) has emerged as a response to the increasing complexity, uncertainty and competitiveness of modern business environments. Traditional supply chains primarily relied on manual processes, fragmented information systems and limited visibility across supply chain activities. The rapid development of digital technologies has transformed this approach, enabling organizations to create more connected, intelligent and data-driven supply chain networks. Digital supply chains use advanced technologies to improve information flow, automate operations and support faster and more accurate decision-making throughout the entire supply chain.

A DSC can be described as a supply chain that integrates digital technologies such as the Internet of Things (IoT), Big Data Analytics, Artificial Intelligence (AI), cloud computing and advanced telecommunication systems into supply chain processes. These technologies allow organizations to collect, process, analyze and share large amounts of information in real time. As a result, companies gain greater visibility over procurement, production, warehousing, transportation, distribution and provide better customer activities [1].

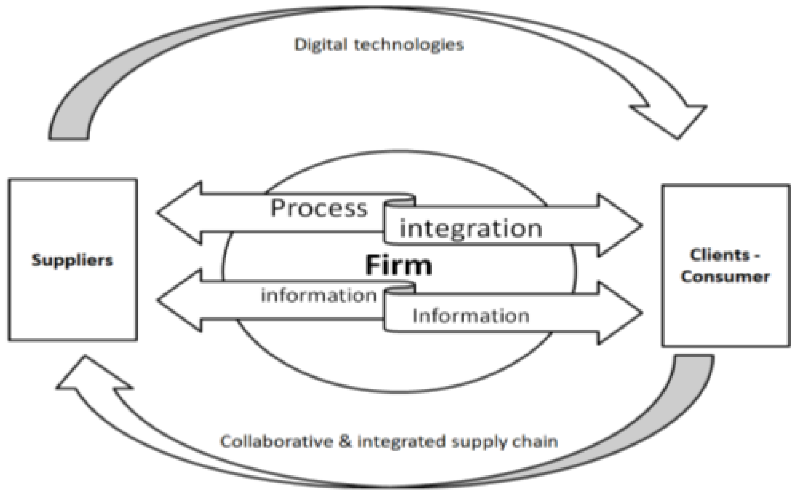
The chapter emphasizes that modern supply chains are becoming increasingly data-driven. Large volumes of data are generated continuously from suppliers, manufacturers, logistics providers, retailers and customers. Through digital technologies, organizations can transform this data into valuable insights that support operational planning, forecasting, inventory management and performance improvement. Rather than relying solely on historical information and managerial intuition, digital supply chains enable decision-making based on real-time information and predictive analytics [128].

DSC also supports stronger integration among supply chain partners. Effective collaboration requires continuous information exchange and coordination between organizations operating across the supply chain network. Digital technologies facilitate communication, improve transparency and enable synchronized business processes among suppliers, staff, manufacturers, distributors and customers. This increased connectivity helps organizations respond more effectively to market changes and operational challenges.

One of the key characteristics of DSC is enhanced visibility. Traditional supply chains often struggle with limited access to information across multiple supply chain stages. In contrast, digital supply chains provide real-time monitoring of products, inventory levels, transportation activities and operational performance. Improved visibility allows managers to identify disruptions earlier, monitor supply chain performance more accurately and make faster decisions when unexpected events occur.

Supply chain visibility (SCV) is widely recognized as a fundamental capability of Digital Supply Chains and plays a critical role in improving operational performance and resilience. SCV refers to the ability of organizations to monitor and access accurate, timely and relevant information regarding the movement of products, materials, financial flows and information across the entire supply chain network. It encompasses three complementary dimensions: supply visibility, which provides information about suppliers, inventory availability and production capacity; demand visibility, which supports customer demand forecasting and planning; and market visibility, which enables organizations to monitor market trends and external conditions. Industry 4.0 technologies, including the Internet of Things (IoT), Machine Learning and Blockchain, significantly enhance end-to-end supply chain visibility by enabling real-time data collection, information sharing and operational transparency. As a result, organizations can detect disruptions earlier, improve coordination among supply chain partners, strengthen resilience and support faster and more informed decision-making [116].

The adoption of digital technologies has also changed the strategic role of supply chain management. Supply chains are no longer viewed solely as operational functions focused on moving products from suppliers to customers. Instead, they are increasingly recognized as strategic assets that contribute to competitiveness, innovation and value creation. Research indicates that organizations adopting digital technologies can improve supply chain efficiency, reduce operational costs, enhance customer satisfaction, better communication between the workers of supply chain.



6Figure : Digital supply chain integration [10].

Another important aspect of digital supply chains is automation. Digital technologies support the automation of routine activities such as inventory monitoring, demand forecasting, procurement processes and logistics operations. Automation reduces manual effort, improves process accuracy and enables organizations to operate more efficiently. Furthermore, automated systems allow companies to respond more quickly to changing customer demands and market conditions [10].

The literature further highlights that the transition from traditional to DSC is closely associated with the broader concept of digital transformation. This transformation involves not only the adoption of new technologies but also changes in organizational structures, business processes, employee skills and management practices. Successful digital supply chains therefore require both technological capabilities and organizational readiness to fully exploit the benefits of digitalization.

Recent studies show that technologies such as IoT, Big Data Analytics and Artificial Intelligence are becoming central components of digital supply chain ecosystems. IoT devices enable real-time data collection, Big Data Analytics supports the processing of large information volumes and AI provides predictive and intelligent decision-making capabilities. Together, these technologies create more agile, responsive and adaptive supply chain systems capable of operating effectively in dynamic business environments.

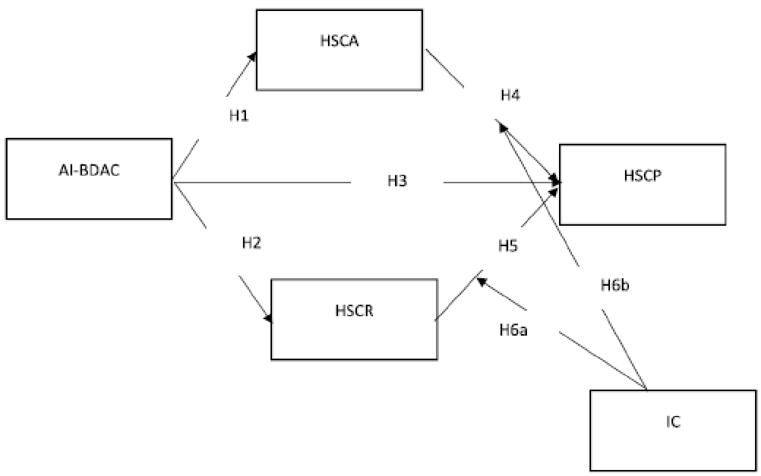
Overall, the DSC represents the evolution of traditional supply chain management toward a more interconnected, intelligent and data-driven model. By leveraging digital technologies, organizations can improve visibility, integration, automation, collaboration and decision-making across supply chain operations. As digital transformation continues to accelerate, digital supply chains are becoming an essential component of modern business strategy and long-term organizational competitiveness.

3.2 Digital Technologies in Supply Chain

Digital technologies have become a fundamental component of modern supply chain management, enabling organizations to improve operational efficiency, visibility, collaboration and decision-making. The rapid development of Industry 4.0 has accelerated the integration of advanced technologies into supply chain processes, transforming traditional supply chains into highly connected and intelligent networks. These technologies support the collection, processing and exchange of information across supply chain partners, allowing organizations to respond more effectively to changing market conditions and customer demands.

Among the most important digital technologies applied in supply chains are the Internet of Things (IoT), Big Data Analytics (BDA), Artificial Intelligence (AI), mobile communication technologies, cloud computing and advanced manufacturing systems. These technologies enable organizations to collect real-time data, analyze complex operational information, automate routine processes and improve coordination throughout the supply chain network. Their integration enhances supply chain visibility, agility and overall performance.

Recent developments associated with Industry 5.0 further extend the role of digital technologies within supply chain management. While Industry 4.0 primarily emphasizes automation and smart manufacturing, Industry 5.0 promotes human-centered collaboration between intelligent technologies and human expertise. Emerging technologies such as collaborative robots (cobots), Digital Twins, Edge Computing, Blockchain, the Internet of Everything (IoE) and future 6G communication networks support higher levels of customization, sustainability and resilience across supply chain operations. These technologies enable organizations to combine real-time data processing with human decision-making, thereby improving operational flexibility, responsiveness and customer-oriented production [115].



7Figure : Theoretical Framework. Notes: AI-BDAC, Artificial Intelligence-driven big data analytics culture; HSCA-humanitarian supply chain agility; HSCR-humanitarian supply chain resilience; IC-information complexity; HSCP-humanitarian supply chain performance [133].

The Internet of Things (IoT) plays a critical role in digital supply chains by connecting physical assets, products, vehicles and equipment through sensors and communication networks. IoT devices continuously generate real-time data regarding inventory levels, production status, transportation conditions and warehouse operations. This information allows organizations to monitor supply chain activities more accurately and identify disruptions or inefficiencies at an early stage. The availability of real-time information significantly improves operational control and responsiveness.

BDA enables organizations to process and analyze the large volumes of data generated across supply chain operations. Modern supply chains produce vast amounts of structured and unstructured data from suppliers, manufacturers, logistics providers and customers. Through advanced analytical techniques, organizations can identify patterns, forecast demand, optimize inventory management and improve resource allocation. As a result, data-driven decision-making replaces traditional approaches that relied primarily on historical information and managerial intuition [133].

AI further enhances supply chain capabilities by supporting predictive, prescriptive and autonomous decision-making. AI systems can analyze complex datasets, identify trends, predict future events and recommend optimal actions. In supply chain environments, AI applications support demand forecasting, procurement decisions, logistics planning, risk management and operational optimization. Research highlights that AI-driven analytics significantly improve supply chain agility and resilience by enabling faster responses to disruptions and changing conditions.

Advanced manufacturing technologies also contribute to digital supply chain development. Technologies such as Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM) and Computer-Aided Engineering (CAE) support digital product development and manufacturing processes. These systems facilitate integration across the product lifecycle, improve product quality, reduce production costs, shorten development times and support lean manufacturing initiatives. The transition from traditional manufacturing methods to digitally supported production environments that represent a key element of DSC [90].

Mobile communication technologies have become increasingly important in logistics and supply chain operations. The development of 5G networks and wireless communication systems enables faster and more reliable data transmission across supply chain activities. Mobile communication technologies support real-time tracking, monitoring, positioning and information sharing throughout transportation, warehousing and distribution processes. These capabilities improve logistics efficiency, enhance operational accuracy and reduce transportation costs [161].

Digital technologies also strengthen collaboration and information sharing among supply chain partners. Modern supply chains require continuous coordination between suppliers, manufacturers, logistics providers and customers. Digital platforms facilitate seamless communication and data exchange, allowing organizations to synchronize activities and improve supply chain integration. Enhanced connectivity contributes to greater transparency and more effective management of supply chain relationships.

Another significant contribution of digital technologies is the improvement of supply chain agility and resilience. Agility refers to the ability of organizations to respond rapidly to market changes and unexpected events, while resilience describes the capability to withstand and recover from disruptions. Technologies such as AI and Big Data Analytics enable organizations to identify risks earlier, process information more efficiently and implement corrective actions faster. Consequently, digital technologies help supply chains maintain continuity and performance in uncertain environments [133].

The successful adoption of digital technologies requires more than technological investment alone. Organizations must also develop the necessary digital capabilities, employee skills, organizational culture and strategic alignment to fully exploit the benefits of digital transformation. Digital maturity has therefore become an important factor in determining an organization's ability to implement and utilize digital technologies effectively. Companies with higher levels of digital maturity are generally better positioned to integrate advanced technologies into their operations and achieve superior supply chain performance [78].

Overall, digital technologies are transforming supply chains from fragmented and reactive systems into integrated, intelligent and data-driven networks. Through the combined use of IoT, Big Data Analytics, Artificial Intelligence, advanced manufacturing technologies and mobile communication systems, organizations can improve visibility, efficiency, agility, resilience and collaboration across supply chain operations. As digital transformation continues to evolve, these technologies will remain central to the future development of supply chain management.

3.3 Impact on Performance and Flexibility

The adoption of digital technologies has significantly influenced supply chain performance by improving operational processes, decision-making capabilities and organizational responsiveness. As supply chains operate in increasingly uncertain and dynamic environments, organizations are investing in digital solutions to enhance efficiency, improve visibility and strengthen their ability to adapt to changing market conditions. The reviewed literature indicates that digital transformation contributes to both operational performance and supply chain flexibility, enabling organizations to achieve higher levels of competitiveness and resilience.

One of the main benefits of digital supply chain transformation is the improvement of operational performance. According to the paper with number [15], DSC practices, supported by digital technology orientation and DSC platforms, positively influence supply chain viability and operational performance. The study demonstrates that organizations adopting digital supply chain practices are better able to absorb disruptions, adapt to changing conditions and maintain operational continuity. Furthermore, supply chain viability was found to play an important role in supporting long-term operational success, particularly during periods of uncertainty such as the COVID-19 pandemic [15].

The literature also highlights the importance of supply chain flexibility as a determinant of organizational performance. Flexibility refers to the ability of a supply chain to adjust its operations and resources in response to changes in customer demand and market conditions. The study in paper with number [131], examines supply chain flexibility as a multidimensional construct consisting of supply flexibility, internal flexibility and distribution flexibility. The findings indicate that these dimensions positively affect customer responsiveness, allowing organizations to react more effectively to changing customer requirements. As a result, flexible supply chains are better positioned to maintain customer satisfaction and improve overall performance.

In addition to flexibility, agility has emerged as a critical capability within digitally enabled supply chains. The research conducted by Alamsjah and Yunus demonstrates that the adoption of Supply Chain 4.0 technologies contributes to higher levels of supply chain agility. Technologies associated with Industry 4.0, including the Internet of Things, Big Data Analytics and blockchain, improve visibility, information sharing and process integration across supply chain networks. The study further shows that supply chain agility positively supports the achievement of Supply Chain 4.0 maturity, enabling organizations to respond more rapidly to environmental changes and operational challenges [126].

AI and BDA have also been identified as important contributors to supply chain performance. The paper in [133] describes the role of Artificial Intelligence-driven Big Data Analytics Capability (AI-BDAC) and found that it positively influences agility, resilience and supply chain performance. The study suggests that organizations capable of effectively utilizing AI and analytics tools can process information more efficiently, reduce information complexity and improve decision-making quality. These capabilities allow organizations to respond more effectively to disruptions and enhance overall operational performance.

The impact of digital technologies on flexibility is also evident in manufacturing environments. Paper in [90] give emphasis to the Advanced Manufacturing Technologies, particularly integrated CAD/CAM/CAE systems, support the transition from traditional manufacturing to digital manufacturing. The adoption of these technologies contributes to improved product quality, reduced production costs, shorter development cycles and greater manufacturing flexibility. By integrating design, engineering and production processes, organizations can respond more efficiently to changing customer requirements while improving operational effectiveness [90].

The reviewed studies collectively demonstrate that digital technologies contribute to performance improvement through multiple mechanisms, including enhanced visibility, better information processing, improved responsiveness, increased agility and greater operational flexibility. While different technologies support different aspects of supply chain management, their common objective is to enable organizations to adapt more effectively to changing business environments and achieve superior operational outcomes.

Overall, the literature indicates that digital transformation has a positive impact on both supply chain performance and flexibility. Digital supply chain practices, Industry 4.0 technologies, Artificial Intelligence, Big Data Analytics and Advanced Manufacturing Technologies enable organizations to improve responsiveness, strengthen agility, increase flexibility and maintain higher levels of operational performance in increasingly complex and uncertain supply chain environments.

3.4 Supply Chain Technologies

3.4.1 Core Digital Technologies in Supply Chains

Core digital technologies have become essential in modern supply chain management because they improve visibility, communication, coordination and decision-making across supply chain operations. Traditional supply chains often depend on delayed information, manual monitoring and disconnected operational systems. The conceptual frameworks in the selected studies show that digital technologies help transform supply chains into more connected and intelligent systems where information moves faster and decisions become more responsive. This transformation is important because modern supply chains are increasingly complex and require stronger operational awareness.

One of the most important digital technologies in supply chains is the Internet of Things (IoT). The visual frameworks in the selected studies present IoT as a system where physical objects, sensors, devices and logistics assets continuously exchange information through connected digital networks. This creates stronger operational visibility across transportation, warehousing and product movement. Instead of relying only on manual updates, supply chain managers can access real-time information about inventory, shipment conditions and operational performance. This makes supply chain operations more transparent and easier to manage [4].

The smart logistics concept further expands this idea by showing digital supply chains as integrated ecosystems rather than isolated operational functions. The visual model presents transportation, warehousing and delivery as interconnected processes supported by IoT, cloud systems, artificial intelligence and data processing technologies. This structure suggests that digital transformation in supply chains is not based on a single technology, but on the integration of multiple technologies working together. As a result, logistics systems become more intelligent, faster and more capable of responding to operational changes [72].

Industrial Internet of Things (IIoT) architectures provide another important technological perspective. The conceptual architecture diagrams show supply chain digital systems as layered structures that connect physical devices, communication networks, data processing platforms and enterprise decision systems. This architecture is important because supply chain management requires information to move efficiently from operational devices to management systems. The visual logic of IIoT demonstrates how connected technologies support stronger automation, monitoring and coordination in industrial supply chain environments [113].

Big data analytics is another important digital technology in supply chain transformation. The conceptual framework in the selected study shows that supply chain performance improves when organizations can collect, process and analyze large volumes of operational data. Rather than making decisions based only on historical reports, big data allows organizations to identify patterns, improve forecasting and support faster decision-making. This improves supply chain agility and adaptability, especially in environments where demand and operational conditions change quickly [121].

Digital Twin technology introduces a more advanced level of supply chain visibility and control. The architecture presented in the selected study shows a connection between the physical supply chain environment and its digital representation. This allows organizations to monitor operations, simulate future scenarios and improve planning decisions using real-time information. Digital Twins are especially useful because they support predictive decision-making rather than only reactive management. This strengthens visibility and improves operational control across logistics systems [124].

Mobile communication technologies also play an important role in digital supply chain management. The selected framework shows that real-time communication improves logistics control by supporting faster tracking, monitoring and coordination across supply chain activities. Transportation systems, warehousing operations and distribution processes benefit from stronger connectivity because operational information becomes available more quickly. This reduces delays, improves scheduling decisions and increases supply chain responsiveness [163].

More recent conceptual models show supply chains evolving toward intelligent digital ecosystems where Artificial Intelligence, big data, communication technologies and connected devices operate together. These visual frameworks suggest that future supply chains will depend less on isolated management systems and more on integrated intelligent networks capable of real-time decision-making. This broader digital transformation improves forecasting, operational coordination and system-wide adaptability, making supply chain management more proactive and efficient [274].

Overall, the selected conceptual frameworks show that core digital technologies are transforming supply chains from traditional operational structures into intelligent, connected and adaptive systems. IoT, IIoT, big data analytics, Digital Twins, mobile communication technologies and intelligent decision systems each contribute to stronger visibility, faster response and improved operational coordination. Together, these technologies form the technological foundation for the more advanced supply chain innovations discussed in later chapters.

3.4.2 Smart Logistics and Intelligent Systems

Smart logistics refers to the use of digital technologies, automation, intelligent devices and connected systems to improve logistics operations and supply chain management. The selected studies present smart logistics as an evolution of traditional logistics, where warehousing, transportation, monitoring and operational coordination become more intelligent, automated and data-driven. Instead of relying mainly on manual work and disconnected systems, smart logistics environments use connected technologies to improve speed, accuracy, flexibility and operational visibility.

A useful conceptual perspective presented in the selected literature describes smart logistics as a combination of digital communication, intelligent technologies and human-machine interaction. The framework from the Logistics Operator 4.0 study explains that logistics systems are becoming more connected through technologies such as IoT, smart sensors, wearable systems, automated vehicles, drones and intelligent software platforms. The structure of this framework shows that logistics operations are no longer isolated physical activities, but part of an integrated digital ecosystem where information and material flows operate together [101].

One important visual model from the cold chain logistics study presents a real-time monitoring architecture where sensors, RFID systems, GPS modules, databases and communication networks continuously exchange operational information. The system diagram shows how logistics environments can monitor temperature, transportation conditions, inventory movement and product location in real time. This type of intelligent monitoring improves supply chain visibility and helps organizations respond faster to operational problems, especially in sensitive logistics sectors such as cold chain transportation.

The system function framework in the same study also presents smart logistics as a highly integrated management environment. The visual structure connects order management, purchasing, warehousing, inventory control, transportation and distribution into one coordinated digital system. This architecture demonstrates that intelligent logistics depends on the integration of multiple operational functions rather than isolated digital tools. By connecting these logistics activities through information systems, organizations improve coordination and operational efficiency [25].

Warehouse automation is another important aspect of smart logistics. The selected study on intelligent sorting equipment presents several automated warehouse systems designed to improve logistics speed and reduce manual operational complexity. One of the most important visuals is the sorting manipulator system, where robotic arms, sensors, cameras and visual recognition systems work together to identify, sort and move products automatically. The figure demonstrates how intelligent systems can perform logistics tasks with higher accuracy and reduced human error.

Another useful warehouse automation visual is the cross-belt sorting system. The figure presents a highly organized conveyor-based sorting structure where products move automatically toward specific operational destinations. The system combines automated transportation, sorting control and digital coordination to improve warehouse performance. This type of intelligent logistics system is especially important in modern distribution centers where large volumes of products must be processed quickly and accurately [51].

The intelligent picking system presented in the same paper further expands the concept of smart warehousing. The visual structure shows an automated picking environment connected with warehouse management systems, enterprise systems and logistics databases. This architecture allows products to be selected, tracked and distributed automatically while reducing operational delays. The framework highlights that smart logistics increasingly depends on intelligent coordination between physical warehouse operations and digital information systems [51].

The Logistics Operator 4.0 framework introduces another important dimension of intelligent logistics by focusing on human-machine collaboration. The conceptual model shows that modern logistics systems do not completely replace human workers, but instead support them through smart devices, wearable technologies, automated transportation systems and decision-support tools. Technologies such as smart glasses, wearable scanners, drones and collaborative robots are visually integrated into logistics operations to improve safety, productivity and operational support. This perspective presents intelligent logistics as a balance between automation and human participation [101].

The broader intelligent logistics research framework also highlights the growing importance of technologies such as IoT, cloud computing, machine learning and big data analytics. The bibliometric visualizations presented in the selected study show that intelligent logistics research increasingly focuses on automation, optimization, sustainability, real-time processing and digital coordination. These conceptual mappings suggest that future logistics systems will continue evolving toward more intelligent, adaptive and interconnected operational environments [201].

Another important trend shown in the visual keyword and network maps is the integration of intelligent logistics with supply chain optimization and sustainability objectives. The conceptual clusters presented in the study connect intelligent logistics with route optimization, machine learning, digital decision-making and green logistics practices. This demonstrates that smart logistics is no longer focused only on operational efficiency, but also on improving long-term sustainability and system adaptability [201].

Overall, the selected conceptual frameworks and system architectures show that smart logistics and intelligent systems are transforming supply chain operations through automation, connectivity, real-time monitoring and intelligent coordination. Technologies such as IoT, RFID, robotics, intelligent sorting systems, digital monitoring platforms and collaborative human-machine systems improve operational visibility, speed and flexibility. Together, these technologies create more responsive and intelligent logistics ecosystems capable of supporting the growing complexity of modern supply chains.

3.4.3 Technology Integration and Supply Chain Performance

Technology integration plays a critical role in improving supply chain performance by enabling real-time communication, operational coordination, data visibility, automation and intelligent decision-making across supply chain networks. The selected studies emphasize that modern supply chains increasingly depend on interconnected digital systems capable of integrating suppliers, manufacturers, logistics providers and customers into a unified operational environment.

One of the most important concepts identified in the literature is digital supply chain integration between suppliers and manufacturers. The framework presented in the study Developing a Framework to Digitize Supply Chain Between Supplier and Manufacturer illustrates how information exchange and digital coordination can improve operational efficiency and reduce non-value-added activities. The visual framework of the supplier value chain presents several interconnected phases, including supplier selection, onboarding, engagement and evaluation, all supported through digital communication and information systems.

The same study also presents a detailed supply chain flow model that highlights the importance of seamless information exchange between operational departments and external partners. The framework demonstrates that integrated systems reduce communication delays, improve coordination and minimize operational inefficiencies caused by fragmented data management. According to the study, problems such as data duplicity, lack of transparency, poor communication platforms and disconnected operational structures negatively affect supply chain performance. Technology integration addresses these issues by enabling synchronized information flows and centralized operational visibility [9].

Another important contribution comes from the Industry 4.0 manufacturing logistics framework, which explains how vertical, horizontal and end-to-end integration improve manufacturing and logistics operations. Vertical integration refers to the coordination between different hierarchical information systems inside the organization, including sensors, shop-floor systems, manufacturing execution systems and enterprise resource planning systems. Horizontal integration focuses on inter-company coordination across supply chain networks, while end-to-end engineering integration connects stakeholders and operational activities across the entire product lifecycle.

The conceptual model of Industry 4.0 integration demonstrates that supply chain performance increasingly depends on the ability of organizations to connect operational technologies, logistics systems and information infrastructures into a unified digital ecosystem. The framework also explains that technologies such as IoT, cyber-physical systems, big data analytics and artificial intelligence support real-time monitoring, process optimization and automated decision-making in manufacturing logistics [103].

The literature further highlights the relationship between Industry 4.0 technologies and supply chain resilience. The systematic review on supply chain resilience presents a comprehensive framework linking Industry 4.0 technologies with resilience capabilities such as visibility, responsiveness, velocity and proactive risk management. The framework explains that technologies including big data analytics, cloud computing, IoT, artificial intelligence, blockchain and cyber-physical systems improve the ability of supply chains to anticipate disruptions, respond faster and recover more effectively from operational disturbances.

One of the most important observations in the resilience framework is that integrated digital systems improve supply chain visibility and information sharing across all operational levels. The study emphasizes that Industry 4.0 technologies support both pre-disruption and post-disruption resilience activities by enabling continuous monitoring, predictive analytics and real-time coordination between supply chain partners. This integrated digital environment became particularly important during the COVID-19 pandemic, where organizations with stronger digital integration demonstrated greater operational adaptability and continuity [59].

The role of information sharing is also strongly emphasized in the mobile supply chain management study. The conceptual framework identifies inter-organizational relationships and information sharing as some of the most influential factors affecting the adoption of mobile supply chain management systems. The study explains that mobile technologies improve supply chain performance by enabling instant access to operational information, customer demand data, inventory levels and logistics coordination from any location and at any time.

The framework further demonstrates that mobile supply chain systems improve responsiveness, operational efficiency, customer satisfaction and competitive advantage. Through mobile integration, organizations can coordinate warehouse operations, distribution systems, retail logistics and inventory management more effectively. The study also highlights that successful technology integration depends not only on technological capability, but also on organizational readiness, top management support and collaboration between supply chain partners [122].

Another important finding from the selected literature is that the effectiveness of technology integration depends on the production environment and operational context of the organization. The multiple case study on Industry 4.0 applications in manufacturing logistics explains that highly repetitive production systems benefit more from advanced automation and integrated logistics technologies compared to low-repetitiveness production environments. This indicates that supply chain performance improvements from technology integration are influenced by operational structure, production complexity and organizational flexibility.

The concept of smart factories presented in the same study also demonstrates the importance of integrating physical and digital systems. The framework describes smart factories as environments where cyber-physical systems, IoT devices, sensors and intelligent software platforms communicate continuously in real time. This integration enables automated process control, operational monitoring and adaptive decision-making across manufacturing and logistics activities [103].

Overall, the selected studies demonstrate that technology integration significantly improves supply chain performance through enhanced visibility, coordination, automation, responsiveness and information sharing. Digital integration between suppliers, manufacturers, warehouses, transportation systems and customers enables more efficient and resilient supply chain operations. Technologies such as IoT, artificial intelligence, mobile systems, cloud computing, cyber-physical systems and big data analytics create interconnected supply chain ecosystems capable of supporting modern operational complexity and improving organizational competitiveness.

3.4.4 Blockchain

3.4.4.1 Fundamentals and Key Characteristics of Blockchain

Blockchain is a digital technology that stores information in connected blocks and allows data to be shared across a network in a secure and transparent way. In supply chain management, blockchain is used to improve traceability, security, coordination and trust between supply chain participants. The technology supports decentralized information sharing without depending on a single central authority.

The literature explains that blockchain first became widely known through Bitcoin, but today it is used in many non-financial sectors such as logistics, manufacturing, healthcare, retail and supply chain management. One of the main ideas behind blockchain is that all participants in the network can access the same information in real time, creating a shared and immutable digital ledger.

A common visual model presented in the papers shows blockchain as a chain of connected blocks. Each block stores transaction data, timestamps and a cryptographic hash connected to the previous block. This structure creates a continuous and secure flow of information because changing one block would affect all following blocks in the chain. The diagrams in the studies clearly show how every block is linked to another, creating transparency and traceability throughout the system [96].

Another important figure presented in the literature illustrates the process of blockchain transactions. The model begins with a transaction proposal between two participants. The transaction is then verified through cryptographic signatures and distributed across a network of computers for validation. After verification, the transaction is permanently added to the blockchain ledger. This process creates a secure, verifiable and tamper-resistant system for exchanging information and digital assets [86].

The studies also explain that blockchain works through decentralized networks. Unlike traditional systems that depend on central databases or intermediaries, blockchain distributes information across multiple nodes. Every participant maintains a copy of the ledger, which increases reliability and reduces the risk of data manipulation or fraud. This decentralized structure is one of the main characteristics of blockchain technology [86].

Transparency is another major blockchain characteristic identified in the literature. Because all authorized participants can view validated transactions, supply chain visibility improves significantly. The papers explain that this visibility helps organizations track products, shipments, suppliers and logistics activities more effectively across the entire supply chain network [123].

Immutability is also frequently highlighted in the selected studies. Once information is verified and stored in the blockchain, it cannot easily be changed or deleted. This characteristic improves data security and creates trust between supply chain partners. The literature explains that blockchain can therefore reduce problems related to counterfeit products, false documentation and unreliable transaction records.

The concept of smart contracts is another important blockchain feature discussed in the papers. Smart contracts are digital agreements that automatically execute predefined actions when specific conditions are met. One diagram presented in the literature shows a producer and a supermarket connected through a blockchain smart contract. Once the agreed conditions are satisfied, payments and product transfers occur automatically without requiring intermediaries. This process reduces delays, operational costs and administrative complexity [96].

The studies also distinguish between public and private blockchains. Public blockchains allow open participation and transparency for all users, while private blockchains restrict access to authorized participants only. In supply chain management, private and consortium blockchains are often preferred becuse they provide better control, confidentiality and operational security between business partners [85].

Another key characteristic identified in the literature is traceability. Blockchain allows organizations to monitor the movement and history of products from raw materials to final delivery. The papers explain that combining blockchain with technologies such as IoT sensors and RFID systems can further improve product monitoring, transportation visibility and inventory management [123].

Several studies also emphasize the relationship between blockchain and supply chain sustainability. Blockchain improves information visibility related to environmental performance, ethical sourcing, product quality and operational transparency. The literature explains that better visibility supports more sustainable supply chain practices and improves decision-making across organizations [123].

The selected papers also note that blockchain adoption still faces several challenges. These include scalability limitations, integration complexity, high implementation costs, legal issues, interoperability problems and limited organizational understanding of the technology. Despite these challenges, blockchain is considered a promising technology for future digital supply chains because of its ability to improve trust, transparency, traceability and operational efficiency.

Overall, blockchain can be described as a decentralized and secure digital system that records transactions in a transparent and immutable way. Its main characteristics include decentralization, transparency, traceability, immutability, security, smart contracts and distributed information sharing. These characteristics make blockchain increasingly important for modern supply chain management and digital logistics systems.

3.4.4.2 Applications of Blockchain in Supply Chain

The selected studies show that blockchain technology is increasingly used in supply chain management to improve transparency, traceability, coordination, security and operational efficiency. The conceptual models and system architectures presented in the papers demonstrate that blockchain is no longer limited to financial applications, but has become an important digital infrastructure for modern supply chains [203].

One important blockchain application identified in the literature is supply chain traceability. The FARMSUPPLY framework presents a blockchain-based food supply chain architecture connecting farmers, manufacturers, distributors, retailers and consumers into one transparent system. The visual model shows how every transaction and product movement is recorded through blockchain and validated using Ethereum smart contracts. This structure improves food traceability, product verification and visibility across the entire food supply chain.

The FARMSUPPLY model also demonstrates how blockchain supports food safety and fraud prevention. According to the framework, blockchain creates immutable transaction records that help organizations track product origin, monitor transportation stages and validate supply chain activities. The architecture combines smart contracts with distributed ledger systems to reduce manual processing and improve trust between supply chain participants [17].

Another important blockchain application presented in the literature is agricultural supply chain management supported by Artificial Intelligence. The AI-enabled blockchain ecosystem proposed in the agricultural study integrates blockchain, AI, IoT devices and smart contracts into one coordinated operational system. The framework explains that AI supports demand prediction, inventory analysis, warehousing and route optimization, while blockchain secures and validates operational information across the agricultural supply chain.

The same paper also presents a proposed agricultural supply chain model where blockchain stores digital records for suppliers, buyers and other stakeholders. The conceptual architecture shows that AI is used to collect and analyze operational data, while blockchain ensures secure storage and decentralized information sharing. This integrated structure improves coordination, transparency and operational efficiency within the agriculture ecosystem [2].

The literature further explains that blockchain improves real-time monitoring and product tracking through technologies such as IoT devices, RFID systems, QR codes, sensors and GPS tracking. In the agricultural blockchain frameworks, operational information collected from transportation, warehousing and production systems is continuously validated and shared through blockchain networks. This improves visibility and reduces dependence on centralized databases [17].

The literature also presents blockchain-based traceability and anti-counterfeiting architectures designed to enhance product authenticity and supply chain transparency. These systems typically consist of several functional modules, including traceability information collection, system architecture management, data storage, transaction verification and user management. Operational data generated at different stages of the supply chain are collected, analyzed and securely recorded on the blockchain, creating a chronological and tamper-resistant history of product activities. Transaction verification mechanisms authenticate participating entities and maintain reliable transaction records, while user management functions supported and controlled access to supply chain information. Such architectures strengthen product traceability, reduce the circulation of counterfeit products, improve information reliability and increase trust among supply chain participants by providing secure and transparent access to operational data [23].

Additional studies focusing on agricultural and food supply chains highlight the role of blockchain in addressing long-standing challenges related to traceability, transparency and operational efficiency. Blockchain-based architectures integrate RFID tags, IoT devices, smart contracts and data analytics to create a secure and decentralized environment for monitoring food products throughout their lifecycle. In these systems, operational data such as harvesting dates, product identification numbers, location history, transportation status and inventory information can be continuously recorded and verified through blockchain networks. This approach improves product traceability, strengthens food safety controls, reduces the risk of fraud and enhances communication among suppliers, distributors, retailers and consumers. Furthermore, the integration of smart contracts enables automated transaction execution, while data analytics supports the extraction of valuable operational insights that can improve overall supply chain performance [14].

Another major blockchain application is supply chain mapping and sustainability management. The blockchain mapping framework explains that modern supply chains are often geographically distributed and highly complex, making visibility and integration difficult. The conceptual model proposes blockchain as a technology capable of mapping upstream, midstream and downstream supply chain activities in real time. This allows organizations to improve supply chain transparency, accountability and sustainability performance.

The visual and theoretical framework from the same study also shows that blockchain improves supply chain integration by enabling better information sharing between supply chain partners. According to the study, blockchain helps organizations monitor suppliers, track operational activities and improve visibility across multi-tier supply chain networks. This becomes particularly important during disruptions where organizations need fast access to reliable supply chain information [120].

The automotive industry is another important application area identified in the selected studies. The blockchain-cloud integration architecture presented in the automotive supply chain paper combines IoT devices, blockchain layers and cloud services into one integrated operational environment. The framework supports transportation monitoring, logistics coordination, vehicle tracking and secure communication between supply chain participants.

The blockchain-cloud model also demonstrates how blockchain improves intelligent transportation systems. The conceptual architecture includes applications such as GPS tracking, accident alerts, speed management, automatic toll collection and smart transportation coordination. Through blockchain integration, automotive supply chain systems improve communication efficiency and operational synchronization between logistics and transportation networks [5].

Another important blockchain application discussed in the literature is smart contract automation. The enterprise transparency framework combines blockchain, Artificial Intelligence and communication networks to create a transparent and automated supply chain system. The architecture demonstrates that smart contracts automatically execute operational activities and transactions when predefined conditions are satisfied. This reduces delays, manual intervention and administrative complexity in supply chain operations.

The same framework also shows that blockchain improves enterprise supply chain transparency by creating secure and tamper-resistant information systems. Artificial Intelligence is integrated into the architecture to optimize demand forecasting, scheduling and operational decision-making, while communication networks support real-time synchronization between blockchain nodes. According to the study, this integrated system improves execution efficiency and reduces response time across supply chain operations [203].

Another important application identified in the literature is blockchain-supported supply chain sustainability. The sustainability framework explains that blockchain helps organizations improve traceability, accountability and sustainability verification throughout supply chain activities. By improving visibility across suppliers, logistics providers and operational processes, blockchain supports more responsible and sustainable supply chain management [120].

Overall, the selected studies demonstrate that blockchain applications in supply chain management focus mainly on traceability, transparency, smart contracts, operational coordination, supply chain mapping, logistics monitoring and secure information sharing. The conceptual models and system architectures presented in the literature show that blockchain increasingly functions as a foundational technology for intelligent and digitally integrated supply chain systems.

3.4.4.3 Benefits, Challenges and Impact on Supply Chain Performance

Blockchain technology offers significant benefits for supply chain management by improving transparency, traceability, coordination, security, sustainability and operational efficiency. At the same time, the literature identifies several technological and organizational challenges related to blockchain adoption, including scalability limitations, interoperability problems, infrastructure requirements and regulatory uncertainty. Overall, the reviewed studies indicate that blockchain positively influences supply chain performance by improving visibility, responsiveness, resilience and collaboration among supply chain partners.

One of the most important benefits of blockchain in supply chain management is transparency. Blockchain creates a decentralized and immutable ledger where all transactions and product movements are recorded and shared among authorized participants. According to the logistics industry study, blockchain improves supply chain openness and responsiveness by enabling real-time information sharing and visibility across logistics operations. The study concludes that organizations adopting blockchain experience better operational responsiveness and stronger market performance [3].

Another major benefit is traceability. Blockchain enables end-to-end product tracking from raw material sourcing to final delivery. The traceability study explains that blockchain records every stage of the product journey, creating a tamper-proof historical record that improves accountability and reduces fraud risks. This capability becomes particularly important in product recalls, quality verification and counterfeit prevention.

The literature also highlights blockchain's role in improving trust and collaboration between supply chain stakeholders. By using a shared immutable ledger, manufacturers, suppliers, distributors, logistics providers and retailers can exchange information more securely and efficiently. The traceability framework explains that blockchain increases coordination and cooperation among supply chain partners because all participants have access to reliable and verified operational data [6].

Beyond operational transparency and traceability, blockchain technology can also transform the overall business model of supply chain organizations. Morkunas et al. argue that blockchain creates value by reducing transaction costs, improving information verifiability and strengthening collaboration among supply chain partners through secure and decentralized information sharing. The authors further explain that blockchain can eliminate certain intermediaries, automate business processes and support more efficient coordination across supply chain networks. A well-known example presented in the study is Walmart's blockchain-based food traceability system, which significantly reduced the time required to identify the origin of food products, improving supply chain responsiveness, product safety and operational efficiency. These capabilities demonstrate that blockchain not only supports operational improvements but can also contribute to broader organizational transformation and competitive advantage within modern supply chains [85].

Another significant benefit identified in the literature is operational efficiency. Smart contracts automate transactions and operational procedures once predefined conditions are satisfied. The logistics industry study states that blockchain reduces manual intervention, simplifies communication and improves transaction processing efficiency within supply chain operations [3]. Similarly, the enterprise transparency framework explains that blockchain-based smart contracts improve execution efficiency and reduce response time in supply chain systems [203].

Blockchain also contributes to supply chain sustainability and resilience. The resilience study explains that blockchain supports sustainable supply chains by improving visibility, transparency and product authentication while reducing fraud and counterfeiting activities. During disruptions such as the COVID-19 pandemic, blockchain enables faster information sharing and better coordination between supply chain participants, helping organizations maintain operational continuity [7].

Another important benefit is improved security and data integrity. Blockchain's cryptographic structure and decentralized architecture protect supply chain information from tampering and unauthorized modification. The automotive industry review explains that blockchain improves cybersecurity, privacy, accountability, robustness and authentication throughout supply chain systems. The study also highlights that blockchain eliminates single points of failure by distributing data across multiple network nodes [67].

The literature further emphasizes blockchain's impact on supply chain integration and information sharing. The sustainability and mapping study explains that blockchain improves supply chain visibility across upstream, midstream and downstream operations. Better mapping and integration allow organizations to monitor suppliers, coordinate logistics activities and improve decision-making processes [120].

Despite these advantages, the literature identifies several important challenges related to blockchain adoption in supply chain management. One major challenge is the lack of standardization and interoperability between blockchain platforms. According to the traceability study, different organizations may use incompatible blockchain systems, making communication and information exchange difficult across supply chain networks [6].

Scalability and system performance are also significant concerns. The traceability literature explains that blockchain networks may become slower and more congested as transaction volumes increase, leading to delays and higher operational costs [6]. Similar concerns are identified in logistics and freight transportation systems where large-scale data processing requires substantial computational power and infrastructure support.

Another important challenge is infrastructure and technological readiness. The freight logistics adoption study identifies infrastructural facilities, availability of blockchain tools and technological support as critical requirements for successful blockchain implementation. Organizations with limited digital infrastructure may face difficulties integrating blockchain into existing supply chain systems.

The literature also highlights regulatory and organizational barriers. The freight logistics study emphasizes that government policy, institutional support and regulatory frameworks significantly influence blockchain adoption decisions. In many industries, the absence of clear legal standards and governance mechanisms creates uncertainty regarding blockchain implementation and data management responsibilities [87].

Cost and implementation complexity are additional challenges identified in the literature. The shipping industry study explains that organizations must address data privacy, system integration, project maturity and operational compatibility before successfully implementing blockchain solutions [29]. Integrating blockchain with ERP systems, IoT devices, cloud platforms and legacy databases may require significant investment and organizational restructuring [29].

Another challenge concerns knowledge and expertise limitations. According to the freight logistics literature, many logistics professionals still misunderstand blockchain technology and lack sufficient knowledge regarding its operational applications and strategic value. This slows adoption and limits organizational readiness for digital transformation.

The literature also discusses concerns regarding data privacy and governance. While blockchain improves transparency, organizations must still protect sensitive commercial information. The automotive blockchain review explains that privacy management, cryptographic security and identity protection remain critical issues in blockchain-based ecosystems [67].

Overall, the reviewed studies conclude that blockchain has a positive impact on supply chain performance. Blockchain improves transparency, visibility, flexibility, coordination, traceability, resilience, sustainability and operational efficiency across supply chain networks. The logistics industry study specifically states that blockchain adoption positively affects supply chain performance and integration, helping organizations achieve stronger competitiveness and improved market positioning [3].

Variables	BTU	SCT	SCF
Blockchain Technology (BCT)	1		
Supply Chain Transparency (SCT)	0.490	1	
Supply Chain Flexibility (SCF)	0.422	0.502	1

8Figure : Corellation Statistics Between Variables [3].

Similarly, the supply chain empowerment study concludes that blockchain enhances supply chain operations mainly through information sharing, information traceability and trust establishment among stakeholders [117]. The resilience framework also confirms that blockchain improves the ability of supply chains to respond to disruptions and unexpected events by supporting reliable, real-time and secure information exchange [7].

In conclusion, blockchain technology provides substantial benefits for supply chain management by improving transparency, automation, traceability, security, sustainability and operational performance. However, organizations must also address important challenges related to scalability, interoperability, infrastructure readiness, costs, regulation and technical expertise before blockchain can achieve widespread adoption across global supply chain networks.

3.4.5 IoT – RFID – Sensors – Networks

3.4.5.1 Fundamentals of IoT and Sensor-Based Technologies

The rapid digital transformation of supply chains and industrial operations has significantly increased the importance of Internet of Things (IoT), RFID systems, sensors and communication networks. These technologies enable organizations to collect, transmit, process and analyze real-time operational data, thereby improving visibility, automation, coordination and decision-making across supply chain activities.

The Internet of Things (IoT) refers to a network of interconnected physical objects, devices, machines and systems equipped with sensors, software, communication capabilities and data-processing technologies that allow them to exchange information through the internet or other communication networks. According to the IoT and supply chain integration study, IoT represents the next generation of internet-connected embedded information and communication technologies (ICT) that seamlessly integrate supply chain and logistics processes through intelligent and autonomous applications [155].

IoT technology combines physical devices with digital systems to create smart environments capable of monitoring, sensing, tracking and controlling operational activities in real time. The IoT framework enables objects to be identified, located, sensed and managed through internet-based communication platforms. These capabilities significantly improve operational visibility, responsiveness and coordination throughout supply chain networks.

The architecture of IoT systems generally consists of several interconnected components. According to the intelligent supply chain system study, IoT infrastructures typically include resource integration modules, sensing and recognition layers, data transmission networks, information integration systems and application service platforms. These layers collectively support data acquisition, communication, processing, storage and intelligent decision-making.

Sensors are one of the fundamental components of IoT systems. Sensors are electronic devices that detect, measure and transmit physical or environmental information such as temperature, humidity, pressure, vibration, motion, location, or product conditions. The IoT literature explains that sensors enable comprehensive perception and real-time monitoring of physical objects and operational environments [24].

Different types of sensors are used depending on operational requirements. For example, supply chain and logistics operations may utilize temperature sensors for cold-chain monitoring, GPS sensors for location tracking, pressure sensors for equipment monitoring and motion sensors for warehouse automation. In industrial systems, sensors also support predictive maintenance, equipment diagnostics and operational safety management [31].

Load cells represent another important category of sensors used in industrial IoT environments and smart warehousing applications. These sensors measure weight and mechanical force by utilizing strain gauges that convert physical deformation into electrical signals. Since the resulting resistance changes are extremely small, instrumentation amplifiers such as the HX711 are commonly employed to amplify and process the sensor output. Load-cell-based monitoring systems enable real-time weight measurement, inventory tracking, stock monitoring and automated warehouse management. By integrating load cells with IoT communication platforms, organizations can continuously monitor inventory levels and operational conditions, improving warehouse visibility, automation and resource management [26].

RFID (Radio Frequency Identification) technology is another critical component of IoT-based supply chain systems. RFID enables automatic identification and tracking of objects using radio-frequency signals. According to the RFID-SCOR study, RFID systems consist of RFID tags attached to products or objects, RFID readers, antennas and information systems that process collected data [16].

RFID tags contain electronically stored information that can be automatically read without direct physical contact or line-of-sight scanning. Unlike traditional barcode systems, RFID technology enables continuous and automated data collection in real time [16]. RFID systems improve inventory control, warehouse management, transportation monitoring and product traceability across supply chain operations.

9Figure : Structure of RFID tag [16].

The RFID framework described in the logistics case study demonstrates that RFID technologies improve real-time information sharing, reduce delivery times, increase product traceability and support faster ERP system implementation through standardized performance indicators. RFID systems are particularly useful in warehousing, logistics, transportation, retail operations and manufacturing environments.

Communication networks are equally essential for IoT operations because they enable data exchange between sensors, devices, cloud systems and management platforms. IoT communication networks may include wireless sensor networks (WSNs), Wi-Fi, Bluetooth, GPS, mobile communication systems, cloud infrastructures and advanced 5G communication technologies [24].

In addition to communication infrastructures, IoT systems rely on specialized communication protocols that enable efficient data exchange between connected devices, sensors and management platforms. Several protocols have been widely adopted in IoT environments, including Advanced Message Queuing Protocol (AMQP), Constrained Application Protocol (CoAP) and Message Queuing Telemetry Transport (MQTT). AMQP supports reliable message exchange between applications and enterprise systems, while CoAP is specifically designed for resource-constrained devices and low-power networks using a lightweight request-response architecture. MQTT has become one of the most widely used IoT communication protocols due to its lightweight publish/subscribe messaging model, which enables efficient data transmission between multiple devices over TCP/IP networks. MQTT-based systems typically rely on message brokers, such as HiveMQ and Mosquitto, to coordinate communication between connected devices and applications. These protocols play a critical role in ensuring reliable, scalable and efficient communication within modern IoT ecosystems [30].

The development of 5G networks has significantly improved IoT capabilities by enabling faster data transmission, lower latency, larger connectivity capacity and more reliable real-time communication. According to the 5G intelligent supply chain study, 5G-supported IoT systems improve resource allocation, service integration, automation and intelligent supply chain management.

Wireless sensor networks (WSNs) allow multiple distributed sensors to communicate and exchange data automatically. These networks support large-scale monitoring systems and facilitate continuous data collection across complex supply chain and industrial environments. WSNs are widely used in logistics monitoring, smart warehousing, transportation management and industrial automation.

Cloud computing and big data technologies are closely integrated with IoT systems. IoT devices generate large volumes of operational data that require storage, processing and analysis. The IoT big data study explains that intelligent processing technologies such as cloud computing, data mining and big data analytics enable organizations to transform raw sensor data into actionable information for operational decision-making [24].

IoT technologies also contribute significantly to supply chain visibility. The supply chain visibility review defines visibility as the ability to capture timely information regarding the location, identity and status of products, resources and operational activities throughout the supply chain. IoT systems support this capability by providing real-time data collection, monitoring and information sharing among supply chain stakeholders [150].

The literature introduces the concept of "Supply 4.0," which refers to the digital transformation of supply chains through Industry 4.0 technologies, including IoT, sensors, big data, cyber-physical systems and intelligent automation. Supply 4.0 improves efficiency, flexibility, transparency and collaboration across supply chain operations.

IoT-based technologies also improve supply chain integration. According to the organizational capability study, IoT systems positively affect internal integration, supplier integration and customer integration by facilitating real-time information sharing and synchronized operational processes. These capabilities enhance supply chain performance, operational coordination and organizational responsiveness [155].

Another important aspect of IoT systems is automation. Smart devices and automated systems can independently collect data, monitor operational conditions, trigger alerts and support autonomous decision-making processes. The e-commerce optimization study explains that IoT technologies support automated warehousing, intelligent transportation systems and smart collaboration mechanisms.

Data security and privacy represent important concerns in IoT-based systems. Since IoT networks continuously exchange large amounts of operational data, organizations must implement encryption, authentication, access control and cybersecurity mechanisms to protect sensitive information. The power IoT study further emphasizes the importance of secure communication architectures and protected data transmission systems in large-scale IoT infrastructures [31].

Overall, IoT, RFID, sensors and communication networks form the technological foundation of modern intelligent supply chain systems. These technologies enable real-time data collection, automated monitoring, operational visibility, resource coordination, predictive analytics and intelligent decision-making. Their integration within supply chain management significantly improves efficiency, responsiveness, traceability, transparency and operational performance.

3.4.5.2 Applications in Logistics and Warehouse Management

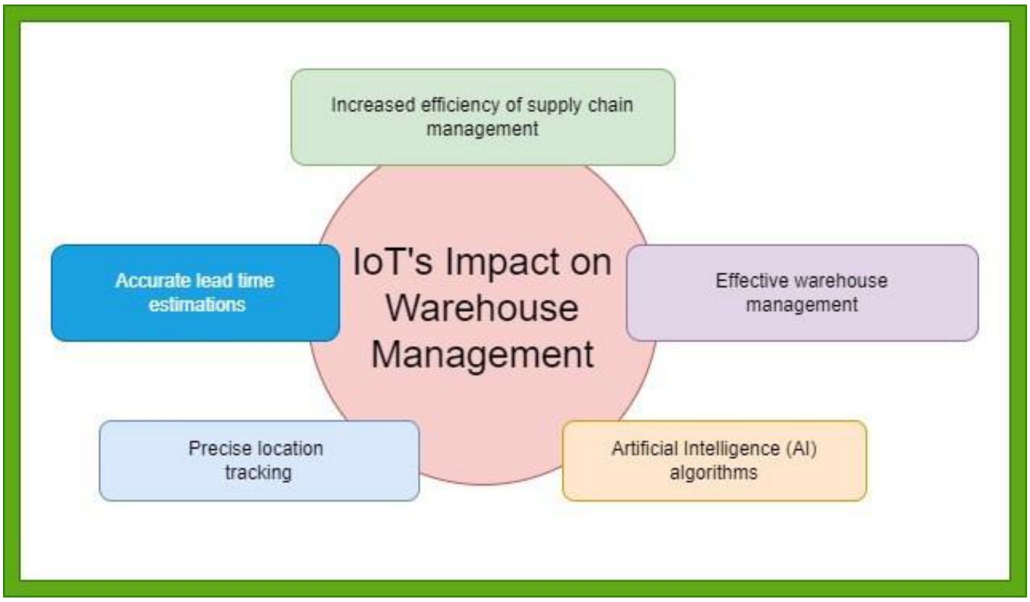
The rapid development of Internet of Things (IoT) technologies has significantly transformed logistics and warehouse management operations. Modern warehouses increasingly rely on IoT infrastructures, RFID systems, wireless sensor networks, cloud computing and intelligent automation to improve operational efficiency, inventory visibility, accuracy and decision-making processes. These technologies support the transition from traditional manual warehousing toward intelligent and automated "smart warehouse" environments.

Traditional warehouse management systems mainly depended on manual recording, paper-based inventory control and labor-intensive operational procedures. However, the increasing complexity of logistics operations, large-scale inventories and growing e-commerce demands have made conventional approaches inefficient and error-prone [40]. Modern logistics environments require real-time visibility, automation, accurate inventory tracking and intelligent coordination across warehousing operations.

IoT technologies enable the creation of smart logistics systems where physical goods, storage equipment, transportation devices and warehouse infrastructures are interconnected through communication networks and intelligent sensing technologies. According to the intelligent logistics supply chain study, IoT-based logistics systems integrate technologies such as RFID, cloud computing, wireless communication, artificial intelligence and logistics information systems to support intelligent supply chain operations [20].

One of the most important applications of IoT in warehousing is inventory management. IoT-enabled inventory systems use RFID tags, sensors, wireless communication technologies and cloud-based databases to automatically monitor stock levels, track product movement and update inventory information in real time. This significantly reduces human intervention, minimizes inventory errors and improves operational transparency [46].

RFID technology plays a central role in IoT-enabled warehouse management systems by supporting automatic identification, tracking and monitoring of goods throughout warehouse operations. RFID-based architectures integrate electronic tags, readers, wireless communication networks, middleware platforms and centralized databases to enable real-time inventory visibility and automated data collection. Unlike traditional barcode systems, RFID technology supports non-contact operation, simultaneous identification of multiple items and continuous monitoring of inventory movements. These capabilities improve warehouse efficiency, product traceability, inventory accuracy and operational coordination while reducing manual intervention and logistics costs. Furthermore, the integration of RFID with IoT communication infrastructures enables real-time synchronization of warehouse information and supports the development of intelligent warehousing environments capable of automated inventory management and decision support systems [11].



10Figure : IoT's Impact on Warehouse Management [46].

RFID technology plays a central role in intelligent warehouse management systems. RFID systems allow automatic identification and tracking of goods using radio-frequency signals without requiring direct visual scanning. The RFID warehouse management study explains that RFID systems consist of electronic tags, readers, antennas, servers and management software that collectively support automatic data collection and inventory monitoring.

RFID-based warehouse systems support multiple warehouse functions, including goods receiving, in-warehouse storage management, inventory checks, stock transfers and outgoing shipments [32]. RFID readers installed on warehouse shelves or transportation equipment automatically detect tagged products and transmit inventory information to centralized warehouse management systems.

Compared to traditional barcode technologies, RFID systems provide several advantages, including non-contact operation, long-distance reading, fast scanning, simultaneous multi-item recognition, accurate positioning and real-time monitoring capabilities. These advantages significantly improve warehouse efficiency and inventory accuracy [32].

IoT-based warehouse management systems also improve inventory visibility and traceability. Real-time tracking allows managers to monitor the exact location, movement and status of products throughout warehouse operations. Such visibility enhances supply chain coordination and supports faster operational decision-making [39].

Automation represents another major application of IoT in warehouse management. Modern smart warehouses increasingly use autonomous systems, intelligent carts, robotic systems and automated monitoring infrastructures to reduce labor dependency and operational inefficiencies. The IoT gateway warehouse study developed a human-following cart integrated with RFID and IoT gateway technologies to assist warehouse staff during order-picking operations.

The proposed system automatically followed warehouse workers, reduced physical workload and improved order-picking efficiency through intelligent navigation and RFID-based product identification. The study further demonstrated that IoT gateways support reliable communication and real-time inventory tracking even in unstable network environments [33].

Order picking and inventory management are among the most labor-intensive warehouse activities. Traditional manual order-picking systems often lead to delays, incorrect item selection and increased operational costs. IoT-enabled automation helps reduce these challenges by improving inventory accuracy and operational speed.

Smart warehouse systems also integrate advanced sensing technologies for environmental monitoring and operational safety. Sensors can continuously monitor temperature, humidity, pressure, vibration, lighting conditions and equipment performance within warehouse environments. Such monitoring is especially important in pharmaceutical, food and agricultural warehouses where environmental conditions directly affect product quality.

Study in paper [271] shows that smart sensing technologies are becoming fundamental components of food logistics and cold-chain management. Intelligent sensor networks incorporating IoT devices, biosensors, RFID systems, cloud computing, Artificial Intelligence (AI) and 5G communication continuously monitor environmental parameters such as temperature, humidity, microbial activity, gas concentration and product freshness throughout storage and transportation. These integrated monitoring systems improve traceability, enable early detection of quality deterioration and support real-time decision-making, thereby enhancing food safety, reducing spoilage and improving overall supply chain performance.

The intelligent warehouse monitoring study highlights the use of RFID and multiple sensors for pharmaceutical warehouse monitoring. The system collected environmental data in real time and generated automatic alerts whenever operational conditions exceeded predefined safety thresholds. Such systems help prevent product spoilage, equipment damage and operational disruptions [38].

Additional studies highlight the use of IoT-based monitoring systems in agricultural storage and warehouse environments where product quality depends heavily on environmental conditions. These systems combine sensors, wireless communication technologies, cloud platforms and machine learning algorithms to continuously monitor parameters such as temperature, humidity, carbon dioxide levels, soil moisture and light intensity. Sensor data are collected through devices such as ESP32, ESP8266, Arduino and wireless sensor networks (WSNs) and are transmitted using communication protocols such as MQTT, GSM, ZigBee and Wi-Fi to cloud-based monitoring platforms and management dashboards. Machine learning algorithms can further analyze the collected information, generate alerts and support operational decision-making by identifying abnormal conditions that may affect product quality. Such architectures have been applied in smart storage facilities, cold-chain environments and agricultural warehouses, where continuous monitoring helps reduce spoilage, improve traceability, optimize storage conditions and enhance overall supply chain efficiency [49].

Cloud computing technologies further enhance warehouse intelligence by enabling centralized data storage, real-time synchronization, remote monitoring and large-scale analytics. The IoT-cloud warehouse management system integrated RFID technology with Firebase cloud platforms to support automated inventory synchronization and real-time visibility. The study reported significant improvements in operational efficiency, scalability and inventory accuracy.

Cloud-based warehouse systems also facilitate remote access to operational information and support decision-making through web dashboards, analytics platforms and centralized management interfaces. Managers can monitor warehouse status, inventory levels and operational alerts from multiple locations in real time [39].

Artificial intelligence and image recognition technologies are increasingly integrated into smart warehouse systems. The intelligent warehouse management study combined RFID technology with Faster R-CNN image recognition algorithms to improve product identification and warehouse automation. RFID systems provided real-time positioning information, while image recognition technologies enabled automatic product detection and classification.

The integration of RFID and image recognition significantly improved delivery efficiency and operational stability. According to the experimental results, the RFID and Faster R-CNN model reduced average delivery times compared to traditional CNN-only approaches. These technologies support advanced automation and reduce dependency on manual warehouse operations [34].

IoT systems also support predictive analytics and intelligent decision-making in logistics operations. Continuous data collection from sensors, RFID systems and operational devices enables organizations to analyze warehouse performance, optimize storage allocation, forecast inventory demand and improve resource utilization.

The concept of "Inventory Management 4.0" reflects the integration of Industry 4.0 technologies into warehouse and inventory operations. IoT devices, RFID tags, sensors and intelligent communication systems continuously monitor inventory status and provide real-time stock information to organizations. This improves demand forecasting, operational planning and supply chain responsiveness [46].

Beyond inventory management, IoT technologies also support end-to-end tracking and monitoring of goods throughout supply chain operations. A representative IoT-based smart supply chain architecture combines RFID technology for indoor tracking and GPS technology for outdoor monitoring, enabling continuous visibility of products across warehouse and transportation environments. In this system, RFID readers automatically identify and track tagged goods within warehouse facilities, while GPS modules provide real-time location information during transportation activities. Operational data are transmitted through IoT communication infrastructures to centralized servers and databases, allowing managers to monitor the location, status and movement of goods in real time. The architecture further incorporates geo-coding, reverse geo-coding and geo-fencing capabilities that support location-based monitoring and automated event detection when assets enter or leave predefined operational areas. By integrating indoor and outdoor tracking technologies within a unified IoT environment, the system improves supply chain visibility, enhances traceability, supports real-time decision-making and increases overall logistics efficiency [28].

IoT applications are also highly valuable in specialized warehouse environments such as agricultural storage systems. The onion buffer stock management study developed a smart warehouse infrastructure using RFID readers, temperature sensors, moisture sensors, cloud servers and cooling systems to optimize onion storage conditions [50]. The system enabled real-time environmental monitoring and automated control mechanisms to reduce spoilage and improve supply chain efficiency.

Another important advantage of IoT-enabled warehouse systems is operational integration. IoT technologies connect suppliers, warehouses, logistics providers and customers through synchronized information systems. This integration improves coordination across supply chain operations and supports faster information exchange between stakeholders [20].

Despite these advantages, several challenges remain associated with IoT implementation in logistics and warehouse management. These include high infrastructure costs, cybersecurity concerns, interoperability problems, data management complexity and system integration difficulties. Organizations must also address network reliability, data privacy and technical standardization issues during IoT adoption [46].

The smart object study adds another practical warehouse application by presenting a smart hand pallet truck for IoT-enabled warehouses. The system combines UHF RFID, load cells, Raspberry Pi, Wi-Fi communication, a server and a web application to identify pallets, validate quantities, match goods with put-away locations and support warehouse workers through a tablet interface. This shows that IoT can improve warehouse operations not only through fixed infrastructure, but also through smart mobile equipment inside the warehouse [35].

The milk quality monitoring review also supports the importance of IoT in logistics and storage environments where product quality depends on continuous monitoring. The IoT architecture presented in the study includes physical devices and sensors, communication networks, service layers and application interfaces. Although the paper focuses on dairy quality, its logic is relevant to cold-chain logistics because IoT and AI can monitor composition, adulteration, microbial quality indicators and storage conditions in real time, improving quality control and decision-making in sensitive supply chains [268].

Overall, IoT technologies have fundamentally transformed logistics and warehouse management by enabling real-time inventory visibility, intelligent automation, environmental monitoring, predictive analytics and integrated supply chain coordination. RFID systems, sensors, cloud computing, artificial intelligence and wireless communication technologies collectively support the development of smart warehouses capable of achieving higher operational efficiency, improved inventory accuracy, reduced labor costs and enhanced supply chain responsiveness.

3.4.5.3 Impact on Supply Chain Visibility and Performance

IoT technologies, RFID systems, sensors, cloud computing and intelligent communication networks have significantly transformed supply chain visibility and operational performance. The literature explains that modern supply chains increasingly depend on real-time information sharing, intelligent monitoring systems and digital integration to improve coordination, responsiveness and operational decision-making across logistics networks.

The concept of Supply 4.0 further strengthens this transformation. According to Ahmed et al. (2021), Supply 4.0 refers to the digitization of supply chains through Industry 4.0 technologies such as IoT, cyber-physical systems, big data analytics, cloud computing, RFID, sensors, robotics and machine-to-machine communication. These technologies create more agile, efficient, transparent and customer-focused supply chains by enabling stronger integration between suppliers, manufacturers, logistics providers and customers.

One of the most important impacts of IoT on supply chains is improved visibility. Ahmed et al. explain that visibility in supply chains refers to the ability to capture, monitor and share information regarding the location, identity, status and movement of products and activities across the supply chain in real time. Highly visible supply chains enable organizations to manage operations more effectively while reducing operational costs and improving customer satisfaction [150].

The IoT integration framework presented in the literature explains that connected devices, sensors, RFID tags, GPS systems and communication platforms continuously collect and exchange operational information in real time. This allows organizations to monitor purchasing, transportation, warehousing, distribution, sales and return activities more effectively across the entire supply chain network [155].

Ahmed et al. further emphasize that IoT improves transparency and information visibility throughout the supply chain by enabling reliable, consistent and up-to-date data sharing among all supply chain stakeholders. Through IoT-enabled systems, organizations gain access to real-time operational information that supports better coordination and faster decision-making.

Another important contribution of IoT technologies is real-time tracking and traceability. RFID systems enable organizations to identify, monitor and track products throughout logistics operations. The RFID warehousing study explains that RFID tags generate continuous data records related to product movement, warehouse locations, transportation activities and timestamps. This creates detailed operational visibility across supply chain environments [47].

Ahmed et al. also identify RFID as one of the most important IoT technologies used in supply chains. RFID systems improve inventory accuracy, product traceability, inventory replenishment and timely delivery performance. Unlike traditional barcode systems, RFID tags can transfer data without direct visual contact, enabling faster and more efficient tracking across logistics operations [150].

The RFID data warehouse architecture presented in the literature demonstrates how organizations can store, clean, process and analyze large volumes of RFID-generated data to support supply chain monitoring and business intelligence. The conceptual schema integrates products, warehouses, RFID readers, locations, transportation flows and time dimensions into a unified information management system [47].

The literature also highlights the role of IoT-enabled analytics and cloud technologies in improving supply chain performance. Ahmed et al. explain that IoT-generated operational data can be processed through cloud systems and big data analytics platforms to improve decision-making, operational coordination and supply chain responsiveness. Cloud technologies also enhance scalability, real-time visibility, quality control and secure information sharing among supply chain actors [150].

Another major impact of IoT technologies is stronger operational integration. Ahmed et al. explain that IoT has significant effects on both internal and external integration within supply chains by improving communication between suppliers, manufacturers, logistics operators and customers. This integration strengthens collaboration, improves synchronization of operational activities and enhances the overall performance of supply chain networks.

The selected studies also demonstrate that IoT-enabled visibility improves supply chain efficiency. The organizational capability model explains that IoT capabilities positively influence supplier integration, customer integration and internal operational coordination. These improvements contribute directly to stronger supply chain performance and better organizational outcomes [155].

The visual adoption framework presented in Ahmed et al. identifies the most important IoT technologies currently implemented in supply chains. These include RFID systems, cyber-physical systems, big data analytics, sensors, cloud computing, machine-to-machine communication and augmented reality technologies. According to the study, these technologies improve transparency, integration, collaboration, responsiveness and efficiency within supply chain operations.

Another important impact identified in the literature is enhanced logistics efficiency. The cross-border e-commerce study explains that intelligent logistics systems supported by IoT, artificial intelligence, cloud computing and 5G communication technologies improve transportation monitoring, warehouse management, logistics coordination and customer service performance.

Additional evidence of the impact of IoT and RFID technologies on supply chain visibility can be observed in smart warehouse management systems. Recent research proposes an intelligent warehouse architecture that combines RFID tags, wireless communication networks, distributed control nodes, sensors and centralized database platforms to automate inventory monitoring and warehouse operations. In this architecture, RFID tags continuously provide identification and location information, while IoT communication infrastructures enable the real-time transmission of operational data to warehouse management systems. The proposed framework supports automated inbound and outbound logistics processes, inventory monitoring, goods positioning and warehouse resource management. By replacing manual recording procedures with automated identification and data collection mechanisms, the system improves inventory accuracy, operational transparency and decision-making efficiency. Experimental results demonstrated RFID recognition rates exceeding 99%, highlighting the potential of RFID-enabled IoT systems to strengthen supply chain visibility, warehouse performance and overall logistics efficiency [48].

The logistics communication framework presented in the study demonstrates how IoT communication modules support intelligent warehouse systems, automated logistics operations and continuous information exchange between logistics platforms and transportation systems. The architecture integrates sensors, communication networks, logistics databases, cloud systems and intelligent processing technologies into one operational structure.

The literature also explains that 5G communication technologies further improve supply chain visibility and responsiveness. According to the logistics optimization framework, 5G enables ultra-low latency, high-speed data transmission and large-scale connectivity, allowing organizations to improve logistics tracking, transportation management and real-time operational synchronization [242].

IoT technologies additionally improve customer responsiveness and demand management. Through synchronized information systems and real-time operational monitoring, organizations can react faster to changing customer demands, improve delivery reliability and reduce operational uncertainty [155].

Supply chain performance is also enhanced through improved data accuracy and business intelligence capabilities. RFID systems, sensors and IoT devices continuously generate operational data that can be analyzed to identify transportation patterns, warehouse utilization trends, inventory conditions and operational inefficiencies. The RFID OLAP architecture presented in the literature demonstrates how integrated RFID data warehouses support more effective operational analysis and performance monitoring [47].

Despite these advantages, the literature also identifies several implementation challenges. Ahmed et al. explain that organizations may face difficulties related to infrastructure costs, data security, interoperability, data processing complexity, privacy concerns and system integration during IoT adoption. In particular, challenges associated with real-time data analysis, large-scale sensor deployment and secure cloud management remain important concerns for organizations implementing Supply 4.0 technologies [150].

Overall, the selected studies demonstrate that IoT, RFID systems, sensors, cloud technologies and intelligent communication networks significantly improve supply chain visibility and operational performance. These technologies support real-time monitoring, integrated communication, logistics optimization, intelligent warehousing, transportation coordination and data-driven decision-making. Their integration enables supply chains to become more transparent, agile, responsive, efficient and digitally connected.

3.5 Cloud, ERP, Industry 4.0

3.5.1 Impact of Cloud Computing and Enterprise Systems Integration

Cloud computing, Enterprise Resource Planning (ERP) systems and Industry 4.0 technologies have become fundamental components of digital supply chain transformation. Their integration enables organizations to improve operational efficiency, information sharing, resource management, decision-making and collaboration across supply chain networks. The literature highlights that cloud-based technologies provide scalable computing resources, while ERP systems support organizational integration and Industry 4.0 technologies create intelligent, interconnected and data-driven operational environments.

Cloud computing is defined as a technology that provides on-demand access to computing resources such as servers, storage systems, software applications, platforms and network services through the internet. Organizations can access these resources remotely without investing heavily in internal information technology infrastructure. Cloud computing offers scalability, flexibility, reliability and cost efficiency, making it an important technological foundation for modern supply chains and Industry 4.0 environments.

According to paper [64], cloud computing contributes to both strategic and operational performance improvements. At the operational level, cloud systems reduce infrastructure costs, improve resource utilization and increase service availability. At the strategic level, cloud computing enhances business agility by allowing organizations to respond quickly to market changes, deploy new technologies rapidly and support continuous innovation.

The literature further explains that successful cloud computing implementation positively affects overall firm performance. Organizations benefit from improved information quality, enhanced system quality, stronger IT capabilities and higher user satisfaction. These factors contribute to better operational efficiency, improved decision-making and stronger competitive advantages [64].

Cloud computing also plays a crucial role in supporting digital supply chain integration. In cloud-based environments, information can be shared in real time among suppliers, manufacturers, logistics providers and customers. The cloud acts as a centralized platform that enables continuous communication, data accessibility and collaborative decision-making across the supply chain. This capability significantly improves visibility, responsiveness and coordination between supply chain partners [192].

The relationship between cloud computing and Industry 4.0 is particularly significant. Industry 4.0 relies on technologies such as the Internet of Things (IoT), cyber-physical systems, big data analytics, artificial intelligence and cloud platforms to create intelligent and connected production environments. Cloud computing provides the infrastructure required to process, store and distribute the large volumes of data generated by these technologies [92].

The cloud manufacturing literature explains that Industry 4.0 promotes the transformation of traditional manufacturing systems into interconnected networks of autonomous services and intelligent components. Through cloud-based architectures, manufacturing resources, software applications, equipment and operational capabilities can be shared and accessed on demand across organizational boundaries. This creates more flexible, agile and collaborative manufacturing systems.

Cloud manufacturing represents one of the most important applications of Industry 4.0 principles. Xu (2012), as cited in Moghaddam and Nof (2018), defines cloud manufacturing as a model that provides convenient, on-demand network access to shared manufacturing resources such as software tools, equipment and manufacturing capabilities. These resources can be rapidly allocated and released according to operational requirements with minimal management effort.

Another critical component of digital transformation is Enterprise Resource Planning (ERP). ERP systems evolved from earlier planning systems such as Material Requirement Planning (MRP) and Manufacturing Resource Planning (MRP II). Modern ERP systems integrate various organizational functions, including purchasing, production, inventory management, sales, accounting, finance, human resources and supply chain management into a unified information system.

The literature describes ERP systems as integrated software platforms built around a centralized database and standardized business processes. ERP systems support real-time planning, scheduling, coordination and resource allocation throughout the organization. Their primary objective is to improve operational integration, standardization and information consistency across departments.

ERP systems contribute significantly to supply chain performance by improving information flow and organizational coordination. Through centralized databases and integrated business processes, ERP systems provide organizations with accurate and timely information regarding inventory levels, production activities, purchasing requirements, customer orders and financial transactions. This integrated view improves planning accuracy and operational control.

The literature also emphasizes that ERP systems are increasingly integrated with emerging Industry 4.0 technologies. Traditional ERP systems primarily focused on internal organizational integration, whereas Industry 4.0 extends this integration to external supply chain partners through real-time connectivity and digital collaboration. Cloud technologies facilitate this transition by enabling ERP platforms to operate within broader digital ecosystems [19].

The integration of ERP systems with cloud computing provides several operational advantages. Organizations gain access to scalable computing resources, lower infrastructure costs, simplified software maintenance and improved accessibility. Cloud-based ERP systems also support real-time data sharing and collaboration among geographically dispersed supply chain participants. These capabilities improve organizational responsiveness and decision-making speed.

The literature further suggests that cloud technologies support the development of collaborative supply chain networks. Through cloud platforms, organizations can share resources, services, operational data and manufacturing capabilities. Cloud-based collaboration enables more effective coordination between different organizations and improves overall supply chain agility.

Beyond operational efficiency, cloud computing also contributes significantly to supply chain resilience, organizational agility and knowledge management. The literature highlights that cloud-based environments provide secure data storage, backup capabilities, information sharing and remote access to organizational knowledge, allowing firms to maintain operational continuity during disruptions. By centralizing documentation and business information, cloud platforms improve process visibility and support risk management activities, reducing the likelihood of disruptions caused by information loss or limited access to organizational knowledge. These capabilities are particularly valuable in dynamic environments where operational procedures require continuous adaptation and rapid information exchange. Furthermore, evidence from organizations operating during the COVID-19 pandemic demonstrates that cloud-integrated business management systems enabled remote collaboration, digital communication and decentralized decision-making across geographically dispersed operations. Cloud-based business intelligence tools also improved the identification of critical operational paths and provided managers with real-time visibility into organizational activities. As a result, cloud computing not only improves operational performance but also strengthens organizational flexibility, resilience and the ability to respond effectively to unexpected disruptions [53].

A practical example of cloud-enabled supply chain management can be observed in cold-chain logistics systems. The literature explains that cloud computing platforms continuously collect and update information regarding transportation routes, storage conditions, vehicle status and delivery schedules. This real-time information supports route optimization, delivery coordination, inventory monitoring and customer service improvements.

Cloud computing also enables integration with IoT technologies in logistics operations. Sensors and IoT devices collect operational information from warehouses, transportation systems and storage facilities, while cloud platforms process and distribute this information to relevant stakeholders. This improves visibility, operational monitoring and supply chain coordination [192].

Another important benefit of cloud-enabled systems is enhanced decision support. Cloud platforms provide organizations with access to large-scale data analytics capabilities without requiring substantial investments in local computing infrastructure. As a result, managers can analyze operational data more effectively and make informed decisions regarding inventory management, logistics planning, production scheduling and resource allocation.

Industry 4.0 technologies further strengthen these capabilities by enabling intelligent automation and decentralized decision-making. The literature explains that modern industrial systems are increasingly characterized by connectivity, interoperability, agility and decentralization. Cloud technologies provide the digital infrastructure necessary to support these characteristics and enable real-time coordination among distributed operational units.

Despite these benefits, the literature also identifies several implementation challenges. Organizations may encounter difficulties related to system integration, data security, technological complexity, organizational readiness and IT capability requirements. Successful implementation requires strong technical capabilities, managerial support, high-quality information systems and effective user adoption [64].

Overall, the literature demonstrates that cloud computing, ERP systems and Industry 4.0 technologies collectively support the digital transformation of supply chains and manufacturing systems. Cloud computing provides scalable digital infrastructure, ERP systems enable organizational integration and Industry 4.0 technologies create intelligent and interconnected operational environments. Their combined implementation improves visibility, collaboration, flexibility, operational efficiency, decision-making and overall supply chain performance.

3.5.2 Intelligent Systems and Industry 4.0 Applications

The emergence of Industry 4.0 has accelerated the adoption of intelligent systems across manufacturing, logistics, warehousing and supply chain operations. Intelligent systems combine advanced technologies such as cloud computing, artificial intelligence (AI), the Internet of Things (IoT), robotics, big data analytics, machine vision and cyber-physical systems to enable autonomous decision-making, real-time monitoring and intelligent process optimization. These technologies transform traditional industrial environments into interconnected, adaptive and data-driven ecosystems.

Industry 4.0 is characterized by the integration of digital technologies with physical operations. Through intelligent systems, organizations can collect large volumes of operational data, analyze information in real time and respond quickly to changing customer requirements and market conditions. The primary objective is to improve operational efficiency, flexibility, responsiveness and competitiveness.

One important application of intelligent systems in Industry 4.0 is intelligent supply chain management. Traditional supply chain systems often struggle to respond effectively to rapidly changing customer demands and market dynamics. Intelligent supply chain systems utilize cloud computing and data analytics to collect, process and analyze customer information, enabling organizations to better understand demand patterns and improve decision-making. According to paper [45], intelligent supply chain control systems significantly improve customer demand analysis accuracy and supply chain agility compared to traditional supply chain management systems.

Cloud computing serves as a fundamental technological foundation for intelligent systems. Cloud platforms allow organizations to collect and process large amounts of information through distributed computing environments. Through centralized data analysis and cloud-based services, intelligent systems can provide real-time operational insights, support automated decision-making and improve organizational responsiveness. Cloud computing also enables scalable processing capabilities that support the increasing data requirements of Industry 4.0 applications.

Virtual reality (VR) technologies are increasingly integrated into intelligent systems to enhance user interaction and data visualization. The paper [45] explains that virtual reality environments can be used to create interactive interfaces that capture customer requirements more effectively and support personalized service delivery. By combining virtual reality with cloud computing and intelligent analytics, organizations can improve customer engagement and develop more accurate demand forecasting models.

Another key component of Industry 4.0 intelligent systems is the Internet of Things (IoT). IoT technologies enable physical devices, sensors, machines and equipment to communicate and exchange information through interconnected networks. These devices continuously collect operational data that can be transmitted to cloud platforms for analysis and decision support. IoT integration allows organizations to achieve real-time visibility, predictive monitoring and automated process control [45].

Smart warehousing represents a practical example of Industry 4.0 implementation. According to the same paper, smart warehouses integrate cloud computing, IoT, artificial intelligence, digital communication technologies and automation systems to achieve real-time inventory control, intelligent monitoring and automated warehouse operations. These technologies improve inventory accuracy, operational efficiency and resource utilization while reducing human intervention in warehouse activities.

The smart warehouse architecture presented in paper [45] includes several intelligent subsystems, including warehouse control systems, identification systems, security systems, environmental monitoring systems, video analytics systems and information management systems. Together, these components create an integrated digital environment capable of autonomous operation and intelligent decision support. The system architecture diagram on page 2 illustrates how these components interact within a unified smart warehouse management platform.

Automation technologies are another major element of intelligent systems within Industry 4.0 environments. Smart warehouses utilize Automated Guided Vehicles (AGVs), stacking robots and picking robots to automate material handling, storage, transportation and inventory management tasks. These robotic systems improve operational speed, accuracy, safety and productivity while reducing labor requirements.

Radio Frequency Identification (RFID) technology also plays a critical role in Industry 4.0 applications. RFID systems enable automatic identification and tracking of materials, products and assets throughout operational processes. By integrating RFID with databases, cloud computing and IoT infrastructures, organizations can achieve real-time inventory visibility, automated warehouse operations and improved supply chain traceability.

Artificial intelligence contributes significantly to the intelligence of Industry 4.0 systems. AI technologies enable systems to process large amounts of structured and unstructured data, identify patterns, predict future outcomes and support autonomous decision-making. In warehouse environments, AI applications include intelligent video analytics, anomaly detection, behavior recognition and predictive maintenance. These capabilities improve operational reliability and support proactive management strategies.

Video intelligent analysis systems represent an advanced Industry 4.0 application. Using computer vision and machine learning techniques, these systems automatically identify faces, recognize vehicle license plates, monitor employee activities, detect abnormal behaviors and evaluate operational compliance. Unlike traditional surveillance systems, intelligent video analytics can actively identify risks and generate alerts in real time.

Environmental monitoring systems further demonstrate the practical implementation of intelligent systems. Sensors continuously monitor environmental conditions such as temperature, humidity, smoke levels and water intrusion. Real-time monitoring helps maintain product quality, prevent operational disruptions and support risk management activities. This capability is particularly important in industries where environmental conditions directly affect product integrity and safety.

A key advantage of Industry 4.0 intelligent systems is the ability to support data-driven decision-making. Through cloud computing and big data analytics, organizations can collect information from multiple operational sources, integrate these datasets and generate actionable insights. Intelligent systems transform raw data into valuable knowledge that supports planning, forecasting, inventory management and operational optimization.

Research findings demonstrate the performance benefits of intelligent systems. In paper [8] found that the average accuracy of customer demand analysis increased from 83.68% in traditional supply chain systems to 94.40% in intelligent supply chain control systems. Furthermore, supply chain agility improved from an average of 76.80% to 92.60% after implementing intelligent control technologies. These results indicate the substantial operational benefits of Industry 4.0 technologies [8].

Despite these advantages, the implementation of intelligent systems also presents challenges. Organizations must address issues related to information infrastructure, system integration, interoperability, cybersecurity, data management and employee readiness. Successful implementation requires substantial technological investment and organizational commitment to digital transformation.

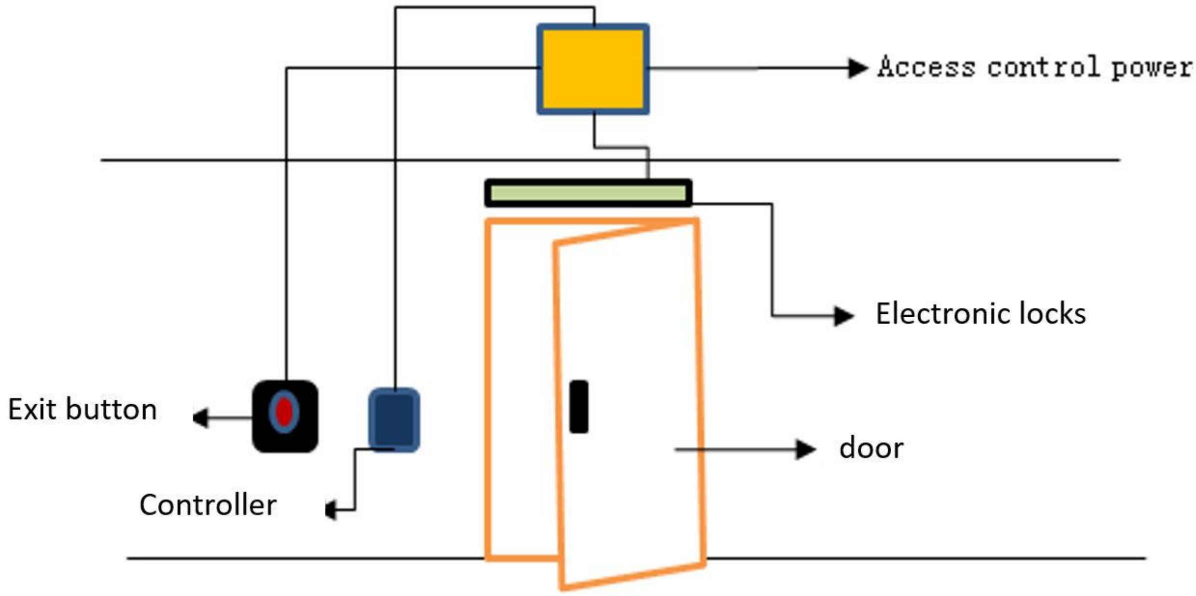
Overall, intelligent systems represent a core element of Industry 4.0. By integrating cloud computing, IoT, artificial intelligence, robotics, virtual reality, RFID and advanced analytics, organizations can create highly connected, automated and intelligent operational environments. These technologies improve efficiency, agility, visibility and decision-making capabilities while supporting the broader goals of digital transformation and sustainable competitive advantage.

3.6 Other Warehouse Technologies

3.6.1 Artificial Intelligence and Data-Driven Warehouse Systems

Besides IoT, RFID, cloud computing and automation systems, the selected papers present several additional warehouse technologies that support the transition toward intelligent logistics environments. Most of these technologies are described through system architectures and operational frameworks rather than individual devices, showing how different technologies work together inside modern warehouses.

The paper [36] presents an intelligent logistics warehousing system where artificial intelligence is integrated into multiple warehouse operations. One of the main figures in the paper [36] illustrates a smart access-control system that combines electronic locks, controllers, communication networks and centralized management software. Rather than using traditional warehouse security methods, the proposed system integrates password authentication, fingerprint recognition and facial recognition technologies into a single intelligent access platform. The figure shows how different components communicate with each other and how warehouse access can be monitored and controlled digitally. This demonstrates that warehouse intelligence extends beyond inventory management and also includes security and facility management functions.

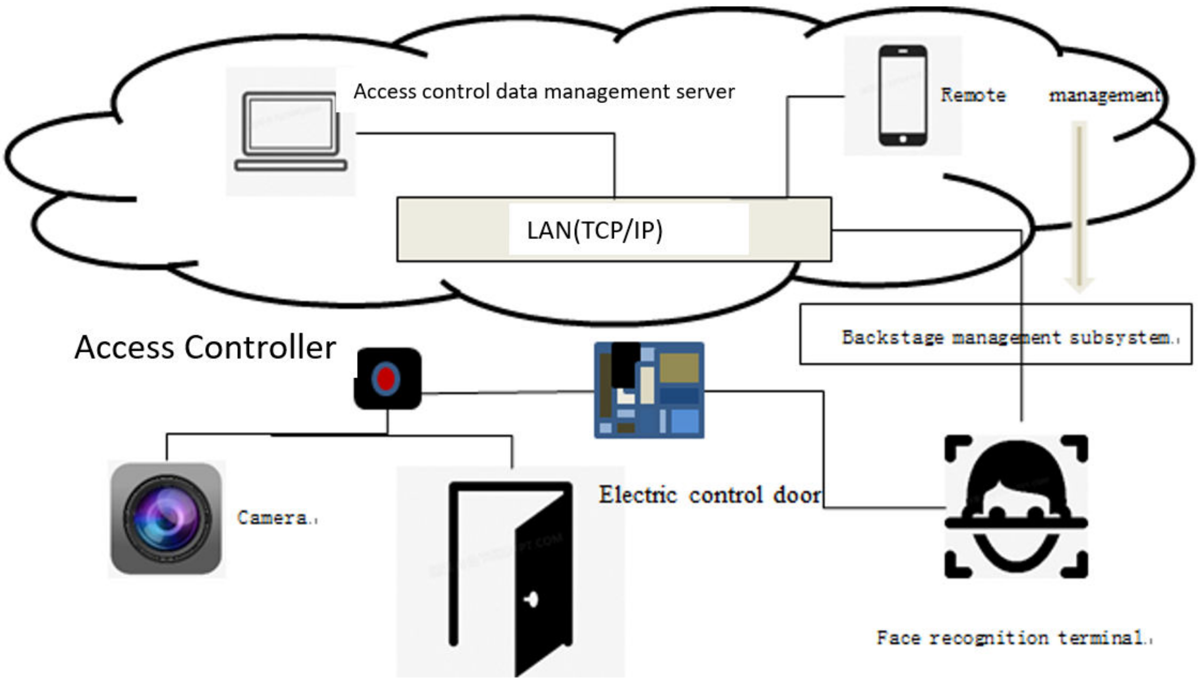


11Figure : Wiring diagram of basic single door access control system [36].

The same paper explains that intelligent warehousing increasingly relies on dynamic information integration. Through RFID tags, automatic identification technologies and digital reporting systems, warehouse activities such as receiving, inventory counting, transfers and shipping can be recorded automatically and transformed into real-time operational information. The overall warehouse architecture presented in the paper shows how data generated at different operational stages can be integrated into one management platform to improve efficiency and reduce manual work [36].

Another interesting perspective is provided by the smart logistics cyber-physical systems framework. The architecture illustrated on the same paper presents logistics as a connected network that links manufacturers, warehouses, transportation systems, distribution centers and customers. Beneath this logistics network, several intelligent technologies are shown, including parcel stacking, automatic measurement, automatic monitoring, integrity inspection, facility location selection, intelligent loading, vehicle routing, autonomous driving, time-efficiency estimation and simulation systems. The figure highlights that modern warehouse operations are no longer isolated activities but part of a larger intelligent logistics ecosystem where data continuously flows between different operational units.

The framework introduces automatic measurement and monitoring technologies as important warehouse functions. According to the architecture, sensors, computer vision systems and monitoring devices continuously collect information about goods, equipment and warehouse conditions. These technologies allow organizations to monitor warehouse operations automatically, improve safety and reduce the need for manual inspections [88].



12Figure : AI based on IoT access control system in paper [36].

Artificial intelligence also supports decision-making within logistics and warehouse systems. The review on supply chain risk management and artificial intelligence explains that AI technologies can provide prediction, learning and decision-support capabilities that help organizations handle complex operational environments. The paper classifies AI applications into areas such as mathematical optimization, machine learning, automated reasoning, big data analytics and intelligent decision support. Although the study focuses on supply chain risk management, its framework demonstrates how AI technologies can be applied to warehouse operations where large volumes of operational data must be analyzed continuously [80].

Another AI-based technology identified in the literature is the use of Multi-Agent Systems (MAS) for warehouse and logistics management. Multi-Agent Systems consist of multiple intelligent agents that communicate, exchange information and coordinate operational activities through predefined interaction protocols. These systems can support functions such as inventory management, production planning, resource allocation and process monitoring by enabling distributed decision-making across different warehouse operations. The literature also highlights the use of blackboard-based communication architectures, where agents share information through a common workspace and collaboratively solve operational problems. By facilitating autonomous coordination and real-time information exchange, Multi-Agent Systems contribute to greater operational flexibility, improved responsiveness and more efficient management of complex warehouse environments [22].

The intelligent logistics system study introduces another important technology area: big data analytics. The paper explains that modern logistics operations generate enormous amounts of information from equipment, vehicles, products, warehouses and personnel. Big data technologies allow organizations to collect, process and analyze these datasets in order to improve logistics planning, resource allocation, forecasting and operational control. The study describes Logistics 4.0 as an environment where data becomes a strategic resource for managing logistics operations more effectively.

The paper also emphasizes the role of data warehouses and data mining technologies. These systems collect information from multiple logistics activities and transform it into useful operational knowledge.

By analyzing historical and real-time data, warehouse managers can identify patterns, improve inventory planning, optimize transportation activities and support strategic decision-making [246].

Another technology highlighted in the literature is cyber-physical systems (CPS). The logistics CPS architecture presented in the smart logistics study shows how physical warehouse activities are connected with digital information systems. Sensors collect information from the physical environment, communication networks transfer the data and processing platforms analyze the information before supporting operational decisions. This integration creates a warehouse environment that can monitor itself, exchange information automatically and respond more effectively to operational changes [89].

Overall, the selected papers show that modern warehouses increasingly rely on a combination of intelligent technologies beyond traditional inventory systems. AI-based access control, facial recognition, automatic monitoring, big data analytics, cyber-physical systems, intelligent decision support, data mining and integrated logistics platforms are becoming important components of smart warehouse environments. The figures and frameworks presented in the literature illustrate a gradual shift from isolated warehouse operations toward fully connected, intelligent and data-driven logistics systems.

3.6.2 Smart Warehousing and Automation Technologies

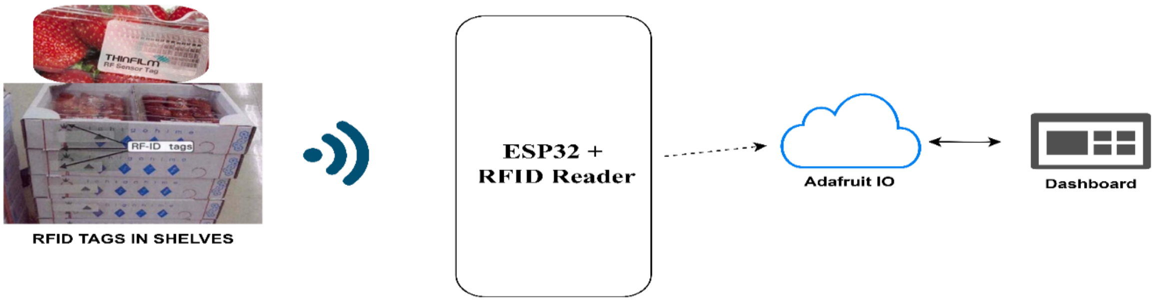
The reviewed papers show that modern warehousing is evolving from traditional storage facilities into intelligent, automated and interconnected environments. Smart warehousing combines technologies such as IoT, RFID, edge computing, wireless communication systems, autonomous mobile robots, artificial intelligence and real-time monitoring platforms to improve inventory visibility, operational efficiency, safety and decision-making processes.

One important smart warehousing technology identified in the literature is edge computing. Gowrishankar et al. propose an edge computing-enabled warehouse management system designed for food processing industries. The system integrates ESP32 microcontrollers, wireless sensor networks, RFID technology, environmental sensors, dashboards and mobile notifications into a unified warehouse platform. Instead of transmitting all information to cloud servers, data processing is performed closer to the source, enabling faster responses, reduced latency, lower network traffic and improved real-time monitoring capabilities. The authors argue that this architecture improves warehouse efficiency while reducing food waste and contamination risks.

The smart warehouse architecture presented in the paper demonstrates how multiple sensors continuously monitor warehouse conditions. Temperature, humidity, methane, ethylene, carbon monoxide and color sensors are connected to an ESP32 controller, which processes the information and transmits results to dashboards and notification systems. Figure 2 of the paper illustrates this intelligent shelf architecture, while Figure 3 presents the RFID-based tracking mechanism used for monitoring food products stored inside the warehouse. These technologies provide continuous visibility of inventory conditions and support proactive decision-making when abnormal situations are detected.

Another major technology identified in the literature is RFID-based inventory tracking. The proposed smart warehouse uses RFID tags attached to products, allowing managers to track individual items and entire product batches throughout storage and distribution processes. RFID systems store information such as batch numbers, manufacturing dates, expiration dates and quality indicators. According to the authors, RFID improves traceability, simplifies inventory management, supports recall procedures and enhances supply chain visibility.

The study also highlights the importance of real-time monitoring and automated alert systems. Sensors continuously evaluate environmental conditions and product quality indicators. When anomalies such as temperature changes, toxic gases, spoilage indicators, or approaching expiration dates are detected, automated alerts are generated and sent to warehouse personnel through dashboards, Telegram notifications and mobile applications. Figure of the paper presents the operational workflow of this monitoring system, showing how sensor data is collected, processed, visualized and converted into alerts for warehouse managers [37].



13Figure : RFID structure for food items tracking [37].

A different approach to intelligent warehousing is presented in the LoRa-based warehouse management system. This study focuses on low-power wireless communication technologies that support remote warehouse operations. The proposed architecture consists of a central management platform, gateway boards and electronic label boards connected through LoRa communication modules. Warehouse managers can remotely update product information, locate goods and manage inventory without physically accessing warehouse shelves. The system is specifically designed to overcome the limitations of traditional manual warehouse management processes.

One innovative feature of this system is the use of electronic ink displays (e-ink screens) integrated into warehouse labels. These displays present product information such as item names, quantities and categories while consuming very little power. The system can remotely modify label content through wireless communication, ensuring that warehouse information remains accurate and up to date. Additionally, roadway lights and buzzers are integrated into the labels, allowing warehouse workers to quickly locate target products inside large storage facilities.

The paper also demonstrates how LoRa wireless technology supports long-distance communication within warehouses. The architecture enables data exchange between management software, gateway devices and shelf labels over distances significantly larger than traditional wireless solutions while maintaining low power consumption. Experimental results indicate that the system achieves reliable communication and enables remote software updates, inventory synchronization and warehouse management functions [41].

Automation is further enhanced through the use of Autonomous Guided Vehicles (AGVs) and intelligent handling robots. Zhang et al. describe an intelligent warehousing system based on AGV handling robots that combine artificial intelligence, industrial internet technologies, cameras, sensors, wireless communication systems and autonomous navigation capabilities. The proposed system aims to automate material transportation and inventory movement within warehouse environments while improving operational efficiency and reducing manual labor requirements.

The AGV system integrates multiple sensing technologies, including cameras, pressure sensors, infrared sensors, Wi-Fi communication modules, laser scanners and obstacle detection systems. The robots are capable of recognizing targets, navigating warehouse routes, avoiding obstacles and transporting materials autonomously. The architecture combines navigation sensors with industrial internet connectivity, enabling real-time communication between robots and warehouse management systems.

An important aspect of the AGV solution is its navigation and positioning mechanism. The robots utilize QR-code guidance, LiDAR sensors, laser obstacle avoidance systems and onboard scanners to determine their position and execute specific actions at designated locations. Figures 6 and 7 of the paper illustrate the robot structure and QR-code navigation system. This approach enables autonomous transportation tasks while ensuring accurate positioning and safe operation within warehouse environments.

The AGV framework also incorporates concepts of swarm intelligence and decentralized control. Instead of relying exclusively on a central controller, multiple vehicles cooperate through Internet of Things technologies, allowing coordinated movement and intelligent decision-making among robot fleets. This approach supports scalable warehouse automation and enables efficient management of complex material-handling operations [44].

Recent research further extends warehouse automation through the use of Autonomous Mobile Robots (AMRs) supported by advanced wireless communication technologies. Unlike conventional AGVs that typically operate on predefined routes, AMRs can dynamically adapt their movements according to warehouse conditions and operational requirements. To support reliable communication among large fleets of mobile robots, intelligent wireless networking mechanisms have been proposed based on IEEE 802.11be (Wi-Fi 7) and Multi-Link Operation (MLO) technologies.

These systems dynamically organize robots into communication communities and allocate wireless channels to reduce interference while maintaining continuous connectivity. Through adaptive topology control mechanisms, robot groups can be reconfigured according to traffic density, operational workloads and communication requirements. The use of entropy-based optimization and dynamic channel assignment improves communication reliability, scalability and coordination among robot fleets. As a result, AMRs can exchange information in real time, coordinate transportation tasks more efficiently and support decentralized warehouse operations without introducing significant communication delays.

The combination of AMRs, intelligent wireless communication infrastructures and real-time coordination mechanisms represents an important step toward fully autonomous warehouse environments. Such architectures improve operational flexibility, increase warehouse throughput, reduce congestion and enhance the overall efficiency of smart warehousing systems [111].

Overall, the reviewed studies indicate that smart warehousing is increasingly based on the integration of sensing technologies, wireless communication networks, intelligent monitoring systems, RFID tracking, edge computing, low-power communication platforms, autonomous robots and AI-supported decision-making tools. These technologies collectively improve warehouse visibility, inventory accuracy, operational efficiency, product traceability and automation capabilities, supporting the broader transition toward Industry 4.0 and intelligent logistics environments.

3.6.3 Digital Twins, Simulation and Cyber-Physical Systems

Digital Twins (DTs), simulation technologies and Cyber-Physical Systems (CPS) are among the most transformative technologies supporting Industry 4.0 and modern supply chain management. These technologies create digital representations of physical assets, processes and systems, enabling organizations to monitor operations in real time, predict future conditions, evaluate alternative scenarios and optimize decision-making across the entire product lifecycle. The reviewed literature highlights their growing importance in manufacturing, logistics, energy systems, transportation networks and supply chain resilience.

A Digital Twin can be defined as a virtual representation of a physical object, process, or system that continuously exchanges information with its physical counterpart. According to Wagner et al., a digital twin consists of three fundamental elements: the physical asset, the virtual model and the data connections that continuously synchronize information between the two domains. This integration allows the digital model to mirror the behavior, condition and performance of the physical system throughout its lifecycle.

The concept of Digital Twins originated from the need to shift problem identification and solution development toward earlier stages of product and process design. Through the use of sophisticated virtual models combined with real-world operational data, organizations can evaluate design alternatives, predict performance outcomes and identify potential failures before physical implementation. This "front-loading" approach significantly reduces development costs, shortens product development cycles and improves overall system performance [112].

One of the most significant applications of Digital Twins is in supply chain resilience and risk management. Lv et al. demonstrate how Digital Twins can support resilient supply chains during disruptive events such as the COVID-19 pandemic. Their study develops a digital twin-enabled supply chain architecture capable of continuously monitoring suppliers, manufacturers, distributors and retailers. By integrating real-time data, simulation models and decision-support systems, organizations can evaluate disruption scenarios, activate contingency plans and optimize emergency response strategies. The authors show that Digital Twin-based supply chains improve visibility, responsiveness and operational continuity compared to traditional supply chain structures.

The reviewed literature emphasizes that Digital Twins are closely linked to the Internet of Things (IoT), artificial intelligence and advanced analytics. IoT devices continuously collect operational data from physical systems, while Digital Twins use this information to create real-time simulations and predictive models. This capability allows organizations to assess operational risks, evaluate alternative strategies and optimize system performance dynamically. According to Lv et al., Digital Twins enable continuous scenario planning and support rapid decision-making by providing accurate virtual representations of supply chain operations [58].

Another key technology area is simulation-based decision support. Ferreira et al. describe simulation as a fundamental Industry 4.0 technology used to model, analyze and optimize complex production and logistics systems. Simulation enables organizations to evaluate different operational scenarios without disrupting real-world activities, making it particularly valuable for planning, resource allocation, system design and process optimization. The review identifies multiple simulation approaches, including discrete-event simulation, agent-based simulation, system dynamics, virtual reality, augmented reality and hybrid simulation methods.

Simulation technologies support organizations in assessing implementation risks, estimating costs, evaluating operational performance and developing roadmaps for Industry 4.0 adoption. By creating virtual models of manufacturing and logistics systems, organizations can test alternative configurations, predict system behavior and identify performance bottlenecks before implementing changes in physical environments. The authors conclude that hybrid simulation approaches and Digital Twins have emerged as the dominant simulation-based technologies within Industry 4.0 applications [81].

The integration of Digital Twins and simulation technologies is particularly important for product development and production planning. Wagner et al. argue that future manufacturing systems will increasingly rely on integrated digital product twins and digital production twins. Product Digital Twins provide detailed virtual representations of products and their performance characteristics, while Production Digital Twins model manufacturing systems, processes and resources. Together, these technologies enable organizations to evaluate design alternatives, optimize production parameters, improve quality management and support more efficient product development processes.

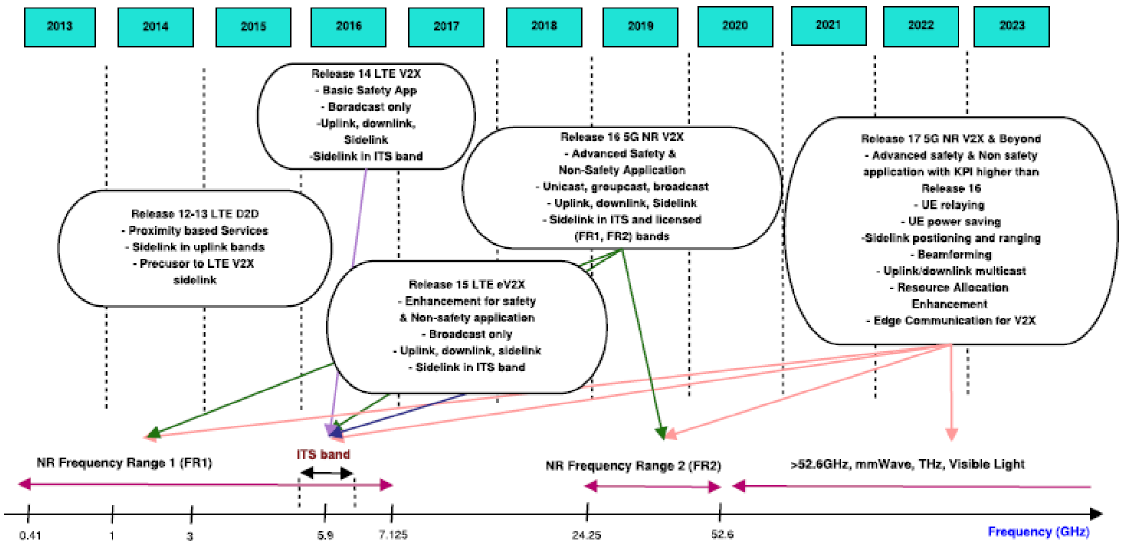
Digital Twins also play an important role in Cyber-Physical Production Systems (CPPS). As Industry 4.0 technologies evolve, production systems increasingly combine physical equipment with digital monitoring, control and optimization capabilities. Real-time data from sensors, machines and operational systems are continuously integrated into digital models, allowing production systems to react autonomously to deviations, disturbances and changing operational conditions. Wagner et al. note that these cyber-physical systems can automatically initiate corrective actions, increasing system robustness, flexibility and operational efficiency [112].

The literature also highlights the role of Digital Twins in predictive maintenance and asset management. A practical example is provided by General Electric (GE), which has developed advanced Digital Twin solutions for energy systems and power plants. GE combines physics-based models, engineering expertise, sensor technologies, artificial intelligence and real-time analytics to create high-fidelity digital representations of industrial assets. These Digital Twins continuously monitor equipment conditions, predict failures and optimize operational performance throughout the asset lifecycle.

GE's Digital Twin framework utilizes thermodynamic models, fluid dynamics simulations, combustion models, failure prediction models and real-time sensor data to assess equipment performance under different operating conditions. The system continuously compares measured operational data with model predictions using adaptive filtering techniques and automatic model updating mechanisms. This capability enables early anomaly detection, proactive maintenance planning and improved reliability of critical energy infrastructure [112].

An important enabling technology for Cyber-Physical Systems is advanced communication infrastructure. The reviewed literature on Cellular Vehicle-to-Everything (C-V2X) technology demonstrates how intelligent transportation systems increasingly rely on cyber-physical architectures that connect vehicles, infrastructure, pedestrians and network services through real-time communication networks. These systems integrate sensors, communication platforms, edge computing, artificial intelligence and distributed decision-making mechanisms to support autonomous and connected transportation environments.

C-V2X technologies provide a practical example of large-scale Cyber-Physical Systems operating in dynamic environments. Vehicles continuously exchange information with other vehicles, infrastructure and cloud services through LTE and 5G communication networks. This connectivity enables cooperative decision-making, traffic optimization, accident prevention and intelligent transportation management. The integration of real-time communication, sensing technologies and distributed intelligence reflects the core principles of Cyber-Physical Systems and demonstrates their potential for future autonomous mobility ecosystems [107].



14Figure : GPP'sJourneytowardsAdvancedC-V2Xcommunication [107].

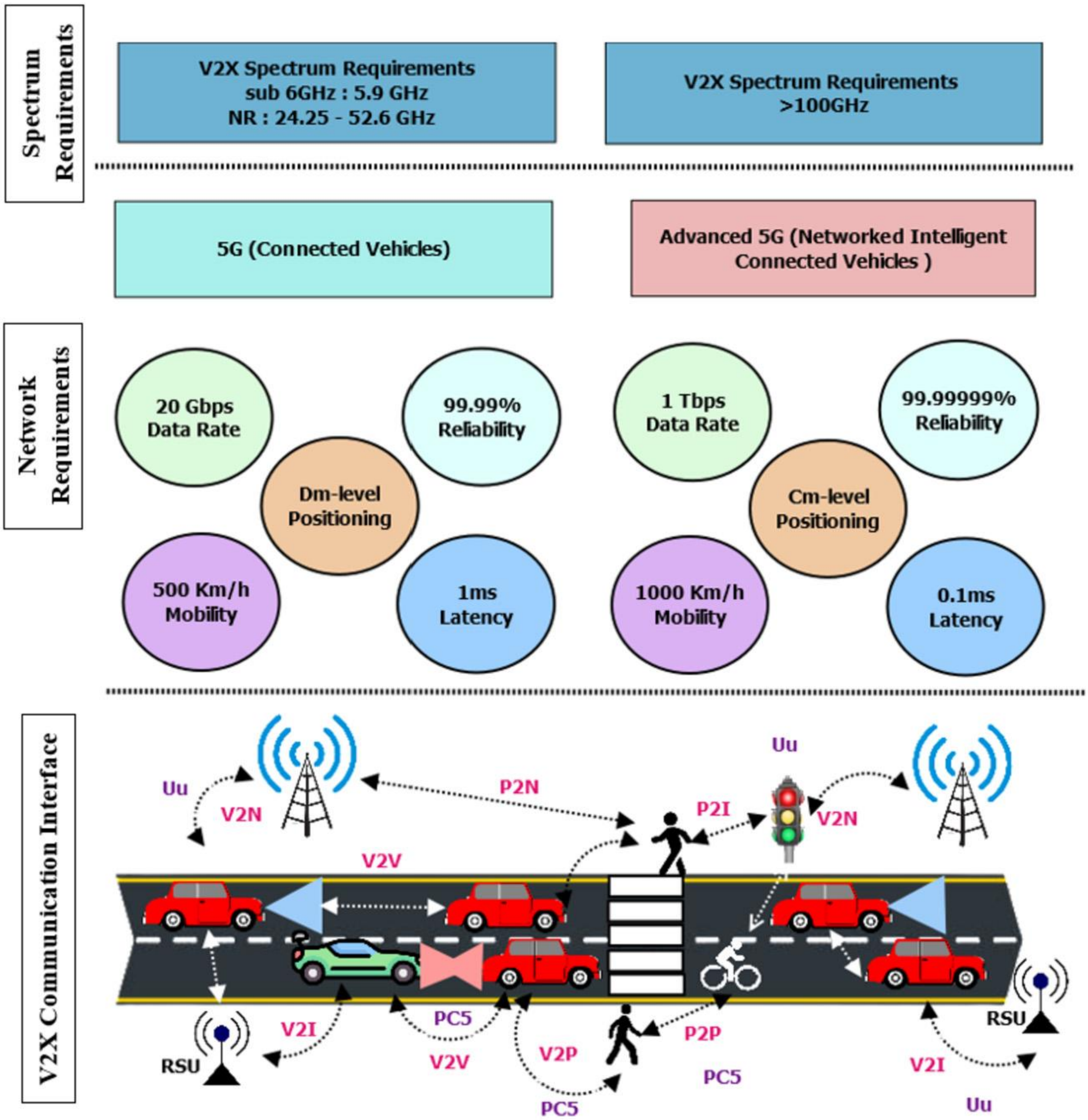
Overall, the reviewed studies demonstrate that Digital Twins, simulation technologies and Cyber-Physical Systems form a highly interconnected technological ecosystem that supports Industry 4.0 transformation. By integrating real-time sensing, virtual modeling, advanced analytics, simulation capabilities, artificial intelligence and communication networks, these technologies enable organizations to improve operational visibility, enhance resilience, optimize decision-making, reduce risks and create more adaptive and intelligent industrial systems. Their applications span manufacturing, logistics, supply chains, transportation and energy infrastructure, highlighting their strategic importance for the future development of smart industries and digital enterprises.

3.6.4 Emerging and Future-Oriented Technologies in Logistics

Emerging technologies are changing logistics from a traditional operational activity into a connected, intelligent and future-oriented system. The selected papers show that future logistics will depend more on real-time communication, smart sensors, artificial intelligence, human-centered systems and sustainable digital networks. These technologies do not work separately. They are connected with each other and support faster decisions, safer transport, better monitoring and more efficient distribution processes.

One important future-oriented technology is Cellular Vehicle-to-Everything communication, also known as C-V2X. The paper on intelligent transportation systems explains that C-V2X allows vehicles to communicate with other vehicles, pedestrians, infrastructure and networks. This technology is important for logistics because transportation is one of the main parts of supply chain activity. When trucks, roads, traffic systems and logistics platforms can exchange information in real time, delivery becomes safer, faster and more coordinated [107].

The figures and tables in the C-V2X paper show that future transportation will move toward connected and automated mobility. The paper compares older DSRC communication with C-V2X and explains that C-V2X is more suitable for future transport because it can use LTE and 5G networks, support direct communication and also connect vehicles with network services. For logistics, this means that fleets can become more intelligent, traffic can be managed more efficiently and delivery routes can be adjusted based on real-time road conditions.



15Figure : Gandadvanced5GtechnologynetworkrequirementsforV2X [107].

Wireless communication is also presented as a key future technology for logistics. The paper on collaborative innovation in wireless communication shows that wireless technologies are becoming part of the next generation of logistics infrastructure. These technologies improve network speed, reliability, capacity, latency and security. This is important because modern logistics needs continuous communication between warehouses, vehicles, ports, distribution centers and customers.

The same paper also shows that wireless communication innovation in logistics is growing through patents, universities, companies and research institutions. This means that future logistics will not only depend on one company or one technology, but on wider collaboration between industry, research and government. The paper highlights technologies such as New Radio, New Core and LTE as important technological areas connected with logistics innovation. This shows that logistics is becoming strongly linked with advanced communication networks [197].

Another future-oriented direction is Industry 5.0. While Industry 4.0 focuses mainly on automation, digitalization and efficiency, Industry 5.0 gives more attention to human-centered, sustainable and resilient systems. The selected paper explains that Industry 5.0 does not remove humans from industrial systems. Instead, it supports cooperation between humans and machines, where technology improves human work instead of replacing it completely.

This idea is important for logistics because future warehouses and transport systems will include robots, smart devices, artificial intelligence, sensors and digital platforms, but human workers will still remain important. Industry 5.0 suggests that these technologies should be designed with human values, safety, ethics and well-being in mind. In logistics, this means that future technologies should improve productivity, but also support workers, reduce physical strain and make operations safer and more understandable [141].

The Industry 5.0 review also organizes future technologies around three main pillars: human orientation, resilience and sustainability. This is useful for logistics because future supply chains must not only be fast and automated, but also able to recover from disruptions and reduce environmental impact. The paper mentions technologies such as artificial intelligence, digital twins, cyber-physical systems, smart sensors, robotics and big data analytics as important technologies for the future industrial ecosystem [259].

Smart sensors are another important emerging technology in logistics, especially in food distribution and safety networks. The paper on future-oriented smart sensors explains that food distribution requires better monitoring from farm to fork, including production, packaging, storage, transportation and delivery. Smart sensors can detect physical, chemical and biological changes in food products and convert them into electronic signals for analysis.

This technology is very relevant for logistics because product quality often depends on transport and storage conditions. In food logistics, sensors can monitor temperature, humidity, microbial growth, contamination, adulteration, freshness and storage conditions. When these sensors are connected with IoT, 5G, artificial intelligence, machine learning and cloud computing, food distribution becomes safer and more transparent.

The same paper also explains that smart packaging and smart distribution networks can help reduce human involvement while improving monitoring and sustainability. This does not mean that humans become unnecessary, but that routine checking can be supported by intelligent systems. In this way, logistics workers and managers can receive alerts and make decisions before food quality problems become serious.

Overall, the selected papers show that the future of logistics will be based on connected, intelligent, sustainable and human-centered technologies. C-V2X and wireless communication improve transport connectivity. Smart sensors improve product monitoring and food safety. Industry 5.0 introduces a more human-centered and ethical direction. Artificial intelligence, cloud systems, IoT, digital twins and cyber-physical systems support more adaptive logistics networks. Together, these technologies show that future logistics will not only focus on speed and cost reduction, but also on safety, resilience, sustainability and better cooperation between people and intelligent systems.

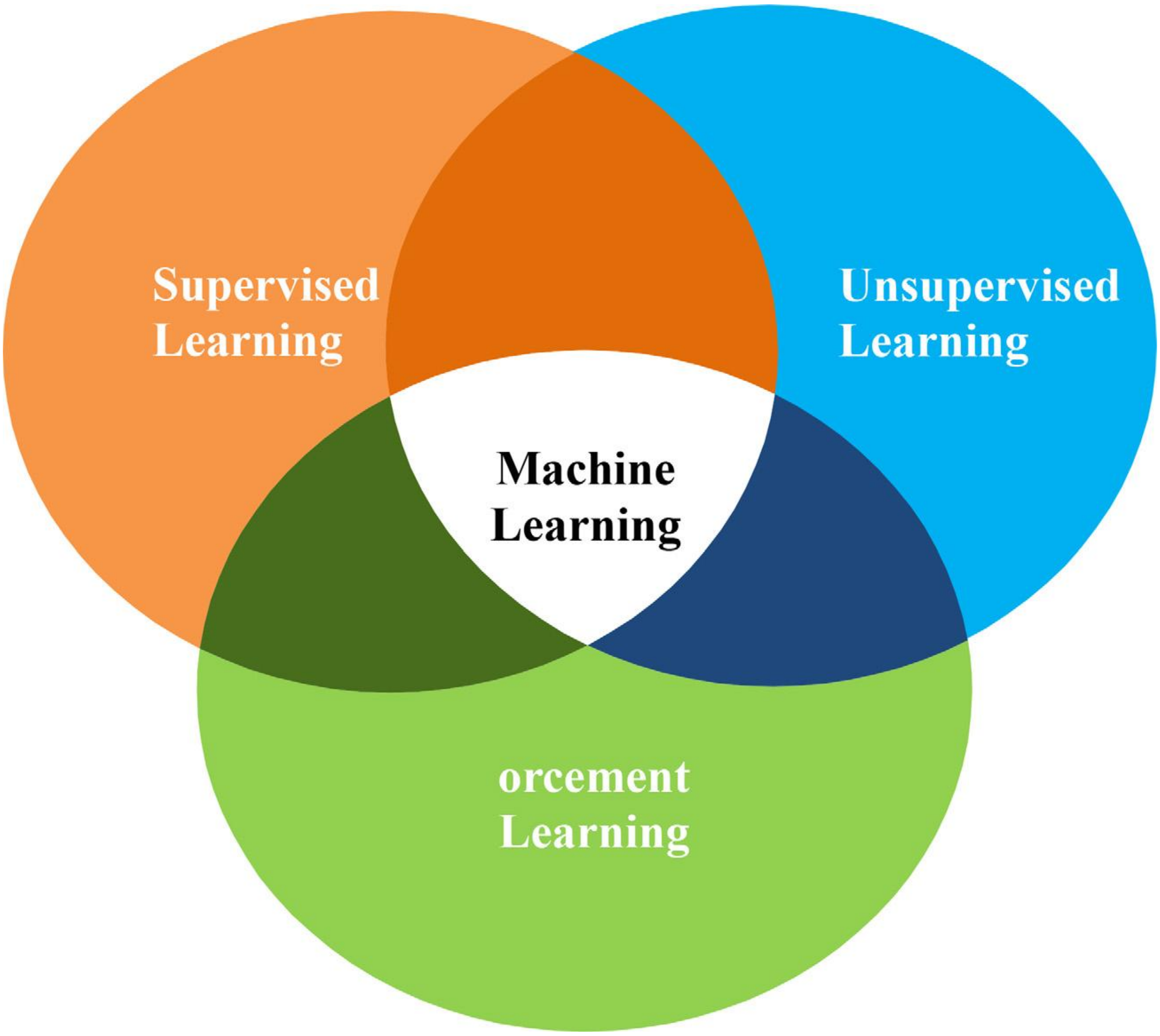
3.7 Algorithms and Machine Learning

3.7.1 Machine Learning Applications in Supply Chain Management

Machine Learning (ML) has become one of the most important digital technologies supporting modern Supply Chain Management (SCM). The reviewed papers show that supply chains generate large amounts of data from procurement, production, warehousing, transportation, distribution and customer activities. Machine learning allows organizations to analyze this data automatically, identify patterns, predict future events and support better decision-making across the entire supply chain. As supply chains become more complex and dynamic, ML helps companies improve efficiency, reduce uncertainty and respond faster to market changes.

The paper by Nagar et al. presents machine learning as one of the key technologies of Industry 4.0. The authors explain that supply chains involve many interconnected business activities and require continuous monitoring of resources, products, suppliers and customer demands. Machine learning supports these activities by processing large datasets and transforming them into useful information for planning and decision-making. Instead of relying only on human analysis, ML systems can recognize patterns, learn from historical data and provide accurate forecasts for future operations.

One of the figures presented in the paper illustrates the Machine Learning Taxonomy, showing three major learning approaches: supervised learning, unsupervised learning and reinforcement learning. The figure demonstrates that different learning methods can be applied depending on the type of data and the decision-making requirements of the organization. Supervised learning uses labeled historical data, unsupervised learning identifies hidden patterns and clusters within datasets, while reinforcement learning improves decisions through continuous feedback and experience. This classification highlights the flexibility of machine learning applications in supply chain environments.



16Figure : Machine learning taxonomy [154].

Demand forecasting is one of the most common applications of machine learning in supply chains. Traditional forecasting methods often struggle when market conditions change rapidly or when customer behavior becomes unpredictable. Machine learning models can analyze large volumes of historical sales data, customer preferences, market trends and external factors to generate more accurate forecasts. Better forecasting helps organizations reduce inventory costs, avoid stock shortages and improve customer satisfaction.

Another important application is inventory and production planning. According to the reviewed literature, machine learning helps organizations predict future demand and align production schedules with market requirements. By analyzing demand patterns and operational data, ML systems can support inventory management decisions and improve resource utilization. This reduces waste, lowers operating costs and improves overall supply chain performance.

The paper also emphasizes the role of machine learning in supplier management. Supply chains often involve many suppliers with different performance levels and quality standards. Machine learning algorithms can analyze supplier data, evaluate performance patterns, identify risks and support supplier selection processes. These capabilities allow organizations to improve supplier relationships and maintain higher quality standards throughout the supply chain.

Machine learning is also widely used in logistics and transportation management. The reviewed studies indicate that ML can analyze transportation data, customer locations, delivery times and traffic conditions to optimize logistics operations. By identifying efficient routes and predicting potential disruptions, organizations can reduce transportation costs and improve delivery performance. This capability is particularly valuable in modern supply chains where customer expectations for fast and reliable deliveries continue to increase.

The literature further highlights the role of machine learning in supporting operational decision-making. The figure describing machine learning applications in supply chains presents several areas where ML contributes, including smart workstations, decision support systems, scalability management, cross-functional collaboration, logistics optimization, supplier evaluation and product development. These applications demonstrate that machine learning is not limited to a single operational function but can support multiple supply chain activities simultaneously [154].

Recent research also shows growing interest in combining machine learning with simulation models. The comprehensive review by Badakhshan et al. explains that hybrid Simulation-Machine Learning (Sim-ML) approaches are becoming increasingly important for supply chain management. Simulation models can represent complex supply chain systems and their uncertainties, while machine learning algorithms can analyze large datasets and improve predictive capabilities. When combined, these approaches provide more accurate decision support and enable organizations to evaluate different supply chain scenarios before implementation.

The review identifies several machine learning approaches used in supply chains, including supervised learning, unsupervised learning and reinforcement learning. These methods are applied to various supply chain challenges such as inventory management, production planning, transportation optimization, supplier selection, risk management and demand forecasting. The study also shows that machine learning is increasingly being integrated with Industry 4.0 technologies such as digital twins, advanced analytics and intelligent decision-support systems.

An important observation from the review is that modern supply chains are becoming more data-driven. The bibliometric analysis presented in the paper shows strong connections between machine learning, digital twins, optimization methods, inventory management and supply chain performance. This indicates that machine learning is evolving from a standalone analytical tool into a central component of intelligent supply chain ecosystems [191].

Overall, the reviewed papers demonstrate that machine learning has become a critical technology for modern supply chain management. It supports forecasting, inventory planning, logistics optimization, supplier management, decision support and operational efficiency. Furthermore, the integration of machine learning with simulation models and Industry 4.0 technologies is creating more intelligent, adaptive and resilient supply chains capable of responding effectively to future challenges and uncertainties.

3.7.2 Optimization and Decision-Making Algorithms

Optimization and Decision-Making Algorithms have become increasingly important in modern Supply Chain Management (SCM), helping organizations make better decisions and improve operational performance. As supply chains become more complex and involve multiple stakeholders, companies need effective methods to manage resources, coordinate activities and respond to changing market conditions. Optimization algorithms provide structured approaches for identifying the most efficient solutions while considering various operational constraints and business objectives.

The reviewed literature shows that optimization techniques are widely used across supply chain activities, including production planning, inventory management, transportation, supplier selection and supply chain coordination. These algorithms help organizations evaluate different alternatives and select the option that best achieves their goals. Instead of relying solely on human judgment, optimization models support decision-makers by analyzing large amounts of information and identifying solutions that improve efficiency and reduce costs.

One important application of optimization algorithms in supply chain coordination. The study by Che et al. examines an intelligent vehicle supply chain involving suppliers, manufacturers and retailers. Using a Stackelberg decision model, the authors analyze how different supply chain participants make decisions regarding innovation, pricing and sales activities. The results show that optimization-based decision models can improve cooperation between supply chain partners and contribute to better overall performance [265].

Optimization techniques also play a significant role in strategic decision-making. Supply chain managers often need to balance multiple objectives such as cost reduction, customer satisfaction, product quality and profitability. Optimization models allow organizations to compare alternative strategies and identify solutions that create the greatest overall benefit. These capabilities are particularly valuable in modern supply chains where decisions must be made quickly and under conditions of uncertainty.

Another important area is supplier and partner selection. Choosing the right suppliers and business partners is critical for supply chain success. The study in the paper [156] presents a decision-making framework that helps organizations evaluate potential strategic alliance partners based on multiple criteria. The model considers economic, environmental and social factors, allowing companies to make more comprehensive and objective decisions. The findings demonstrate that optimization-based decision approaches can improve partner evaluation and support long-term supply chain sustainability [156].

The literature further highlights the growing use of multi-criteria decision-making methods. Supply chain decisions often involve several factors that may conflict with each other. For example, a supplier with lower costs may not provide the highest quality products, while a more sustainable supplier may involve higher expenses. Multi-criteria optimization techniques help managers evaluate these trade-offs and select the most appropriate solution according to organizational priorities [266].

Recent studies also show increasing interest in intelligent optimization algorithms inspired by natural processes. These algorithms are designed to solve complex problems more efficiently than traditional optimization methods. The research by Yan et al. presents an improved Sparrow Search Algorithm that enhances prediction performance and decision accuracy. Although the study focuses on energy systems, it demonstrates how advanced optimization algorithms can support forecasting, planning and decision-making in highly dynamic environments. Similar approaches can be applied to various supply chain challenges, including demand forecasting, transportation planning and resource allocation.

In addition, optimization algorithms are increasingly combined with machine learning and artificial intelligence technologies. Machine learning models generate predictions based on historical and real-time data, while optimization algorithms determine the most effective actions based on those predictions. This combination allows organizations not only to understand what may happen in the future but also to identify the best decisions to improve supply chain performance [267].

The reviewed studies indicate that optimization algorithms are becoming a key element of digital supply chains. They support both operational and strategic decisions, helping organizations improve efficiency, reduce uncertainty and strengthen collaboration across the supply chain network. Their integration with Industry 4.0 technologies is further enhancing decision-making capabilities and enabling more intelligent and adaptive supply chain systems.

Overall, the literature demonstrates that optimization and decision-making algorithms contribute significantly to modern supply chain management. They support planning, coordination, supplier evaluation, forecasting and resource allocation while helping organizations achieve higher efficiency and better overall performance. As digital technologies continue to evolve, optimization algorithms are expected to play an even greater role in creating resilient, intelligent and sustainable supply chains.

4. Research Methodology

4.1 Introduction

This chapter presents the research methodology adopted to investigate the role and applications of advanced communication technologies—with particular emphasis on 5G and emerging 6G—in supply chain and logistics systems. The methodological approach follows the same explanatory, application-oriented and technology-driven style used in Chapter 4 (Applications of 5G & 6G) and Chapter 5, aiming to ensure consistency in tone, structure and narrative flow across the thesis.

The methodology is designed to combine a systematic literature review with a technology-centric analysis. Instead of focusing purely on formal review protocols, the approach emphasizes how communication technologies are applied, evaluated and discussed in real-world supply chain and logistics contexts. This allows the research process itself to align with the applied and practical orientation of the subsequent chapters.

4.2 Research Questions

4.2.1 (RQ1) 5G Technology and Supply Chain Transformation

How does 5G technology contribute to the digital transformation, performance improvement and operational efficiency of modern supply chains and logistics systems?

4.2.2 (RQ2) Integration of 5G with Emerging Smart Technologies

What opportunities and challenges emerge from the integration of 5G technology with Artificial Intelligence, Digital Twins and UAV-based systems in smart supply chain and logistics environments?

4.2.3 (RQ3) The Role of 6G in Future Smart Supply Chains

How can emerging 6G technologies transform future supply chain and logistics systems through enhanced connectivity, automation and intelligent decision-making?

4.3 Literature Research Process

The literature review focuses on studies published between 2018 and 2025, a period that captures both the commercial deployment of 5G networks and the early conceptual development of 6G technologies. This time frame is particularly important because it reflects a transition phase in communication systems: 5G has moved from experimental testbeds to practical industrial applications, while 6G is still largely explored through visions, architectures and enabling technologies.

The review targets research related to supply chain management and logistics, with special attention given to communication infrastructures, intelligent systems, automation and real-time data exchange. The scope includes both academic and applied research in order to reflect how these technologies are designed, tested and adopted in operational environments such as warehouses, transportation networks, ports and industrial supply chains.

4.4 Research Strategy and Keyword Selection

The literature search was conducted using a technology-oriented keyword strategy, consistent with the application-focused perspective adopted throughout the thesis. Core keywords included supply chain, logistics, communication technologies, 5G and 6G. These terms were deliberately selected to capture both academic and industry-oriented research, since the terms supply chain and logistics are often used differently across scientific and professional communities.

Additional keyword combinations were formed to ensure broad coverage of relevant studies. These combinations included variations such as 5G and Supply Chain, 6G and Logistics and Communication Technologies in Supply Chain. Related terms and closely connected concepts were also considered to avoid excluding relevant work due to minor differences in terminology. This flexible keyword strategy supports a more complete and representative view of how modern communication technologies are applied in logistics and supply chain systems.

Table 1: Research keywords and corresponding year ranges used for the systematic literature search. The year range column indicates the period during which each keyword was actively used as a search term in the various search engines during the literature review process.

Keywords	**Year Range**
5G and Logistics	**2017-2025**
6G and Logistics	**2017-2025**
5G and Supply Chain	**2017-2025**
6G and Supply Chain	**2017-2025**
Communication Technologies in Supply Chain	**2017-2025**

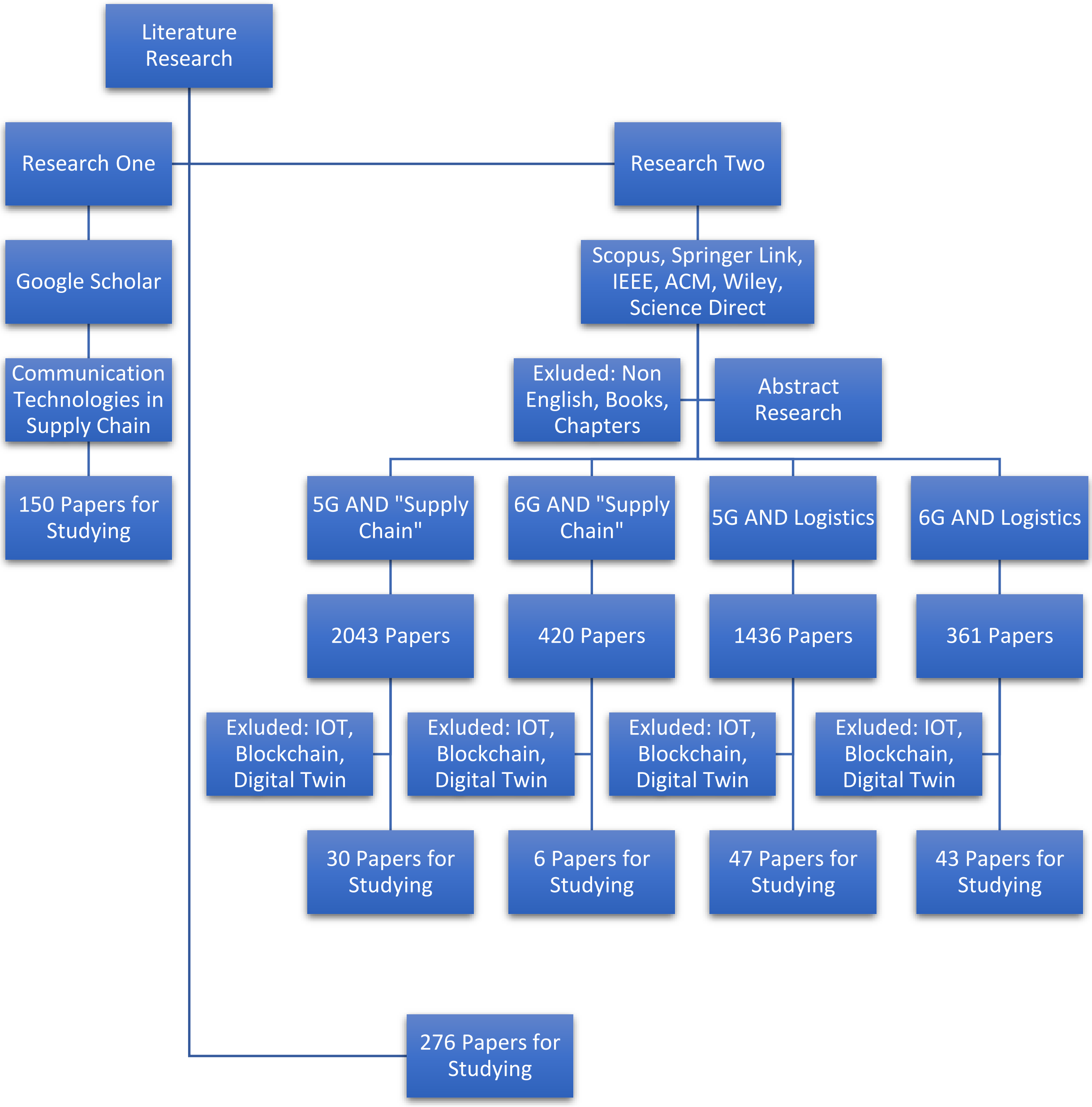


Table 2: The search for the study lasted several months and was divided into two types of searches: the first, via Google Scholar, focused on "Communication Technologies in Supply Chain" and founded 150 papers for study. The second and more extensive search, was conducted across multiple databases (Scopus, Springer Link, IEEE, ACM, Wiley, Science Direct) and with the suitable keywords combinations, was subjected to a first screening round. At this stage, articles that were not in English, as well as Books and Chapters, were excluded and an Abstract Research review was also performed. This second search initially found 4260 articles (via four keyword combinations), which were then subjected to a second round of exclusions (IOT, Blockchain, Digital Twin, food supply chain, AGV), resulting in 127 final articles for study (30, 6, 47 and 43 respectively). The articles from both searches (150 + 127) were compiled in the final stage, leading to a total set of 276 papers for study.

4.5 Data Sources

The literature search was carried out across major peer-reviewed scientific databases that are widely used in engineering, computer science and logistics research. These included IEEE Xplore, SpringerLink, ACM Digital Library, Wiley Online Library, ScienceDirect, Scopus and Google Scholar. These data sources were selected because they provide extensive coverage of communication technologies, industrial applications and interdisciplinary research combining networking, automation and supply chain management.

The search process was conducted in multiple stages. An initial broad search was used to identify a wide set of publications related to communication technologies in supply chain and logistics. This was followed by more focused searches that concentrated specifically on 5G and 6G technologies and their applications, including intelligent systems, UAV-based solutions and AI-enabled logistics platforms. This staged approach reflects the same gradual narrowing of focus that is later applied in the analysis of 5G and 6G applications in Chapters 5 and 6.

4.6 Review and Evaluation Process

The exclusion criterion, as mentioned earlier, was the publication year range between 2018 and 2025. In the search engines IEEE Xplore, SpringerLink, ACM Digital Library, Wiley Online Library and ScienceDirect, the search was performed within the abstract. This approach was chosen because it helped keep the number of retrieved papers at a manageable level for the purposes of this study. However, the procedure in Scopus was different. Due to Scopus indexing and the extremely large number of results (thousands), the search had to be limited to the Title field. The four search terms that was used across all search engines were: 5G and "Supply Chain", 6G and "Supply Chain", 5G and Logistics, 6G and Logistics. Below, the results of each search engine are presented.

(a) IEEEXplore

Using the terms "5G" AND "supply chain" within the abstract field totally 53 papers were initially found. Out of these, 12 papers were selected. With the terms "6G" AND "supply chain" total of 7 papers were found and 2 of them were selected for further analysis.

Using the terms "5G" AND "logistics" 117 articles were retrieved. For the purposes of this study, 14 relevant papers were selected.

With the terms "6G" AND "logistics" in the abstract and within the same time range and filters, 18 papers were found. From these, 6 were selected.

(b) SpringerLink

Using the keywords "6G" AND "supply chain", 395 articles were found and 4 papers were selected. Similarly, with "5G" AND "supply chain", 1,950 articles were retrieved. Searching within the title field produced 7 articles that contained both concepts. Using the terms "5G" AND "logistics", 1,250 articles were found, while "6G" AND "logistics" yielded 328 articles. From this database, 14 papers were finally selected for review.

(c) ACM Digital Library

Using the query Abstract: 5G AND Abstract: "supply chain", only 2 papers were found and both were included in the bibliography. With the terms of Abstract 6G AND "supply chain" only one paper appeared, which had already been identified in previous searches. With the research terms in Abstract

5G AND Logistic 7 papers were found. Finally, with the terms in Abstract 6G AND Logistics under the same date range returned one paper that had already been included earlier. Additional searches were performed using both title and full-text fields, resulting in a total of 18 papers collected for examination and inclusion in the bibliography.

(d) Wiley Online Library

Using the terms 5G AND Logistics within the abstract field and applying the journals filter, 14 papers were found. With 6G AND Logistics, only 2 papers were retrieved. The search "supply chain" AND 5G returned 11 papers, while "supply chain" AND 6G resulted in only 1 paper, which primarily focused on Communication Technologies. As with other databases, additional searches were conducted in both title and full-text fields. In total, 23 papers were selected for review.

(e) ScienceDirect

The search was performed within the fields Title, Abstract, or Author-specified Keywords. Using 5G AND Logistics, 48 papers were found and 5 papers were selected. With the terms 6G AND Logistics, 11 papers were retrieved and 1 paper was selected. Using 6G AND "Supply chain", 8 papers were found, but none were selected. With 5G AND "Supply chain", 27 related papers were identified and 9 of them were selected.

(f) Scopus

In Scopus, as noted earlier, the search was conducted differently. Using the term 6G AND Logistics, 6 results were found and 1 most relevant paper was selected. With the term 6G AND "Supply Chain," 8 results were found and again 1 paper was selected. Using the term 5G AND "Supply Chain," 28 papers were retrieved, of which 9 were selected, while with the term 5G AND "Logistics," 33 papers were retrieved and 8 were selected.

Commentary and Analysis of Scopus Results

The Scopus search results reveal a distinct difference in research maturity between studies on 5G and those on 6G within the fields of supply chain management and logistics. Research on 5G integration began to appear around 2019–2020, showing consistent growth in subsequent years. In supply chain management, publications increased steadily, peaking in 2023 with eight results, while in logistics the topic reached its highest activity between 2022 and 2023, with over a dozen publications each year. This trend demonstrates that both academia and industry have actively investigated of how 5G technologies enhance operational efficiency through real-time data exchange, automation, predictive analytics and networked logistics systems. The sustained number of publications through 2024–2025 suggests that 5G supporting the digital transformation of logistics and supply chain processes.

In contrast, 6G-related research remains in its early conceptual stage. Although search queries for 6G and supply chain appear in Scopus later than 2020, there are few or no recorded publications, indicating that academic exploration is still emerging. For 6G and logistics, initial publications began around 2022, showing a gradual rise to a small number of results in 2025. This limited output reflects the current developmental status of 6G, which is still in a theoretical and experimental phase, with widespread deployment expected after 2030.

Overall, the findings highlight a technological transition period: research on 5G is well-established and application-oriented, focusing on practical implementation and performance improvements, while 6G studies are exploratory, emphasizing conceptual frameworks and future potential. This evolution suggests that the research community is gradually shifting from refining existing 5G-enabled logistics and supply chain systems toward envisioning next-generation 6G architectures that will redefine connectivity, intelligence and automation across global supply networks.

4.7 Overall Summary of Literature Review and Database Findings

In general, the literature review across databases like IEEE Xplore, Springer Link, ACM Digital Library, Wiley, ScienceDirect and Scopus shows how research on new communication technologies in supply chain and logistics has evolved between 2017 and 2025. The keyword searches (5G, 6G, logistics, supply chain) helped cover a wide range of studies and made it easier to see where research is growing. Most of the existing work focuses on 5G, which has now reached a more practical and applied stage. Many papers explore how it improves efficiency, automation and real-time communication in logistics and supply chain systems.

On the other hand, 6G research is still just getting started. Only a few papers have been published so far, which makes sense since 6G is still under development and not yet available. The overall picture shows that we're currently in a transition phase — 5G is being used and studied in real-world applications, while 6G is more about ideas and future possibilities. Researchers are slowly shifting their attention from fine-tuning 5G solutions to imagining how 6G could change the way connected and automated supply chains work in the next decade.

5. Technology 5G

5.1 Introduction in 5G

5.1.1 Fundamentals and Characteristics of 5G Technology

5G technology is a key part of modern digital systems and Industry 4.0 environments. It is designed to support highly connected and intelligent systems where machines, sensors and people can communicate in real time. In modern manufacturing and logistics systems, there is a strong need for fast data exchange, reliable communication and continuous connectivity. 5G provides these capabilities and helps creating more flexible and adaptive production systems. It enables both mobile and stationary connectivity across the industrial environment, allowing different systems to work together more efficiently.

One of the most important characteristics of 5G is its ability to support real-time data communication. In smart factories and logistics systems, large amounts of data are generated from machines, sensors and monitoring systems. This data must be transferred quickly to cloud platforms or data centers where it can be processed and analyzed. With 5G, this process becomes faster and more reliable, which is essential for applications such as predictive maintenance and real-time decision making. The combination of data collection, data transfer and analytics forms a complete data value chain, which is a central concept in modern industrial systems.

Another important feature of 5G is its support for interconnected systems. In Logistic system or the supply chain, systems are not isolated but work as part of a larger network known as Cyber-Physical Production Systems (CPPS). These systems combine physical processes with digital technologies and require continuous communication between different components. 5G enables this interconnection by supporting communication between machines, sensors and control systems. This allows systems to collect data, analyze it and respond automatically to changes in the environment. As a result, production systems become more intelligent, flexible and autonomous vehicles.

5G also supports advanced data-driven applications. In modern industrial environments, decisions are increasingly based on data rather than human intuition. Big Data technologies are used to analyze large volumes of information and extract useful insights. 5G plays an important role in this process by enabling fast and continuous data transmission. This allows systems to monitor operations in real time, detect anomalies and predict future problems. Data-driven decision making is a key element of digital transformation in manufacturing and 5G provides the communication infrastructure needed to support it [98].

In addition, 5G enables new types of services and system architectures. For example, cloud computing platforms can be integrated with industrial systems to store and process large amounts of data. IoT platforms can collect data from multiple sources and send it to central systems for analysis. Mobile devices can also be used as decision-support tools for operators and managers, allowing them to access real-time information from anywhere in the factory or supply chain. This improves communication, coordination and overall system efficiency.

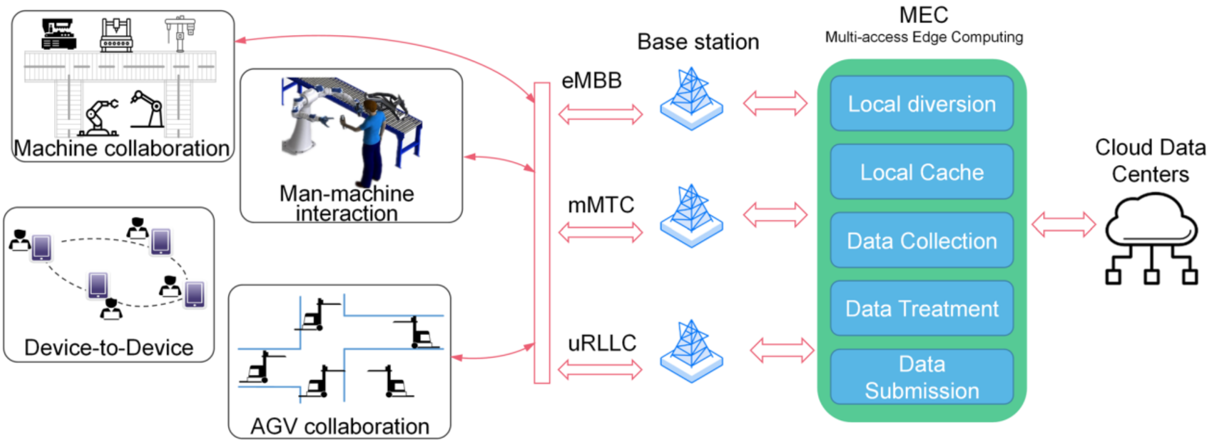
Another key characteristic of 5G is its ability to support complex and dynamic systems. In modern production environments, systems must be able to adapt to changing conditions. This includes variations in demand, machine performance and external factors. 5G supports this adaptability by enabling continuous data flow and fast system response. Through advanced analytics and feedback mechanisms, systems can adjust their behavior automatically and improve performance over time. This leads to more resilient and efficient operations.

Finally, 5G plays a critical role in enabling predictive and proactive systems. By combining real-time data, advanced analytics and intelligent algorithms, systems can move from reactive to predictive operation. For example, in predictive maintenance, data from sensors is analyzed to detect early signs of equipment failure. This allows companies to take preventive actions before problems occur, reducing downtime and improving productivity. The ability to predict and adapt is one of the main advantages of 5G-enabled systems.

Overall, the fundamentals of 5G technology focus on connectivity, real-time communication, data-driven decision making and system integration. These characteristics make 5G a critical technology for modern logistics and industrial systems, supporting the transition to intelligent, automated and highly connected environments.

5G technology plays a central role in the transformation of modern manufacturing systems. As industries move towards smart manufacturing, there is an increasing need for fast, reliable and large-scale communication between machines, systems and people. Traditional communication technologies are not able to fully support these requirements. 5G addresses this gap by offering high bandwidth, low latency and the ability to connect a large number of devices simultaneously. These characteristics make it a key enabler for intelligent production systems and digital transformation in manufacturing.

One of the most important aspects of 5G in manufacturing is its support for different communication scenarios. Specifically, 5G introduces three main types of communication: enhanced mobile broadband (eMBB), ultra-reliable low latency communication (uRLLC) and massive machine-type communication (mMTC). Each of these serves different industrial needs. For example, eMBB supports applications that require high data rates, such as virtual and augmented reality used in training and monitoring. uRLLC enables real-time control of machines and remote operations, where reliability and low delay are critical. mMTC allows the connection of a large number of devices, enabling full interconnection of production systems [100].



17Figure : Explanation of 5G communication in industry [100].

In manufacturing environments, communication is essential across all stages of the production lifecycle. This includes product design, production processes, logistics and maintenance. 5G enables seamless data exchange across these stages, allowing systems to operate in a more coordinated and efficient way. For example, real-time monitoring of machines and production processes becomes possible, which improves transparency and supports better decision making. At the same time, remote maintenance and operation reduce the need for physical presence and improve safety in industrial environments.

Another important contribution of 5G is the support of automation and collaboration. In smart factories, machines do not operate independently but collaborate with each other and with human operators. 5G enables machine-to-machine (M2M) and human-to-machine communication, allowing systems to exchange data, coordinate actions and execute tasks autonomously. This is particularly important in applications such as robotic systems, automated production lines and unmanned factories. Through reliable and fast communication, 5G improves production efficiency and reduces operational costs.

5G also enables advanced digital technologies in manufacturing. It supports the integration of artificial intelligence, Internet of Things (IoT), cloud computing and digital twin technologies. These technologies rely on continuous data exchange and processing, which is made possible by 5G networks. For example, digital twins require real-time data from physical systems to create accurate virtual models. Similarly, AI systems need large amounts of data to analyze and optimize production processes. 5G provides the communication infrastructure that supports these advanced applications.

Despite its advantages, the implementation of 5G in manufacturing still faces several challenges. The integration of 5G with existing industrial systems is still at an early stage. Many manufacturing systems require upgrades in their information infrastructure to fully utilize 5G capabilities. In addition, the lack of standardized solutions and skilled professionals makes the adoption of 5G more difficult, especially for small and medium-sized enterprises. These challenges highlight the need for further research and development in this field.

Overall, 5G technology is a fundamental component of smart manufacturing. It enables real-time communication, large-scale connectivity and the integration of advanced digital technologies. By supporting automation, collaboration and data-driven decision making, 5G helps transform traditional manufacturing into intelligent and efficient systems.

The evolution of 5G wireless technology is not limited to mobile communication, but extends to multiple application domains that require automation and intelligent operation. These domains, often referred to as vertical domains, include smart factories, smart vehicles, smart grids and smart cities. Each of these environments has specific communication requirements, such as high reliability, low latency and the ability to support a large number of connected devices. 5G is designed to meet these requirements and enable a new generation of automated and interconnected systems.

One of the key characteristics of 5G is its ability to support diverse types of services within the same network. Unlike previous generations, which focused mainly on mobile broadband, 5G introduces a more flexible communication framework that can adapt to different use cases. This flexibility is essential for supporting automation in vertical domains, where systems must operate in real time and respond quickly to changing conditions. For example, in industrial environments, machines need to communicate instantly with each other to ensure smooth and efficient production processes.

Another important aspect of next-generation wireless systems is the integration of automation across different sectors. In smart factories, 5G enables the connection of sensors, robots and control systems, allowing real-time monitoring and control of production lines. In transportation, smart vehicles rely on communication with other vehicles and infrastructure to improve safety and efficiency. Similarly, smart grids use communication technologies to manage energy distribution more effectively, while smart cities integrate multiple systems to improve urban services and quality of life.

The success of these applications depends on specific performance requirements. These include ultra-low latency for time-critical applications, high reliability for mission-critical systems and massive connectivity for environments with a large number of devices. For instance, autonomous vehicles and industrial robots require very fast and reliable communication to operate safely. At the same time, applications such as smart cities require the ability to connect thousands or even millions of devices, such as sensors and monitoring systems.

In addition, 5G enables new forms of communication between devices, systems and infrastructure. This includes machine-to-machine communication, as well as communication between devices and centralized systems such as cloud or edge computing platforms. These capabilities allow systems to operate more intelligently, as data can be processed and analyzed in real time. As a result, decision-making processes become faster and more efficient, improving overall system performance.

Another significant advantage of 5G is its support for large-scale automation. Many processes that were previously manual can now be automated through the use of connected devices and intelligent systems. This reduces human intervention, minimizes errors and increases productivity. For example, in smart factories, production processes can be adjusted automatically based on real-time data. In smart cities, traffic systems can adapt dynamically to changing conditions, improving transportation efficiency and reducing congestion [137].

However, despite these advantages, there are still challenges that need to be addressed. The integration of 5G into existing systems requires significant changes in infrastructure and technology. In addition, issues such as security, interoperability and standardization remain important concerns. Ensuring reliable and secure communication across different systems and applications is essential for the successful implementation of next-generation wireless solutions.

Overall, next-generation wireless technologies such as 5G play a critical role in enabling automation across multiple domains. By providing fast, reliable and flexible communication, 5G supports the development of intelligent systems that can operate efficiently in complex environments. As these technologies continue to evolve, they are expected to further enhance the capabilities of smart systems and drive innovation in various industries.

n the era of 5G and future 6G networks, the rapid growth of connected devices has led to the generation of massive amounts of data. These data come mainly from IoT systems, industrial sensors and digital platforms and they play a critical role in modern industrial applications. However, managing and processing this data efficiently remains a major challenge. Traditional centralized systems often face limitations related to scalability, security and data control. This is where Web 3.0 technologies provide a new approach, enabling more secure and decentralized data management in combination with advanced communication networks.

One of the main advantages of Web 3.0 is its decentralized architecture. Instead of relying on centralized servers, data can be stored and managed across distributed networks using technologies such as blockchain. This improves transparency and reduces the risk of data manipulation or unauthorized access. In industrial environments, where sensitive information is exchanged continuously, this level of security is particularly important. It allows organizations to share data more safely and build trust between different systems and stakeholders.

Another important feature of Web 3.0 is the use of smart contracts. These are automated agreements that execute predefined actions when certain conditions are met. In supply chain and logistics systems, smart contracts can simplify processes such as transactions, tracking and coordination between different entities. This reduces delays, minimizes human errors and improves overall operational efficiency. As a result, industrial systems become more automated and capable of handling complex processes without constant human intervention.

Web 3.0 also enhances privacy and data ownership through mechanisms such as self-sovereign identity. This allows users and organizations to control how their data is accessed and used. In large-scale industrial systems, where multiple actors interact, this is essential for maintaining compliance with data protection regulations and ensuring that sensitive information is not misused. At the same time, it encourages more data sharing, since users have greater confidence in how their data is managed.

The integration of Web 3.0 with 5G and 6G networks creates a powerful technological ecosystem. While 5G/6G provide high-speed, low-latency communication, Web 3.0 ensures secure and efficient data handling. Together, they support advanced applications such as digital twins, federated learning and intelligent IoT systems. These applications rely on continuous data exchange and real-time processing, which are enabled by the combination of communication and decentralized technologies.

Furthermore, Web 3.0 contributes to the optimization of resource management in industrial environments. By enabling transparent and automated data exchange, systems can operate more efficiently and adapt to changing conditions. For example, supply chains can be monitored and optimized in real time, reducing delays and improving coordination between different stages of production and distribution. This leads to more resilient and flexible industrial systems.

Despite its advantages, the adoption of Web 3.0 also introduces new challenges. Issues such as network scalability, interoperability between different platforms and security threats still need to be addressed. Additionally, the integration of blockchain and decentralized technologies into existing systems requires significant technological and organizational changes. These challenges highlight the need for further research and development in this field [204].

Overall, Web 3.0 represents a significant step forward in the evolution of digital industrial systems. By combining decentralized data management, enhanced security and automation capabilities with advanced communication technologies such as 5G and 6G, it enables the development of more intelligent, secure and efficient industrial ecosystems.

5.1.2 Applications of 5G in Logistics and Supply Chain

5.1.2.1 Overview of 5G in Logistics Systems

The logistics industry has undergone significant transformation in recent years due to the rapid evolution of digital technologies and communication infrastructures. Traditional logistics systems were mainly based on limited wireless technologies, which often resulted in unstable connectivity, high latency and inefficient data transmission. As logistics operations became more complex and required real-time coordination, these limitations highlighted the need for more advanced communication solutions. The introduction of 5G technology addresses these challenges by providing high-speed data transmission, ultra-low latency and the ability to connect a massive number of devices simultaneously, enabling the development of modern and intelligent logistics systems [176], [181].

5G technology represents the next generation of mobile communication systems, offering significant improvements over previous generations in terms of performance and flexibility. It enables seamless communication not only between users but also between machines, sensors and systems, which is essential for the integration of Internet of Things (IoT) technologies in logistics environments. This capability supports the transition from traditional logistics to smart logistics, where processes are automated, data-driven and highly interconnected [181].

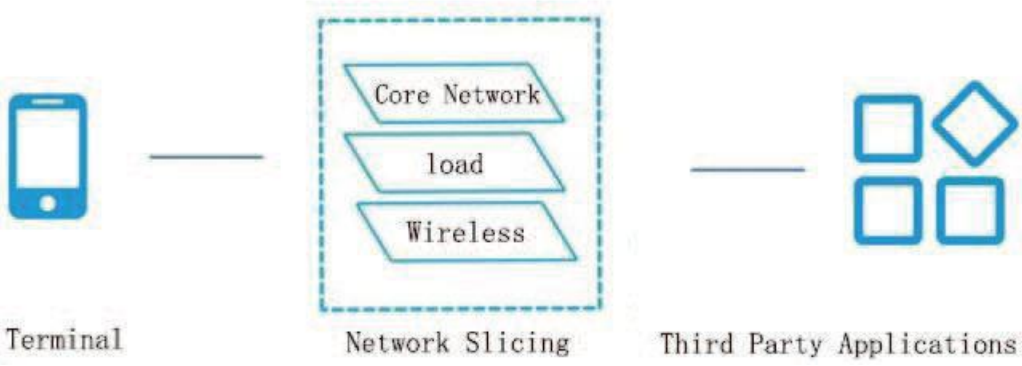
One of the most important contributions of 5G in logistics is the ability to support real-time data exchange across all stages of the supply chain. Logistics systems generate large volumes of data from various sources, including transportation systems, warehouses and distribution networks. With 5G, this data can be transmitted quickly and reliably, allowing companies to monitor operations in real time, improve decision-making processes and enhance overall efficiency. As a result, logistics systems become more responsive, transparent and adaptable to dynamic market conditions [176], [179].

In addition, 5G plays a critical role in enabling the development of smart logistics systems. Smart logistics is based on the integration of advanced technologies such as artificial intelligence, cloud computing, big data and IoT. These technologies work together to automate logistics operations, reduce human intervention and improve accuracy and efficiency. For example, automated warehouses, intelligent transportation systems and unmanned delivery solutions rely heavily on reliable and high-speed communication networks, which are made possible by 5G technology [179].

Also many studies also demonstrate that the transition from conventional wireless communication technologies to 5G is driven by the increasing complexity of modern logistics environments. Traditional Wi-Fi-based communication systems often suffer from limited coverage, unstable connectivity, communication interruptions during mobility and insufficient capacity to support large-scale automation. In contrast, 5G enables reliable low-latency communication, high bandwidth and massive device connectivity, allowing the seamless integration of people, vehicles, equipment and intelligent logistics assets. These capabilities support real-time monitoring, abnormal event detection and coordinated management of logistics parks and warehouse operations, facilitating the transition from simple connectivity toward fully intelligent logistics systems [171].

Recent literature further highlights the strategic role of 5G as an enabling technology for the broader digital transformation of logistics and supply chain operations. According to Cheng et al. [100], 5G supports six major smart manufacturing and logistics domains, including machine-to-machine communication, Industrial Internet of Things (IIoT), cyber-physical systems, logistics and supply chain management, industrial Internet platforms and digital twin–driven manufacturing. The combination of high bandwidth, ultra-low latency and massive device connectivity enables real-time information exchange, intelligent coordination of logistics assets and seamless integration between physical and digital supply chain environments. Furthermore, 5G facilitates the deployment of advanced technologies such as artificial intelligence, cloud computing, edge computing, blockchain and digital twins, which collectively contribute to the development of more connected, responsive and intelligent logistics ecosystems. These capabilities support improved operational visibility, faster decision-making, enhanced automation and greater supply chain agility in Industry 4.0 environments [100].

Another key aspect of 5G in logistics systems is its support for advanced networking capabilities such as network slicing, edge computing and massive connectivity. Network slicing allows the creation of customized network environments for different logistics applications, ensuring optimal performance depending on specific requirements. Edge computing reduces latency by processing data closer to the source, which is particularly important for real-time logistics operations such as autonomous vehicles and robotic systems. These features significantly enhance the performance and reliability of logistics systems [181].



18Figure : Explanation of Network Slicing [181].

Furthermore, 5G contributes to the evolution of supply chains from traditional linear models to more advanced and integrated digital ecosystems. Modern supply chains are increasingly based on a unified digital information space, where physical operations are closely connected with digital systems. This integration enables better coordination between different stakeholders, including suppliers, manufacturers and distributors. Through 5G, information flows more efficiently across the supply chain, reducing information asymmetry and improving collaboration between all participants [229].

The concept of modern supply chains is closely linked to the development of digital infrastructure. With the support of 5G, supply chains are no longer limited by physical boundaries but operate within a digital environment that allows real-time interaction and synchronization. This leads to the creation of more flexible, adaptive and customer-oriented supply chain systems. In this context, 5G acts as a key enabler of digital transformation, supporting the transition from traditional logistics models to intelligent and interconnected systems [229].

Moreover, 5G enables the development of innovative logistics applications such as intelligent warehousing, real-time tracking and automated transportation systems. In intelligent warehouses, 5G supports the use of robots, sensors and augmented reality technologies to improve inventory management and operational efficiency. In transportation, 5G enables real-time communication between vehicles and infrastructure, supporting the development of autonomous driving and smart traffic management systems. These applications significantly enhance the efficiency and reliability of logistics operations [179].

Finally, the integration of 5G technology in logistics systems supports the broader transformation of the industry towards digitalization and automation. By enabling real-time connectivity, high data processing capabilities and large-scale device integration, 5G provides the necessary infrastructure for the development of next-generation logistics systems. As the technology continues to evolve, it is expected to play an even more critical role in shaping the future of logistics and supply chain management, making systems more efficient, intelligent and sustainable [176], [179], [181].

5.1.2.2 Smart Warehousing andAutomation System in Logistics

The rapid evolution of logistics systems has led to the development of smart warehousing and automated logistics processes, which are increasingly supported by advanced communication technologies such as 5G. Traditional warehousing systems were characterized by limited automation, fragmented information flows and delayed decision-making processes. These limitations resulted in inefficiencies in inventory management, increased operational costs and reduced responsiveness to market demands. The introduction of 5G technology significantly transforms these systems by enabling real-time communication, high data transmission rates and reliable connectivity across all logistics operations [179].

One of the most critical contributions of 5G in smart warehousing is the ability to support real-time data transmission between different components of the logistics system. In modern warehouses, large volumes of data are generated from inventory movements, order processing and internal transportation systems. The high-speed and low-latency characteristics of 5G allow this data to be transmitted and processed instantly, enabling more accurate and efficient warehouse management. As a result, warehouse operations become more synchronized, reducing delays and improving overall system performance.

In addition, 5G enables the development of intelligent warehousing strategies based on centralized digital platforms. These platforms integrate data from various logistics processes, allowing stakeholders to monitor and control warehouse operations in real time. The use of cloud-based warehousing systems, supported by 5G connectivity, improves inventory visibility, optimizes storage allocation and enhances demand forecasting capabilities. This leads to a significant reduction in storage time, improved space utilization and increased operational efficiency [160].

Automation is another key element of smart warehousing that is significantly enhanced by 5G technology. Automated systems such as robotic handling equipment, automated sorting systems and intelligent transportation units require stable and ultra-reliable communication to function effectively. 5G provides the necessary communication infrastructure to support these systems, ensuring continuous operation and precise coordination between different automated components. This reduces human intervention, minimizes errors and increases productivity within warehouse environments [179].

Furthermore, 5G supports the operation of automated guided vehicles (AGVs) and smart logistics carts within warehouses and distribution centers. These systems rely on real-time communication to navigate, transport goods and coordinate with other systems. For example, 5G-enabled logistics carts can receive and transmit real-time location and task information, allowing workers to efficiently locate products and follow optimized routes. This improves the speed and accuracy of order fulfillment processes.

The integration of 5G in automated logistics systems also enables advanced control and monitoring capabilities. Through continuous connectivity, warehouse managers can track the status of operations, identify bottlenecks and respond quickly to disruptions. This level of control enhances operational flexibility and allows logistics systems to adapt dynamically to changing conditions, such as fluctuations in demand or unexpected delays.

In manufacturing and logistics environments, 5G also facilitates the use of automated guided vehicles (AGVs) and mobile robotic systems for material handling and internal transportation. These systems benefit from the ultra-reliable and low-latency communication provided by 5G, which allows real-time coordination and remote operation. The use of 5G-enabled AGVs increases the flexibility of logistics operations and supports the development of more resilient and adaptive supply chain systems.

The literature also presents advanced 5G-enabled smart warehouse architectures designed to support fully automated and unmanned logistics operations. A representative framework integrates Intelligent Warehouse Management Systems (IWMS), Robot Control Systems (RCS), enterprise ERP/LMS platforms and Automated Guided Vehicles (AGVs) into a unified operational environment. Through ultra-reliable 5G connectivity, warehouse activities such as receiving, storage, sorting, inventory handling, tallying and distribution can be coordinated automatically with minimal human intervention. The architecture supports real-time task scheduling, intelligent robot dispatching, automated material transportation and goods-to-person logistics, where products are delivered directly to workers through autonomous handling systems. Furthermore, AGV management platforms optimize route planning, storage allocation and operational workflows by continuously exchanging information with warehouse management and enterprise resource planning systems. These capabilities significantly improve warehouse efficiency, reduce labor requirements and enhance the responsiveness of logistics operations within modern industrial environments [43].

Another important aspect of 5G-based logistics is its ability to improve the integration between warehousing and transportation systems. In traditional logistics models, these systems often operate independently, leading to inefficiencies and delays. With 5G, real-time communication between warehouses, transportation units and distribution networks becomes possible, enabling better coordination and synchronization of logistics activities. This results in faster delivery times, improved service quality and reduced operational costs [179].

Moreover, the implementation of 5G in logistics systems supports the broader transition towards digital and automated supply chains. As logistics operations become more complex and interconnected, the need for reliable and high-performance communication networks becomes increasingly important. 5G provides the necessary infrastructure to support this transformation, enabling the development of fully integrated and intelligent logistics ecosystems [164].

Despite its advantages, the adoption of 5G in smart warehousing and logistics systems also presents certain challenges. These include the need for significant investment in infrastructure, the integration of new technologies with existing systems and the requirement for specialized technical expertise. However, as the technology continues to mature and become more widely adopted, these challenges are expected to diminish.

In conclusion, 5G plays a crucial role in the evolution of smart warehousing and automated logistics systems. By enabling real-time communication, supporting automation and improving system integration, 5G significantly enhances the efficiency, flexibility and reliability of logistics operations. As a result, it acts as a key enabler for the development of next-generation supply chain systems that are more intelligent, responsive and sustainable [160], [179], [164].

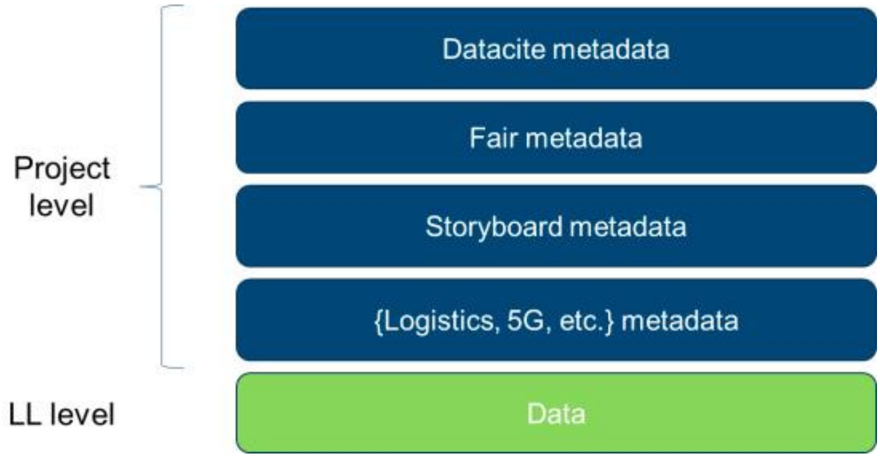
5.1.2.3 Real-Time Monitoring, Data Collection and Cold Chain Logistics

The development of modern logistics systems increasingly depends on the ability to monitor operations in real time, collect accurate data and ensure product quality throughout the supply chain. This is especially critical in cold chain logistics, where goods such as food, pharmaceuticals and other sensitive products must be maintained under strict environmental conditions. The integration of 5G technology plays a fundamental role in enabling these capabilities by providing high-speed, low-latency and reliable communication across all stages of the logistics process.

In traditional cold chain logistics systems, monitoring and control processes are often limited by delayed data transmission and lack of system integration. This leads to inefficiencies in temperature control, increased product loss and reduced reliability of logistics operations. The introduction of 5G communication addresses these limitations by enabling continuous and real-time data exchange between sensors, monitoring systems and control platforms. As a result, logistics operators can monitor environmental conditions such as temperature and humidity instantly and respond immediately to any deviations from required standards.

A key advantage of 5G in cold chain logistics is its ability to support real-time monitoring across the entire supply chain. From storage facilities to transportation and final delivery, data can be continuously collected and transmitted without interruption. This ensures that all stages of the logistics process are transparent and traceable. For example, during transportation in refrigerated containers, environmental conditions can be monitored continuously, allowing early detection of risks that could affect product quality. This significantly reduces the likelihood of spoilage and improves overall supply chain reliability.

Data collection is another critical component of modern logistics systems and 5G enhances this process by enabling efficient and large-scale data handling. In complex logistics environments such as ports and distribution centers, multiple stakeholders need to share and access data in real time. 5G supports this requirement by providing a unified communication infrastructure that facilitates seamless data exchange between different systems and organizations. The 5G-LOGINNOV approach demonstrates how structured data collection, standardized interfaces and centralized platforms can improve collaboration and decision-making in logistics operations.



19Figure : 5G-LOGINNOV's metadata model [188].

Moreover, the ability to collect and process data in real time allows for more advanced analytics and optimization of logistics processes. By analyzing data related to transportation conditions, delivery times and system performance, logistics operators can identify inefficiencies and improve operational strategies. This leads to better route planning, reduced delays and improved resource utilization. In addition, real-time data supports predictive decision-making, enabling proactive responses to potential disruptions in the supply chain.

In cold chain logistics, maintaining product quality is a primary objective and this requires strict control of environmental conditions. 5G enables the deployment of advanced monitoring systems that can track multiple parameters simultaneously, such as temperature, humidity and gas concentration. These systems provide continuous feedback, ensuring that products are stored and transported under optimal conditions. If any abnormal conditions are detected, immediate corrective actions can be taken, preventing product degradation and ensuring compliance with safety standards.

Another important aspect of 5G-enabled logistics is the integration of monitoring and data collection systems with broader supply chain platforms. This integration allows for end-to-end visibility, where all stakeholders have access to real-time information about the status of goods and logistics operations. For example, in e-commerce logistics for perishable goods, real-time tracking and data analysis improve delivery efficiency and customer satisfaction by ensuring timely and reliable distribution.

In addition, 5G supports the scalability of logistics systems, allowing them to handle increasing volumes of data and growing operational complexity. As supply chains become more global and interconnected, the need for reliable and high-performance communication networks becomes more critical. 5G provides the necessary infrastructure to support this evolution, enabling logistics systems to operate efficiently even under high demand and dynamic conditions.

Despite these advantages, the implementation of 5G in real-time monitoring and cold chain logistics also presents challenges. These include the need for infrastructure investment, system integration and data management strategies. Ensuring data security and privacy is also essential, as large volumes of sensitive information are transmitted across the network. However, the benefits of improved efficiency, reduced losses and enhanced supply chain visibility outweigh these challenges.

In conclusion, 5G technology acts as a key enabler for real-time monitoring, efficient data collection and reliable cold chain logistics. By providing continuous connectivity and supporting advanced monitoring systems, 5G improves the quality, safety and efficiency of logistics operations. It enables a more transparent and responsive supply chain, where decisions can be made quickly and based on accurate, real-time information. As logistics systems continue to evolve, the role of 5G in supporting intelligent and data-driven operations will become increasingly important [99], [188], [158].

5.1.2.4 Intelligent Transportation and Optimization in Supply Chain

The integration of 5G technology in transportation systems is a critical enabler for intelligent optimization across modern supply chains. As logistics networks become increasingly complex and time-sensitive, particularly in sectors such as fresh food distribution, the need for efficient routing, real-time decision-making and adaptive transportation models has become more prominent. Traditional logistics systems often suffer from inefficiencies, including high transportation costs, delays and limited responsiveness to dynamic conditions. These challenges highlight the importance of advanced optimization mechanisms supported by high-speed communication infrastructures such as 5G.

One of the key aspects of intelligent transportation is route optimization. In supply chain logistics, especially in cold chain and perishable goods distribution, transportation routes significantly affect both cost efficiency and product quality. Route planning is directly linked to delivery performance, as inefficient routing increases transportation time, operational costs and product deterioration rates. The optimization of delivery paths can reduce logistics costs, minimize spoilage and improve customer satisfaction, which is particularly important in time-sensitive logistics operations [221].

To address these challenges, intelligent optimization algorithms have been introduced. Techniques such as the ant colony algorithm are widely used to determine optimal routing paths in logistics networks. These algorithms simulate real-world decision-making processes and enable the identification of shortest and most efficient routes under multiple constraints, including delivery time windows and vehicle capacity. As demonstrated in paper with number [221], improved optimization approaches can significantly reduce computation time, transportation costs and the number of required vehicles, thereby enhancing overall logistics efficiency.

The role of 5G technology in this context is crucial, as it provides the necessary communication infrastructure to support real-time optimization. High data transmission speeds, ultra-low latency and reliable connectivity enable continuous data exchange between vehicles, logistics platforms and control centers. This allows transportation systems to dynamically adjust routes based on real-time traffic conditions, delivery priorities and operational constraints, resulting in more adaptive and efficient decision-making processes.

In addition to route optimization, 5G facilitates the development of intelligent transportation systems through cyber-physical vehicular networks. These systems integrate communication technologies with transportation infrastructure, enabling seamless interaction between vehicles, logistics hubs and network systems. 5G-enabled vehicular networks support real-time communication between moving entities, enhancing coordination and reducing delays in logistics operations. This connectivity is essential for applications such as autonomous vehicles, fleet coordination and smart traffic management [220].

Moreover, the optimization of communication performance within these networks is equally important. Signal quality, path loss and network reliability directly impact the effectiveness of real-time transportation systems. Research in [220] highlights that optimizing communication parameters within

5G vehicular environments improves data transmission efficiency and ensures stable connectivity, even in complex logistics scenarios such as warehouses or urban distribution systems.

Another important dimension of intelligent transportation is the ability to integrate predictive and adaptive models into logistics operations. By leveraging real-time data and advanced optimization techniques, supply chain systems can anticipate disruptions, adjust routes proactively and optimize resource allocation. This leads to reduced operational uncertainty and improved resilience in logistics networks.

In conclusion, intelligent transportation and optimization in supply chain systems are significantly enhanced by the integration of 5G technology. Through advanced routing algorithms, real-time data exchange and cyber-physical vehicular networks, logistics operations become more efficient, flexible and responsive. These advancements not only reduce costs and improve delivery performance but also support the development of more sustainable and resilient supply chain systems.

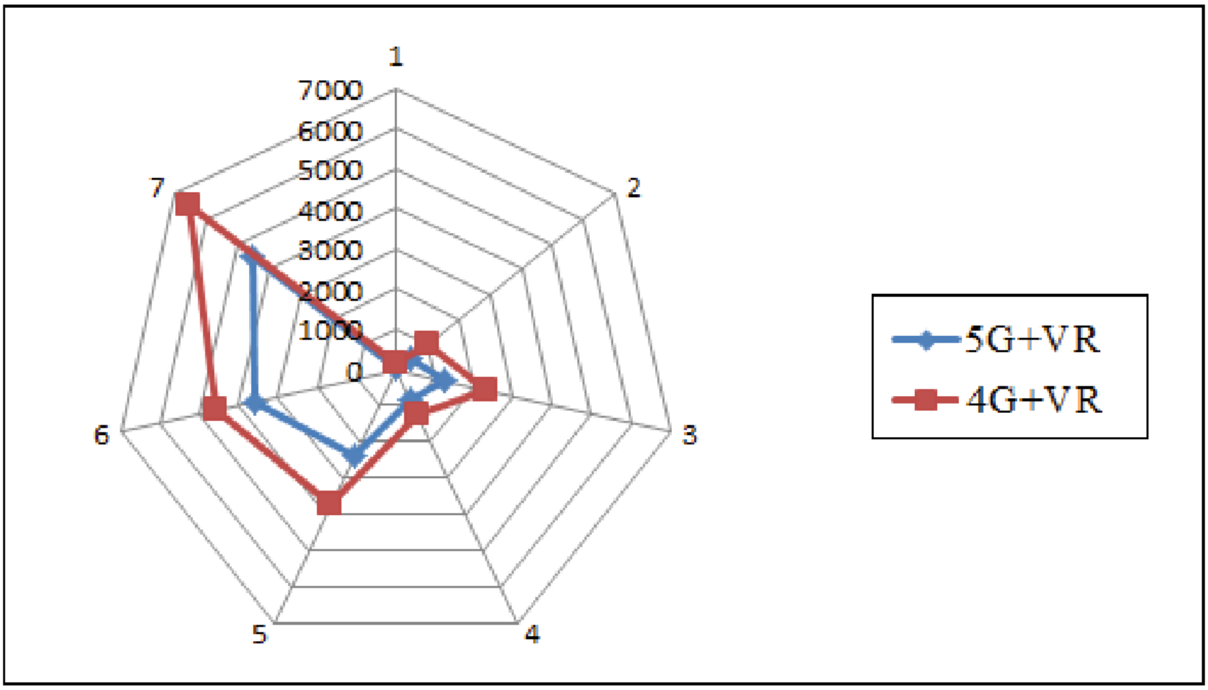
5.1.2.5 Digital Logistics, E-Commerce and Integrated Supply Chain Systems

The rapid evolution of digital logistics and e-commerce has significantly transformed traditional supply chain systems, with 5G technology acting as a key enabler of this transition. Modern supply chains are no longer limited to linear flows of goods but have evolved into integrated, platform-based ecosystems where information, services and stakeholders are interconnected in real time. This transformation is primarily driven by the ability of 5G to support high-speed data exchange, ultra-low latency communication and large-scale connectivity across distributed logistics networks [229].

A fundamental characteristic of digital logistics is the transition from isolated physical systems to unified digital information environments. The development of modern supply chains is closely linked to the evolution of communication infrastructures, leading to the creation of a unified digital information space where physical and digital operations coexist. This dual structure enables synchronized collaboration between supply chain actors, reducing inefficiencies caused by information asymmetry and improving coordination across procurement, production, distribution and retail processes [229].

Within this context, e-commerce plays a central role in shaping integrated supply chain systems. The growth of online platforms has redefined how products are marketed, sold and delivered, shifting supply chain logic from production-driven to demand-driven models. E-commerce systems integrate sales, logistics and data processing into a unified operational framework, enabling real-time interaction between suppliers, logistics providers and consumers. This integration enhances decision-making processes, improves service levels and allows companies to respond more effectively to dynamic market conditions [158].

The role of 5G technology in supporting e-commerce logistics is particularly significant. Enhanced bandwidth and reduced latency facilitate faster data transmission compare to 4G, enabling real-time order processing, inventory management and logistics coordination. 5G improves communication reliability and supports the development of intelligent logistics management systems, which are essential for handling the increasing complexity of e-commerce operations. The ability to process large volumes of data in real time allows logistics systems to optimize routing, reduce delivery times and enhance overall operational efficiency [167].



20Figure : Comparing the results of 5G + VR with 4G + VR in logistics management model [167].

Moreover, 5G contributes to the development of advanced digital logistics models, including cloud-based logistics and integrated service platforms. These systems enable centralized data processing and decentralized execution, allowing different components of the supply chain to operate cohesively. The concept of cloud logistics, supported by 5G infrastructure, allows enterprises to manage logistics resources more efficiently, improving scalability and flexibility in supply chain operations [167].

Another important dimension is the integration of multiple stakeholders within the supply chain ecosystem. Modern supply chains involve not only manufacturers and distributors but also third-party service providers, platform operators and regulatory entities. This multi-actor environment requires seamless communication and coordination, which is enabled by 5G connectivity. The ability to exchange data in real time supports collaborative decision-making and enhances transparency across the supply chain [229].

E-commerce logistics systems also rely heavily on efficient data management and processing capabilities. The integration of advanced communication technologies enables real-time monitoring of logistics activities, from order placement to final delivery. Optimized e-commerce systems can significantly improve delivery performance, reduce operational costs and increase customer satisfaction by enabling more accurate demand forecasting and better coordination of logistics resources [158].

Furthermore, digital logistics systems must address challenges related to scalability, reliability and system integration. The increasing volume of e-commerce transactions requires robust infrastructure capable of handling large-scale data flows without compromising performance. 5G networks provide the necessary support for these requirements by offering high capacity, flexible deployment and enhanced connectivity, which are essential for managing complex logistics environments [167].

In conclusion, the convergence of digital logistics, e-commerce and integrated supply chain systems represents a fundamental shift in how logistics operations are designed and managed. The adoption of 5G technology enables real-time connectivity, enhances system integration and supports the development of intelligent, data-driven logistics networks. These advancements contribute to improved efficiency, reduced operational costs and greater responsiveness to market demands, ultimately shaping the future of modern supply chain ecosystems [229].

5.1.2.6 Advanced Applications: V2X, Industrial and Emerging Use Cases

The evolution of 5G technology has enabled a new generation of advanced applications in logistics and supply chain systems, particularly in areas such as Vehicle-to-Everything (V2X) communication, industrial automation and emerging digital ecosystems. These applications extend beyond traditional logistics operations by integrating intelligent transportation, real-time decision-making and autonomous system coordination into a unified operational framework.

A key area of development is V2X communication, which enables seamless interaction between vehicles, infrastructure and logistics systems. Through the use of 5G networks, V2X supports ultra-low latency, high reliability and high data transmission rates, allowing vehicles to exchange real-time information with other vehicles, road infrastructure and control systems. This capability significantly enhances transportation efficiency, safety and coordination, particularly in complex logistics environments such as ports and industrial zones. The integration of vehicles, roads and network infrastructure creates a fully connected transportation ecosystem, enabling real-time monitoring and intelligent traffic management within supply chain operations [276].

In logistics environments, especially in port and warehouse scenarios, 5G-enabled V2X systems facilitate advanced operational coordination. These systems support automated vehicle movement, real-time route optimization and synchronized logistics processes. The ability to exchange data instantly between different system components improves decision-making and reduces delays, contributing to more efficient cargo handling and transportation workflows. Furthermore, V2X ecosystems enable centralized monitoring and control, allowing authorities and logistics operators to manage transportation networks more effectively and respond dynamically to changing conditions [276].

Another important dimension of advanced 5G applications is the development of cyber-physical vehicular networks in logistics systems. These networks integrate communication technologies with physical transportation assets, enabling intelligent coordination of vehicles within logistics operations. The use of optimized path loss models and advanced communication algorithms enhances signal reliability and network performance, which is critical for maintaining stable communication in autonomous or semi-autonomous logistics systems. Such improvements are particularly relevant for warehouse logistics and retail distribution environments, where precise and reliable vehicle communication is required for efficient operations [220].

The application of 5G in autonomous and connected vehicles further strengthens supply chain performance by enabling real-time data exchange and precise control mechanisms. Autonomous vehicles rely heavily on continuous communication with surrounding systems to perform functions such as navigation, collision avoidance and route optimization. The low latency of 5G ensures that these processes occur almost instantaneously, improving both safety and operational efficiency. In addition, 5G supports high-bandwidth data transmission, allowing vehicles to process large volumes of sensor data and interact with centralized systems without delays [220].

Industrial applications of 5G also play a significant role in shaping advanced logistics systems. In industrial environments, 5G enables real-time control of automated processes, remote monitoring and predictive maintenance. These capabilities allow logistics operations to become more flexible and responsive, reducing downtime and improving productivity. The integration of 5G with industrial systems supports the development of smart factories and intelligent logistics infrastructures, where different components operate in a highly coordinated and data-driven manner [106].

Recent studies further highlight the emergence of 5G-enabled Network Applications (NetApps) designed specifically for transport and logistics environments. Within advanced 5G ecosystems, NetApps support functionalities such as indoor robot navigation, human–robot collaboration, distributed sensor data collection, IoT management platforms, real-time Digital Twins, remote inspection and AI/ML-based fault detection. These applications leverage 5G capabilities including network slicing, virtualization, edge computing and ultra-reliable low-latency communication to support highly automated logistics operations. In smart ports and logistics hubs, NetApps enable continuous monitoring, real-time analytics, data fusion and intelligent decision-making, contributing to safer, more efficient and more autonomous logistics systems. Such developments demonstrate how 5G serves not only as a communication technology but also as a platform for creating intelligent digital logistics ecosystems capable of supporting future industrial and transportation applications [83].

Emerging use cases of 5G extend beyond traditional logistics and transportation systems, contributing to the development of interconnected digital ecosystems. These include applications in healthcare logistics, smart cities and autonomous service systems, where real-time connectivity and data exchange are essential. The ability of 5G to support massive device connectivity and high-performance communication enables the integration of diverse systems into a single operational environment, enhancing overall system efficiency and scalability [106].

Despite these advancements, several challenges remain in the implementation of advanced 5G applications. Issues related to infrastructure development, interoperability and system integration must be addressed to fully realize the potential of these technologies. Additionally, ensuring reliable communication in complex environments and maintaining data security are critical factors for successful deployment. The development of standardized frameworks and continuous technological improvements will be essential for overcoming these challenges and enabling widespread adoption.

In conclusion, advanced 5G applications such as V2X communication, cyber-physical vehicular networks and industrial automation are transforming logistics and supply chain systems. These technologies enable real-time connectivity, enhance operational coordination and support the development of intelligent and autonomous logistics environments. As 5G continues to evolve, its role in enabling innovative and integrated supply chain solutions will become increasingly significant, shaping the future of global logistics systems.

5.1.3 Impact of 5G on Supply Chain Performance and Operations

The introduction of 5G technology constitutes a fundamental shift in how supply chain systems operate, enabling a transition from traditional, fragmented processes to highly integrated, data-driven and real-time responsive environments. Unlike previous generations of mobile communication, 5G is not limited to improving connectivity but actively transforms operational performance, coordination mechanisms and decision-making processes across the entire supply chain.

One of the most significant impacts of 5G lies in its ability to enhance real-time data transmission and operational visibility. The ultra-low latency and high bandwidth characteristics of 5G networks allow continuous monitoring and instant communication between supply chain entities. This capability is particularly critical in complex logistics environments such as cold chain systems, where temperature control, product condition and transport status must be monitored continuously. The integration of 5G with advanced communication technologies enables real-time control of logistics processes, reducing delays, minimizing product loss and improving service reliability. Additionally, the use of 5G-supported networks ensures broader coverage and stable communication even in large-scale or geographically distributed logistics operations.

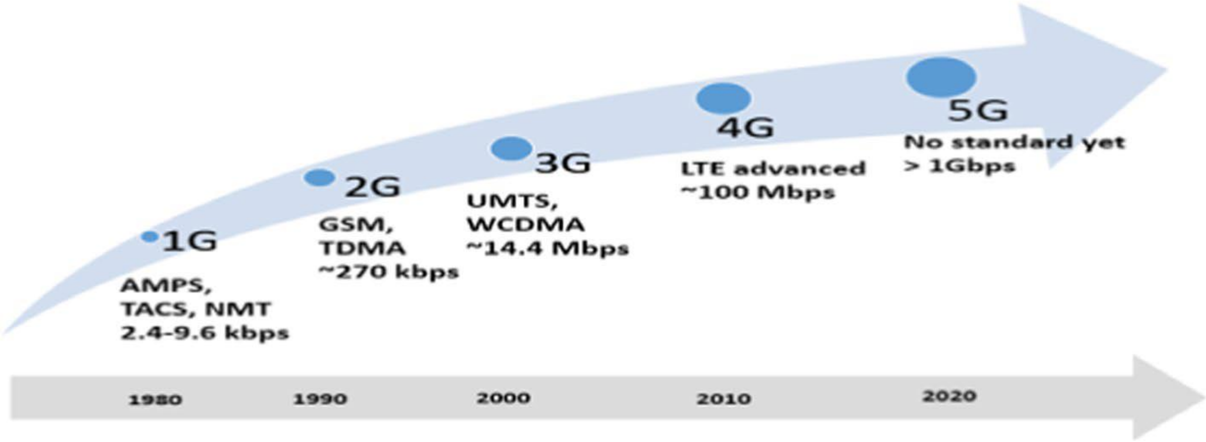
Beyond real-time monitoring, 5G significantly improves decision-making and operational optimization through the integration of advanced analytical models. By enabling the continuous collection and processing of large volumes of data, 5G supports the application of operations research methods in logistics systems. These methods allow for the optimization of transportation routes, inventory management and resource allocation in real time. As a result, supply chain operations become more adaptive and efficient, capable of responding dynamically to changes in demand, environmental conditions and operational constraints. The ability to create flexible and controllable logistics models enhances both performance and cost efficiency, leading to improved service quality and reduced operational risks [195].

Another critical dimension of 5G impact is its role in transforming the value chain structure. Traditional supply chains often suffer from limited information sharing, delayed communication and fragmented coordination between stakeholders. The adoption of 5G enables seamless integration of all value chain activities, from procurement and production to distribution and customer service. According to the value chain framework, 5G enhances both primary and support activities by facilitating real-time communication, improving collaboration between partners and enabling more efficient process execution. This transformation leads to increased transparency, better coordination and improved overall performance across the supply chain network.

In procurement and supplier management, 5G enables more efficient information exchange and coordination between organizations. The ability to transmit large volumes of data بسرعة and reliably allows companies to maintain up-to-date information on supplier performance, inventory levels and demand forecasts. This leads to more accurate decision-making and better alignment between supply and demand. Furthermore, the integration of 5G with digital procurement systems supports automation and reduces the need for manual intervention, improving efficiency and reducing operational costs. The enhanced connectivity provided by 5G also facilitates the development of more collaborative and responsive supplier relationships, contributing to improved supply chain resilience.

In logistics and transportation operations, 5G plays a crucial role in improving efficiency and reliability. The ability to support high-speed communication and real-time data exchange enables better coordination of transportation activities, including route planning, vehicle tracking and delivery scheduling. This leads to reduced transportation times, lower fuel consumption and improved utilization of resources. In addition, 5G supports the implementation of intelligent transportation systems and autonomous logistics solutions, further enhancing operational performance. The improved communication capabilities also enable more accurate tracking and tracing of goods, increasing transparency and reducing the risk of errors or delays.

The impact of 5G extends to warehouse operations and inventory management, where it enables more efficient and automated processes. The use of 5G networks allows for real-time tracking of inventory, precise localization of goods and improved coordination of warehouse activities. This leads to faster order processing, reduced errors and improved overall efficiency. The integration of 5G with automated systems such as autonomous guided vehicles (AGVs) further enhances warehouse operations by enabling real-time communication and coordination between different system components. As a result, warehouses become more intelligent and responsive, capable of adapting to changing operational conditions [193].



21Figure : The mobile wireless evolution [193].

Another important aspect of 5G impact is its contribution to supply chain security and risk management. Modern supply chains are characterized by high complexity and interdependence between different entities, making them vulnerable to various risks. The use of 5G information systems enables the development of advanced security evaluation models that can identify and assess risks in real time. By analyzing the relationships between different components of the supply chain, these models can predict potential disruptions and support proactive risk management strategies. The ability to monitor and analyze supply chain operations continuously enhances resilience and ensures more stable and secure operations.

Furthermore, 5G supports the development of more complex and interconnected supply chain networks. As supply chains evolve from linear structures to complex network systems, the need for efficient communication and coordination becomes increasingly important. 5G enables the integration of different supply chain components into a unified network, allowing for better coordination and collaboration between stakeholders. This leads to improved overall performance and the ability to respond more effectively to changes in the external environment. The enhanced connectivity also supports the development of new business models and operational strategies, further increasing the competitiveness of supply chain systems [166].

The optimization of logistics processes is another key area where 5G has a significant impact. In the context of Industry 4.0, 5G enables the implementation of advanced optimization strategies that improve efficiency and reduce costs. For example, in last-mile delivery, 5G supports the use of intelligent systems that optimize delivery routes, improve customer experience and reduce operational costs. These systems rely on real-time data and advanced algorithms to make decisions, ensuring that logistics operations are performed in the most efficient way possible. The integration of 5G with smart logistics systems also enables better resource allocation and improved coordination between different supply chain components [228].

In addition, 5G contributes to the improvement of customer service and overall supply chain performance. The ability to provide real-time information on order status, delivery times and product availability enhances customer satisfaction and builds trust. The use of advanced communication technologies also enables more personalized and responsive services, allowing companies to better meet customer needs. This customer-centric approach is essential for maintaining competitiveness in modern supply chain environments, where customer expectations are continuously increasing [228].

In conclusion, the impact of 5G on supply chain performance and operations is profound and multifaceted. By enabling real-time communication, enhancing data-driven decision-making, improving operational efficiency and supporting advanced optimization strategies, 5G transforms the way supply chains operate. It facilitates the transition towards intelligent, integrated and highly responsive logistics systems, capable of meeting the demands of modern markets. As the adoption of 5G continues to expand, its role in shaping the future of supply chain management will become increasingly critical, driving innovation and improving performance across all aspects of supply chain operations.

5.2 Requirements and Challenges of 5G

5.2.1 Technical Requirements of 5G Networks

The development of 5G networks introduces a new generation of communication systems designed to support highly demanding applications across multiple industries, including logistics and supply chain operations. Unlike previous generations, 5G is not only focused on improving data speed, but also on enabling a wide range of services that require ultra-low latency, high reliability and massive connectivity. These requirements emerge from the increasing need for real-time data processing, automation and intelligent decision-making in modern digital environments. As a result, the technical requirements of 5G networks are defined by a combination of performance metrics, architectural innovations and deployment strategies that collectively support advanced use cases [138].

One of the most critical technical requirements of 5G networks is the ability to provide extremely high data rates. Modern applications such as high-definition video streaming, virtual reality and real-time monitoring systems require data transmission speeds that can reach multiple gigabits per second. This demand is significantly higher than previous network generations and is driven by the rapid growth of data-intensive services. At the same time, 5G networks must support high data throughput not only per user but also per unit area, especially in environments with dense device populations such as smart warehouses or industrial facilities. This requirement leads to the need for advanced spectrum utilization techniques and wider bandwidth availability, particularly in higher frequency bands such as millimeter-wave (mmWave) spectrum [138].

Table 2
Candidate high-band frequencies.

ITU-R (IMT-2020 candidate bands) - Resolution 238 of WRC 2015 [4]	Allocated to mobile on primary basis?
24.25–27.5 GHz	Yes
31.8–33.4 GHz (Shared with the fixed service)	No
37–40.5 GHz (Shared with fixed-satellite service in 39.5–40 GHz in Region 1 and in 40–40.5 GHz worldwide. Shared with fixed service in 37–40 GHz)	Yes
40.5–42.5 GHz (Shared with fixed-satellite service in 40.5–42 GHz in Region 2. Shared with fixed service in 40.5–43.5 GHz)	No
42.5–43.5 GHz	Yes
45.5–47 GHz (Shared with space radio comm. in 43.5–47 GHz)	Yes
47–47.2 GHz	No
47.2–50.2 GHz (Shared with fixed satellite service in 47.5–47.9/48.2–48.54/49.44–50.2 GHz in Region 1, and in 48.2–50.2 GHz in Region 2. Band 48.94–49.04 GHz is forbidden for airborne stations.)	Yes
50.4–52.6 GHz (Shared with fixed service in 51.4–52.6 GHz)	Yes
66–76 GHz (Shared with space radio comm. in 66–71 GHz)	Yes
81–86 GHz	Yes

22Figure : Several Frequencies in 5G [138].

Another fundamental requirement of 5G technology is ultra-low latency. Many emerging applications, including autonomous vehicles, remote control systems and industrial automation, require near-instant communication between devices. In such scenarios, even small delays can lead to performance degradation or safety risks. 5G networks are designed to achieve latency levels as low as one millisecond, enabling real-time interactions and control. This is especially important in logistics environments and automated vehicles, drones, or robotic systems must respond immediately to dynamic conditions. The ability to maintain low latency across the entire communication process requires optimization at multiple levels, including radio access, network core and data processing infrastructure [244].

In addition to low latency, high reliability is a key technical requirement for 5G networks. Many applications supported by 5G are mission-critical, meaning that communication failures can have serious consequences. Examples include industrial control systems, remote operation of machinery and safety monitoring systems. To address this, 5G networks are designed to achieve extremely high levels of reliability, often exceeding 99.999% service availability. This ensures that data transmission is consistent and dependable, even in complex or high-interference environments. Reliability is achieved through advanced error correction techniques, redundant communication paths and intelligent resource allocation mechanisms [244].

A further important requirement is the support for massive device connectivity. Modern digital systems involve a large number of interconnected devices, including sensors, cameras, vehicles and automated systems. In logistics and supply chain environments, thousands of devices may need to communicate simultaneously within a limited area. 5G networks are designed to handle this high device density efficiently, ensuring that all connected devices can transmit and receive data without significant performance degradation. This capability is particularly important for large-scale operations such as smart ports, warehouses and transportation networks, where continuous data exchange is essential for operational efficiency [244].

The specific performance requirements of 5G networks vary according to the deployment environment and application scenario. While indoor hotspots and dense urban areas primarily require high throughput and network capacity, industrial and logistics environments place greater emphasis on ultra-low latency, reliability and communication service availability. In smart factories, warehouses and automated logistics systems, the timely delivery of data is often more important than maximum transmission speed. Applications such as motion control, autonomous vehicles, robotic systems and automated guided vehicles (AGVs) require communication delays of only a few milliseconds and extremely high reliability to ensure safe and uninterrupted operation. Furthermore, low-latency services are typically associated with geographically limited operational areas, where data processing and control functions are located close to the devices generating the data. These requirements highlight the need for distributed network architectures and edge computing capabilities within modern 5G infrastructures [70].

Beyond performance metrics, 5G networks also introduce significant architectural requirements. One of the most important innovations is network slicing, which allows the creation of multiple virtual networks within a single physical infrastructure. Each network slice can be customized to meet the specific requirements of a particular application or service. For example, a logistics application requiring ultra-low latency can operate on a dedicated slice optimized for real-time communication, while another application focused on data analytics may use a slice optimized for high throughput. This flexibility enables more efficient use of network resources and allows different services to coexist without interference [177].

Closely related to network slicing is the concept of network orchestration and automation. As 5G networks become more complex, manual management of network resources becomes impractical. Therefore, automated systems are required to dynamically allocate resources, manage network configurations and optimize performance based on real-time conditions. This includes the use of advanced software platforms that can control both the radio access network and the core network, as well as integrate edge and cloud computing resources. These capabilities are essential for supporting dynamic and scalable applications in logistics and supply chain systems, where network requirements may change rapidly depending on operational conditions [177].

Another key architectural requirement is the integration of edge computing. In many applications, especially those requiring real-time processing, it is not efficient to send all data to centralized cloud servers. Instead, data processing must occur closer to the source, at the edge of the network. This reduces latency and improves response times, enabling faster decision-making and more efficient system operation. In logistics environments, edge computing can support applications such as real-time tracking, automated decision systems and predictive maintenance. The integration of edge and cloud resources within the 5G architecture is therefore a critical requirement for achieving the full potential of the technology [177].

The use of high-frequency spectrum, particularly millimeter-wave bands, also represents an important technical requirement of 5G networks. These frequency bands provide the large bandwidth necessary to achieve high data rates, but they also introduce challenges such as limited coverage and higher signal attenuation. To address these issues, 5G networks require advanced technologies such as beamforming, dense network deployments and small cell architectures. These solutions allow the network to maintain high performance even in challenging environments, although they also increase the complexity of network design and deployment [138].

In addition to public network infrastructure, the deployment of private 5G networks is becoming increasingly important, particularly in industrial and logistics environments. Private 5G networks allow organizations to have greater control over network performance, security and configuration. They provide dedicated resources tailored to specific operational needs, ensuring consistent performance and enhanced data protection. For example, in a smart port or warehouse, a private 5G network can support autonomous vehicles, monitoring systems and communication between devices without relying on external network providers. This level of control and customization is essential for supporting critical operations and maintaining high levels of efficiency and security [244].

Finally, real-world applications such as teleoperation and automated vehicle systems highlight additional technical requirements related to user experience and system performance. Remote control of vehicles or machinery requires continuous high-quality video streaming, real-time feedback and uninterrupted connectivity. Any delay or loss of communication can significantly impact system performance and safety. Therefore, 5G networks must ensure stable connections, high bandwidth and minimal latency to support such applications effectively. These requirements demonstrate how technical specifications are directly influenced by the needs of advanced use cases, particularly in logistics and transportation systems [215].

In conclusion, the technical requirements of 5G networks are defined by a combination of high performance, flexibility and advanced architecture. Key requirements include high data rates, ultra-low latency, high reliability and support for massive device connectivity. In addition, innovations such as network slicing, automation, edge computing and private network deployment play a crucial role in enabling the effective operation of 5G systems. These capabilities are essential for supporting modern logistics and supply chain applications, where real-time communication, automation and data-driven decision-making are becoming increasingly important. As 5G technology continues to evolve, these technical requirements will form the foundation for the next generation of intelligent and interconnected systems [138][177][244][215].

5.2.2 Integration Requirements in Supply Chain and Logistics Systems

The integration of 5G technology within supply chain and logistics systems requires a comprehensive alignment between communication infrastructure, digital platforms and operational processes. Unlike traditional network integration approaches, 5G introduces a highly dynamic and service-oriented architecture that must seamlessly interconnect heterogeneous systems, devices and stakeholders across the entire logistics ecosystem. This integration is essential to support advanced use cases such as teleoperated transport, real-time coordination and intelligent decision-making, all of which demand high levels of synchronization, reliability and continuous data exchange [73].

A key integration requirement is the establishment of end-to-end connectivity across multiple layers of the supply chain. Modern logistics systems involve interactions between vehicles, infrastructure, control centers and cloud-based platforms. 5G enables this integration by supporting unified communication across radio access networks, transport networks and core network components. In teleoperated logistics scenarios, continuous communication between vehicles and remote operators requires the transmission of high-definition video streams, control commands and sensor data with minimal delay. This necessitates a tightly integrated network architecture capable of ensuring service continuity even in complex and distributed operational environments [73].

Another critical requirement is interoperability between different systems and network domains. Supply chains typically extend across multiple organizations, regions and network providers. Therefore, 5G integration must support seamless interoperability across heterogeneous infrastructures, including different mobile network operators and regulatory frameworks. The ability to ensure uninterrupted service across these domains is essential, particularly for applications such as automated transport systems and cross-border logistics operations. This requirement highlights the importance of standardized interfaces, shared communication protocols and coordinated network management strategies [73].

In addition, effective integration requires the coordination of multiple functional components and services within the logistics system. Advanced logistics operations rely on a variety of enabling functions such as real-time monitoring, route optimization, safety mechanisms and data analytics. These functions depend on the continuous exchange of data between system components and must operate in a synchronized manner. For example, real-time estimation of delivery times and dynamic scheduling require constant communication between vehicles, logistics platforms and terminal systems. Such coordination can only be achieved through a highly integrated 5G-enabled communication framework [73].

A further important aspect of integration is the support for modular and scalable system architectures. Modern supply chains increasingly rely on flexible operational models where resources and processes can be dynamically configured. 5G facilitates this approach by enabling modular system design, where different components—such as manufacturing systems, logistics operations and monitoring services—can be integrated as independent but interconnected modules. This modular integration improves flexibility, enhances resource allocation efficiency and allows rapid adaptation to changing operational conditions [156].

Moreover, the integration of computing resources plays a crucial role in overall system performance. Logistics systems generate large volumes of data that must be processed in real time. While centralized cloud computing provides significant processing power, it may introduce latency and bandwidth constraints. Therefore, integrated architectures combining edge, fog and cloud computing are required to ensure efficient data processing and distribution. These architectures allow tasks to be processed closer to the data source necessary, while still utilizing centralized resources for more complex computations. This layered integration is essential for maintaining high performance and responsiveness in logistics operations [264].

Another important requirement concerns resource management and task allocation within the network. In 5G-enabled logistics systems, tasks such as data processing, analytics and control operations must be dynamically distributed between devices, edge nodes and cloud platforms. This requires intelligent decision-making mechanisms that consider parameters such as latency, bandwidth availability, computational capacity and network conditions. Effective integration ensures that these decisions are made in real time, optimizing both system performance and resource utilization across the supply chain.

Security and data integrity also represent critical integration requirements. As logistics systems become more interconnected, the risk of cyber threats and data breaches increases. Therefore, 5G integration must incorporate robust security mechanisms, including authentication protocols, encryption techniques and secure communication frameworks. Ensuring data integrity and confidentiality is particularly important in logistics operations, where accurate and reliable information is essential for operational efficiency and decision-making [264].

Finally, the integration of 5G in supply chain and logistics systems must support real-time adaptability and system resilience. Logistics environments are highly dynamic, with frequent changes in demand, traffic conditions and operational constraints. Integrated 5G systems must be capable of responding to these changes in real time by adjusting network configurations, reallocating resources and maintaining uninterrupted service. This requires advanced network orchestration and automation capabilities, which enable the system to adapt to varying conditions without compromising performance [156].

In conclusion, the integration of 5G technology in supply chain and logistics systems involves a complex set of technical and operational requirements. These include end-to-end connectivity, interoperability across heterogeneous systems, coordination of multiple services, integration of distributed computing resources and robust security mechanisms. Additionally, scalable architectures and intelligent resource management are essential to support dynamic and data-intensive operations. These requirements form the foundation for the development of next-generation smart logistics systems, where real-time communication, automation and data-driven decision-making are critical for achieving high efficiency and operational excellence [73],[156],[264].

5.2.3 Operational and Emerging Challenges in 5G Adoption

5.2.3.1 Security Risk and System-Level Challenges in 5G Ecosystems

The rapid adoption of 5G technology significantly transforms communication infrastructures, but at the same time introduces critical security and system-level challenges. One of the most fundamental issues lies in the expansion of the attack surface, as 5G networks connect a vast number of devices, services and platforms. This increased connectivity leads to more complex system architectures, making networks more vulnerable to failures, misconfigurations and cyberattacks [224].

A key observation from ICT security analysis is that most incidents are not necessarily caused by external attacks but rather by internal system failures and human errors. Hardware failures, software bugs and operational mismanagement represent a large percentage of network disruptions. This highlights that ensuring system reliability and proper configuration is as important as defending against malicious actions [224]. In 5G environments, where virtualization and software-defined networking are dominant, these risks become even more critical.

Another major challenge concerns the security of the 5G supply chain. The deployment of 5G infrastructure depends on a global network of vendors, manufacturers and service providers. This creates a complex ecosystem where vulnerabilities can be introduced at multiple stages, including design, production and deployment. Supply chain attacks may involve sabotage, insertion of malicious components, data leakage, or system manipulation, which can compromise the entire network [217]. As a result, ensuring trust among stakeholders and implementing strict supplier evaluation processes becomes essential.

In addition, the evolution of 5G introduces new types of cyber threats. The high data transmission rates and low latency enable more sophisticated attacks such as distributed denial-of-service (DDoS), ransomware and large-scale data breaches. At the same time, the integration of cloud computing and edge technologies increases the number of access points that can be exploited by attackers. This requires advanced security mechanisms, including encryption, authentication, continuous monitoring and incident response strategies [217].

The digital transformation of supply chains further amplifies these risks. Modern supply chains operate in highly interconnected environments and data flows continuously between different entities. While 5G improves visibility and real-time decision-making, it also increases exposure to cyber threats. The lack of clear boundaries and the involvement of multiple partners create opportunities for attackers to intercept or manipulate data, leading to operational disruptions and financial losses [89].

Beyond cybersecurity, operational risks also emerge from the complexity of integrating multiple technologies. The success of 5G-enabled systems depends on the interaction between various technologies such as cloud platforms, data analytics and automation tools. However, these dependencies can create bottlenecks and vulnerabilities, especially when one component fails or is not properly integrated. This highlights the need for coordinated system design and robust interoperability standards [89].

Another important aspect is the challenge of ensuring data integrity, availability and confidentiality in 5G networks. These three pillars of information security become more difficult to maintain as networks become more distributed and dynamic. Critical components such as core network functions, virtualization layers and management systems must be protected against both internal and external threats. Any compromise in these areas can have severe consequences for the entire system [224].

Furthermore, emerging infrastructures such as space-based communication systems introduce additional security challenges. Satellite networks and space internet architectures extend 5G capabilities by providing global coverage, but they also create new vulnerabilities. These systems are difficult to defend due to their scale and distributed nature and they may be targeted through software supply chain attacks or network-level exploits. The lack of comprehensive testing environments further complicates the development of secure solutions [263].

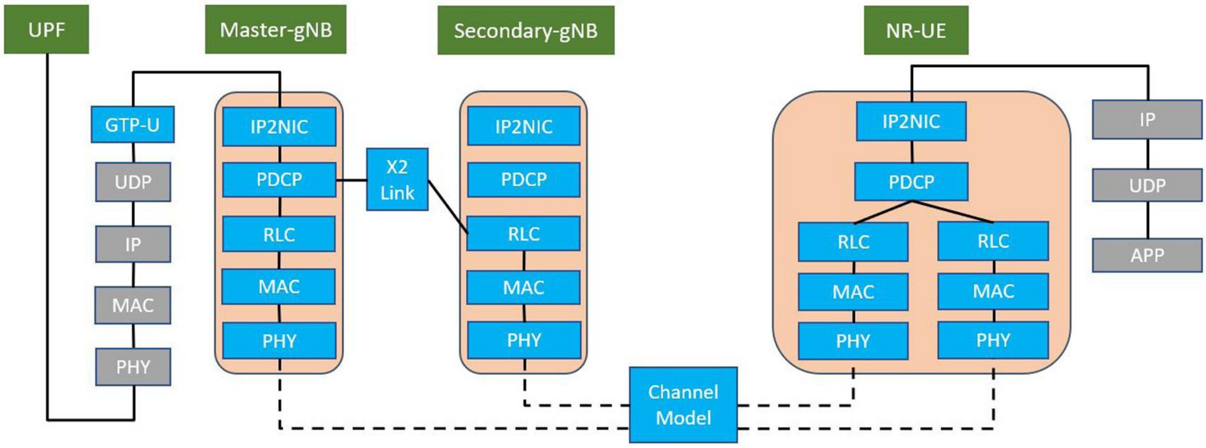
The integration of advanced technologies such as the metaverse and Industry 5.0 adds another layer of complexity. These environments require real-time interaction, high data processing capabilities and seamless connectivity between physical and digital systems. However, they also introduce new risks related to data privacy, system reliability and cyber-physical security. Ensuring secure and efficient operation in such environments remains a major research challenge [236].

In summary, security and system-level challenges in 5G ecosystems are multidimensional, involving technical, organizational and operational aspects. Addressing these challenges requires a comprehensive approach that combines technological innovation, strong governance frameworks and continuous risk management strategies.

5.2.3.2 Perfomance, Integration and Emerging Technological Challenges

In addition to security concerns, the adoption of 5G introduces significant challenges related to network performance, system integration and emerging technologies. Although 5G is designed to support high data rates, low latency and massive connectivity, achieving these performance targets in real-world environments remains complex.

One of the main challenges is related to network architecture and deployment. The use of millimeter-wave (mmWave) frequencies enables high data throughput but suffers from limited coverage and high signal attenuation. To overcome this limitation, 5G networks rely on ultra-dense deployments of small cells. However, this approach introduces new challenges such as increased interference, frequent handovers and higher energy consumption. Managing these factors effectively is essential for maintaining network performance and quality of service [272].



23Figure : Simu5G NR-DC Deployment with Packet Duplication [272].

Mobility management is another critical issue. In dynamic environments such as transportation systems or smart cities, maintaining stable connections while users move between network cells is difficult. Frequent handovers can lead to increased latency and packet loss, affecting the reliability of communication. Techniques such as multi-connectivity and packet duplication can improve performance, but they also increase resource usage and system complexity [272].

The integration of 5G into logistics and industrial systems also presents significant challenges. Smart logistics environments require real-time communication between devices, vehicles and systems, which demands high reliability and low latency. However, existing infrastructures may not be fully capable of supporting these requirements. Issues such as interoperability, scalability and high deployment costs can slow down the adoption of 5G in these sectors [97].
Beyond technical integration issues, several organizational and strategic factors influence the successful implementation of 5G technologies in supply chain environments. Biswas et al. [105] identify a range of critical success factors that determine whether organizations can effectively adopt and utilize 5G-enabled systems. These factors include spectrum availability, awareness of technological capabilities, workforce skill development, the availability of supporting digital technologies and the development of smart-city infrastructures. The study further emphasizes the importance of top management commitment, government and regulatory support, organizational culture and supply chain compatibility with high-technology operations. Although 5G offers substantial opportunities for enhancing visibility, connectivity and real-time decision-making, its successful deployment depends on the readiness of both technological and organizational infrastructures. Consequently, firms seeking to leverage 5G technologies must address not only technical performance requirements but also broader managerial, educational and policy-related challenges that influence digital transformation initiatives across the supply chain [105].

In industrial applications, such as the petrochemical sector, the challenges become even more critical. These environments require highly reliable communication systems to ensure safe and efficient operations. Traditional networks often fail to meet these requirements, while 5G introduces new opportunities but also raises concerns about network stability, interference and security. Any failure in communication systems can lead to serious operational and safety risks [231].

The integration of UAVs into 5G networks represents another important emerging challenge. UAVs are increasingly used in logistics, monitoring and emergency operations, benefiting from 5G's low latency and high-speed communication. However, UAV networks face challenges related to communication reliability, data freshness and security. Maintaining up-to-date information is critical for decision-making, especially in time-sensitive applications. At the same time, UAV systems are vulnerable to threats such as jamming, eavesdropping and interference, which can disrupt communication and compromise system performance [254].

From a communication perspective, UAVs also introduce challenges related to network coverage and resource allocation. Their mobility and dynamic positioning require adaptive network management strategies to ensure stable connectivity. The integration of UAVs with 5G networks must consider factors such as trajectory planning, interference management and coordination between multiple UAVs [243].

Energy efficiency and operational sustainability are also important considerations. UAV systems are limited by battery capacity, which restricts their operational time. Wireless charging technologies provide a potential solution by enabling automated energy replenishment without physical contact. However, these technologies introduce challenges related to efficiency, alignment and system design, particularly in lightweight UAV platforms [255].

Another emerging challenge is the development of advanced network management and orchestration mechanisms. The increasing complexity of 5G networks requires intelligent resource allocation and service management. Technologies such as network function virtualization (NFV) and service function chaining (SFC) enable flexible and scalable network operation, but they also introduce new challenges related to optimization, resource management and quality of service. Efficient placement and management of network functions are essential for maintaining performance and reducing operational costs [162].

Finally, the evolution toward next-generation communication systems, including 6G and beyond, introduces additional challenges and uncertainties. These future networks aim to support even more demanding applications, such as immersive virtual environments and fully autonomous systems. However, achieving these goals requires overcoming existing limitations in network performance, security and integration. The transition from 5G to next-generation technologies must therefore be carefully managed to ensure continuity and reliability [245].

Indicator	Priority Value
Priority	High: Battlefield real-time confrontations Medium: Training activities Low: Logistics devices
Availability	99.9999%
Delay	$<<1$
User rate	peak rate can approach 20 Gbps
Reliability	Weapon strike: 99.999% C2: 99.9% Service support: 99%
Mobility	High: >200 km/h Medium: $2 \sim 200$ km/h Low: <2 km/h
User density	High: $>10^4$ per km^2 Medium: $100 \sim 10^4$ per km^2 Low: <100 per km^2
Security	High: Classified Medium: Secretive Low: Unsecured
Energy efficiency	High: Weapon sensors Medium: Battlefield scenario Low: Remote operations

24Figure : Communication System [245].

In conclusion, performance, integration and emerging technological challenges represent critical barriers to the widespread adoption of 5G. Addressing these challenges requires continuous research and development, as well as the implementation of advanced technologies and innovative solutions. A holistic approach that considers both technical and operational aspects is essential for unlocking the full potential of 5G in supply chain and logistics systems.

5.3 5G Network Architecture and Core Components

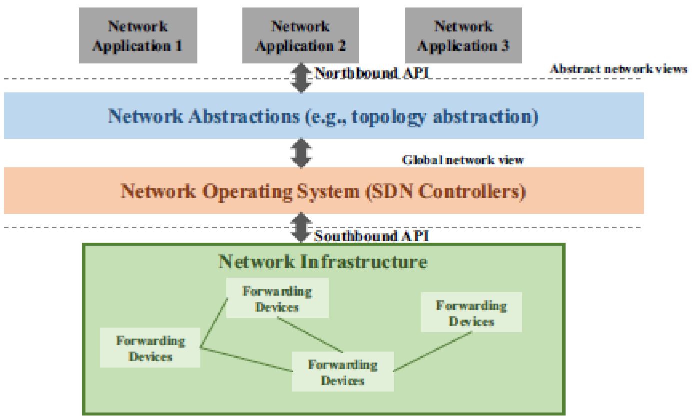
The architecture of 5G networks represents a significant shift from traditional mobile network designs, introducing a flexible, software-driven and service-oriented framework. Unlike previous generations, which relied on dedicated hardware and static configurations, 5G adopts a virtualized and cloud-native architecture that enables dynamic deployment, scalability and efficient resource utilization across multiple application domains [84].

At the core of this transformation lies the integration of Network Function Virtualization (NFV) and Software Defined Networking (SDN). NFV enables the decoupling of network functions from physical hardware, allowing them to run as software instances on general-purpose servers. This reduces infrastructure costs and enhances flexibility in service deployment. At the same time, SDN separates the control plane from the data plane, enabling centralized network management and programmability. This combination allows operators to dynamically allocate resources and optimize network performance based on real-time demand [139].

The 5G architecture is structured around three main components: the Radio Access Network (RAN), the transport network and the core network. The RAN provides wireless connectivity between user devices and the network and in 5G it evolves toward a more flexible and disaggregated model. Open-RAN approaches further enhance this flexibility by introducing open interfaces and enabling interoperability between vendors, reducing dependency on proprietary solutions [232].

The 5G core network (5GC) introduces a service-based architecture, where network functions operate as independent and modular services. These functions communicate through standardized interfaces, enabling scalability and rapid service deployment. This modularity allows operators to tailor network behavior according to specific application requirements, supporting diverse use cases such as ultra-low latency communications and massive IoT deployments [139].

A key innovation within 5G architecture is network slicing, which allows multiple virtual networks to be created on top of a shared physical infrastructure. Each slice is optimized for specific service requirements, such as high bandwidth, low latency, or high reliability. This capability is essential for supporting heterogeneous applications without the need for separate physical networks. Network slicing relies on the combined operation of SDN, NFV and cloud technologies to provide end-to-end service customization [139].



25Figure : SDN Architecture [139].

In addition, 5G architecture heavily relies on cloud-native principles and distributed computing. Network functions can be deployed across centralized cloud data centers and edge computing nodes, enabling low-latency communication and efficient data processing. As indicated in the architecture descriptions, orchestration platforms and lifecycle management tools play a critical role in coordinating these distributed resources and ensuring seamless service delivery.

Another important aspect of 5G architecture is the evolution of the physical layer, particularly with the adoption of advanced communication technologies such as Multiple-Input Multiple-Output (MIMO). MIMO and massive MIMO systems significantly improve network capacity and throughput by enabling multiple simultaneous data streams. However, these technologies introduce increased computational complexity, especially in software-based implementations. The processing requirements of 5G physical layer operations are substantially higher compared to previous generations, requiring efficient parallelization and optimized processing techniques.

The transition toward software-based and disaggregated architectures, such as Open-RAN, further enhances flexibility and innovation but also introduces implementation challenges. These include increased computational demands, synchronization issues and the need for efficient resource management. Despite these challenges, the benefits of openness, interoperability and scalability make such architectures a key component of modern 5G deployments [232].

Overall, the 5G network architecture is designed to provide a highly adaptable and efficient communication environment. By combining virtualization, programmability and advanced communication technologies, it enables the delivery of diverse services across multiple industries. This architectural evolution is essential for supporting the increasing complexity and performance requirements of next-generation digital systems.

5.3.1 5G Architecture for Logistics and Supply Chain Applications

The application of 5G architecture in logistics and supply chain systems focuses on enabling real-time communication, automation and precise coordination between different components such as vehicles, warehouses and control centers. Unlike traditional systems, where communication delays and limited connectivity reduce efficiency, 5G introduces a flexible and high-performance architecture that supports complex logistics operations across large geographic areas.

Recent developments in 5G architecture have also introduced the concept of Open Radio Access Network (Open RAN), which aims to increase flexibility, interoperability and resilience in communication infrastructures. Unlike traditional proprietary architectures, Open RAN separates hardware and software components through standardized interfaces, allowing equipment from multiple vendors to operate within the same network. This multi-vendor approach reduces dependence on single suppliers, facilitates system integration and supports more competitive and resilient 5G ecosystems. Furthermore, Open RAN incorporates advanced capabilities such as RAN Intelligent Controllers (RICs), AI-driven resource management, network slicing and digital twins for real-time monitoring and anomaly detection. These features enable more adaptive, programmable and intelligent network management, making Open RAN a promising architectural solution for future logistics and supply chain applications that require secure, scalable and highly interoperable communication infrastructures [184] This ensures that all logistics services can operate efficiently without interference..

One of the most important applications of 5G architecture in logistics is teleoperated transport. In modern supply chains, vehicles such as trucks, cranes and even ships can be remotely controlled from centralized control centers. This is possible because 5G networks provide ultra-low latency and high reliability, which are critical for real-time control. For example, teleoperation systems require continuous video streaming and instant response between the operator and the vehicle. Even small delays can affect safety and performance, so 5G enables these systems by maintaining latency at very low levels and ensuring stable communication even in complex environments [82].

In addition, 5G architecture supports advanced logistics operations such as automated docking, remote loading and unloading and cooperative vehicle movement. A typical logistics process may include multiple stages, from port operations to warehouse delivery. Through 5G connectivity, these stages can be interconnected into a unified system. For example, containers can be unloaded using teleoperated cranes, transferred to trucks and then transported in coordinated platoons to distribution centers. This integration improves efficiency, reduces delays and allows better coordination between different logistics actors [82].

Another key element of 5G architecture in logistics is positioning and tracking. Accurate and continuous positioning is essential for managing goods, vehicles and personnel throughout the supply chain. Traditional positioning technologies such as GNSS provide good performance in outdoor environments, but they are less effective indoors or in obstructed areas. To solve this problem, modern systems combine GNSS with 5G-based positioning. This hybrid architecture allows continuous tracking both indoors and outdoors, improving accuracy and reliability.

In such systems, 5G base stations provide positioning signals that complement GNSS data. When GNSS signals are weak or unavailable, 5G can take over and maintain positioning accuracy. This is especially important in warehouses, urban environments and complex logistics facilities where signal obstruction is common. The system can dynamically switch between GNSS and 5G positioning based on signal quality, ensuring continuous and reliable tracking of logistics assets.

Scheme	ISD	Accuracy	Cost	Maturity
GNSS	$\sim$ 40 km	$\sim$ 10m	Low	High
GNSS-RTK	$\sim$ 40 km	$<$ 1m	High	High
E-CID	0.4 $\sim$ 1 km	$\sim$ 60m	High	High
5G(UL-TDoA)	100m/20m	1 $\sim$ 3m	High	High
5G(Multi-RTT)	40 $\sim$ 140 m	$\sim$ 1m	High	Middle
5G(UL-AoA)	50 $\sim$ 60 m	$\sim$ 1m	High	Middle
Bluetooth	5 $\sim$ 10m	$<$ 1m	Middle	High
UWB	$\sim$ 20 m	$<$ 50cm	High	High
RFID	$\sim$ 10 m	$>$ 10m	Low	High

26Figure : Comparison between technologies [187].

Furthermore, the architecture of 5G enables intelligent decision-making through real-time data collection and processing. Positioning data, vehicle status and operational information are transmitted instantly to central systems, where they are analyzed to optimize logistics processes. For example, vehicle routing, warehouse operations and personnel management can be improved using real-time data. This leads to better resource allocation, reduced operational costs and improved service quality [187].

Recent studies on Warehouse 5.0 further highlight the role of UAVs as intelligent warehouse management tools supported by 5G communication networks. In these environments, UAVs equipped with computer vision technologies are used for inventory management, warehouse inspections, surveillance and operational monitoring. By utilizing onboard cameras and image-processing algorithms, UAVs can automatically identify, classify and track inventory items without requiring additional sensing infrastructures such as RFID tags. This approach improves inventory visibility while reducing the time and labor associated with manual stock inspections. The deployment of 5G networks is particularly important in such scenarios because the high bandwidth and ultra-low latency characteristics of 5G enable real-time transmission of high-definition video streams and operational data. Consequently, warehouse managers can receive immediate insights regarding inventory status, warehouse conditions and security events, while multiple UAVs can coordinate their activities simultaneously. The integration of UAVs, computer vision and 5G technologies therefore represents an important step toward autonomous warehouse operations and the broader Warehouse 5.0 vision, where logistics processes become increasingly intelligent, connected and data-driven [52].

Beyond logistics operations, 5G architecture also plays an important role in connecting logistics with manufacturing systems. In modern industrial environments, logistics is closely linked with production processes. Materials, products and equipment must be continuously tracked and coordinated across factories and supply chains. 5G enables this integration by supporting communication between machines, sensors and control systems in real time.

In collaborative intelligent manufacturing environments, 5G supports multiple types of communication, including machine-to-machine interaction, real-time monitoring and process automation. The architecture is often based on layered systems, where data is collected from devices, processed in edge or cloud systems and used for decision-making. This allows logistics and production systems to operate together as a unified digital ecosystem, improving efficiency and flexibility [168].

Another important feature of 5G architecture is the ability to support different types of services through network slicing. In logistics systems, different applications may have different requirements. For example, teleoperation requires ultra-low latency, while tracking systems may require high connection density. Through network slicing, the 5G network can create separate virtual networks optimized for each application. This ensures that all logistics services can operate efficiently without interference.

Recent research has further extended the application of 5G architectures through integrated experimentation platforms such as VITAL-5G, which was specifically designed to support innovation in transport and logistics. The platform combines 5G connectivity, cloud and edge computing resources, network slicing, virtualization technologies and programmable Network Applications (NetApps) within a unified architecture that enables the development, deployment and validation of logistics services. VITAL-5G has been implemented across multiple real-world testbeds, including the ports of Antwerp and Galati and the Athens logistics hub, where applications such as automated vessel transport, assisted navigation, warehouse automation and Automated Guided Vehicles (AGVs) are evaluated under realistic operating conditions. By providing standardized interfaces and reusable NetApps, the platform simplifies the deployment of advanced logistics applications while improving interoperability, scalability and efficient resource management across heterogeneous 5G environments [189].

Overall, the 5G architecture for logistics and supply chain applications provides a strong technological foundation for modern digital logistics systems. It enables real-time communication, accurate positioning, remote control and seamless integration between logistics and industrial systems. By combining these capabilities, 5G transforms traditional logistics into a more automated, intelligent and efficient system, supporting the growing demands of modern supply chains.

5.3.2 Performance Optimization and Real-World Implementation

Performance optimization is a critical aspect of 5G networks, especially in logistics systems where real-time communication, automation and reliability are essential. Unlike older communication technologies, 5G is designed to adapt dynamically to different application requirements. This means that the network can be optimized based on the type of service, such as real-time control, video transmission, or data collection, improving both efficiency and overall system performance.

In logistics environments, different applications have different communication needs. For example, tracking systems require stable connectivity for many devices, while teleoperation and autonomous vehicles require very low latency and high reliability. To address this, 5G uses advanced optimization techniques that analyze application traffic and adjust network parameters accordingly. This allows the system to provide the required Quality of Service (QoS) for each application, reducing delays, avoiding congestion and improving communication efficiency.

One of the most important tools for performance optimization in 5G is network slicing. Through this mechanism, the network is divided into virtual parts, each optimized for a specific use. For example, one slice can support high-bandwidth applications such as video streaming, while another slice supports ultra-reliable and low-latency communication for control systems. This separation ensures that critical logistics operations, such as remote vehicle control, are not affected by other network traffic [208].

Real-world implementation of 5G in logistics environments, such as ports and transportation systems, shows how these optimization techniques are applied in practice. In port environments, for example, 5G networks are used to support teleoperated vehicles, where operators control machinery remotely using real-time video and control signals. These systems require high data rates and extremely low latency to function safely. Measurements from real deployments show that 5G can meet these requirements by maintaining stable connections and ensuring fast response times even in complex industrial environments [252].

In addition, Multi-Access Edge Computing (MEC) plays an important role in improving performance. By processing data closer to the user, instead of sending it to distant cloud servers, MEC reduces communication delays and improves system responsiveness. This is particularly useful in logistics applications such as teleoperation, where immediate feedback is necessary for safe and efficient operation [252].

Another important aspect of performance optimization is the validation of 5G systems in real-world conditions. Unlike theoretical models, real environments include many challenges such as interference, obstacles and varying signal quality. For this reason, pilot projects and testing scenarios are used to evaluate how 5G performs in practice. These tests measure key performance indicators such as latency, reliability and bandwidth, ensuring that the network can support critical logistics operations under real conditions [212].

Another real-world example of 5G performance optimization is presented in cyber-physical vehicular logistics environments, where maintaining reliable wireless communication is essential for autonomous warehouse operations. Recent research has shown that optimizing radio propagation and path loss models significantly improves communication reliability for intelligent logistics vehicles operating in complex indoor environments. Using an Agile Gravitational Search Algorithm (AGSA), the proposed approach refines conventional path loss models to reduce signal attenuation and interference in heterogeneous 5G vehicular networks. Experimental validation conducted in warehouse logistics scenarios demonstrated improved signal quality, lower communication errors and more reliable connectivity for autonomous logistics vehicles, highlighting the importance of wireless network optimization for supporting real-time control, automation and efficient supply chain operations [216].

Another practical example of 5G performance optimization is presented by Lee et al. (2021), who developed a 5G-based Smart Logistics Cart for warehouse operations. The proposed system integrates a 5G communication module with cameras, RFID readers, barcode scanners, QR-code localization, IMU sensors and Enterprise Resource Planning (ERP) systems to support real-time warehouse activities. Through continuous 5G connectivity, warehouse operators receive dynamic picking instructions, navigation guidance and real-time inventory updates, while operational and video data are transmitted instantly to a central database. Experimental results demonstrated that the system successfully maintained reliable real-time communication and synchronized warehouse operations with the ERP platform, improving operational efficiency, reducing manual errors and supporting more responsive logistics processes. The study highlights how 5G enables practical warehouse automation by providing the low latency and high reliability required for intelligent logistics applications [175].

For example, in teleoperation scenarios, the network must support high-definition video transmission from vehicles to control centers, while also ensuring fast and reliable control commands. This requires a combination of high bandwidth, low latency and high reliability, which is difficult to achieve with older technologies. 5G is specifically designed to handle this combination, making it suitable for advanced logistics applications such as remote driving and automated transport systems [212].

Recent large-scale pilot projects further validate the performance capabilities of 5G in real logistics environments. The European 5G-Blueprint project demonstrated that private 5G Standalone (SA) networks combined with network slicing can successfully support teleoperated transport vehicles, intelligent traffic lights and Vulnerable Road User (VRU) awareness services within a unified communication infrastructure. Dedicated uRLLC slices ensured ultra-reliable and low-latency communication for vehicle control, while enhanced Mobile Broadband (eMBB) slices supported high-definition video transmission without compromising network performance. Field trials confirmed that the integration of network slicing with teleoperation enables stable, real-time communication for safety-critical logistics applications, demonstrating the practical benefits of 5G for intelligent transport and supply chain operations [253].

Finally, performance optimization in 5G is not only about technical improvements, but also about improving operational efficiency in logistics systems. By ensuring reliable communication, reducing delays and supporting automation, 5G helps companies improve productivity, reduce operational costs and enhance service quality. Real-world implementations demonstrate that optimized 5G networks can support complex logistics operations, making supply chains more flexible, intelligent and efficient.

5.3.3 5G-Enabled Supply Chain Transformation

The development of 5G technology has introduced significant changes in the way modern supply chains operate, especially in logistics systems where speed, reliability and real-time communication are essential. Compared to previous generations of communication technologies, 5G offers higher data transmission rates, ultra-low latency and the ability to connect a massive number of devices simultaneously. These features create the foundation for transforming traditional supply chains into more digital, connected and intelligent systems. As a result, supply chain operations are becoming more efficient, flexible and capable of responding to rapidly changing market demands [91].

One of the most important contributions of 5G is the improvement of connectivity across the entire supply chain. In traditional logistics systems, information often flows slowly between different stakeholders, creating delays and inefficiencies. With 5G, real-time communication becomes possible, allowing all participants in the supply chain to exchange information instantly. This reduces information gaps and enables better coordination between suppliers, manufacturers, distributors and retailers, improving overall system performance [206].

Last studies further demonstrate that one of the most significant contributions of 5G to supply chain transformation is the reduction of information transmission delays across different supply chain tiers. Traditional supply chains often experience fragmented information flows, where delayed communication between suppliers, manufacturers, distributors and retailers leads to forecasting errors, excessive inventory and the bullwhip effect. By enabling real-time synchronization of operational information and integrating technologies such as Artificial Intelligence (AI), Big Data, Internet of Things (IoT), Blockchain and Cloud Computing, 5G supports collaborative decision-making and improves coordination throughout the entire supply chain network [205].

At the same time, 5G supports the development of end-to-end visibility in supply chain operations. This means that products, processes and resources can be monitored continuously throughout the entire supply chain lifecycle. Real-time tracking of goods and logistics activities allows companies to identify problems early and respond quickly to disruptions. This level of visibility improves decision-making, reduces uncertainty and enhances the reliability of supply chain operations [95].

Another important aspect of 5G-enabled transformation is the support of smart logistics systems. With high-speed and reliable communication, logistics operations such as transportation, warehousing and distribution can be optimized and automated. This leads to faster processing times, reduced operational costs and improved productivity. In addition, the integration of 5G with logistics systems allows machines and digital platforms to communicate efficiently, supporting the development of intelligent logistics environments [176].

The role of 5G in automation is particularly important in modern logistics systems. By enabling real-time communication between devices, systems and control units, 5G allows automated processes to operate with high accuracy and coordination. This reduces the need for manual intervention and improves the efficiency of logistics operations, especially in large-scale and complex supply chain networks [182].

In transportation and distribution, 5G enables more efficient and intelligent systems. Vehicles and logistics infrastructure can communicate with each other in real time, allowing better route planning and dynamic adjustments during delivery operations. This improves delivery speed and reduces delays, while also optimizing the use of resources. As a result, transportation systems become more reliable and capable of adapting to changing conditions [206].

Another key benefit of 5G is the ability to support real-time data collection and analysis. Logistics systems generate large amounts of data from sensors, tracking devices and operational platforms. With 5G, this data can be transmitted quickly and processed efficiently, allowing companies to monitor system performance continuously. This enables better decision-making, improved planning and more effective resource management across the supply chain [218].

Real-time data also allows companies to move toward more predictive and intelligent supply chain management. By analyzing current and historical data, companies can forecast demand, identify potential risks and optimize logistics operations. This leads to more efficient supply chain planning and reduces the likelihood of disruptions or inefficiencies [147].

5G also plays an important role in supporting the development of cold chain logistics and sensitive goods transportation. In such systems, maintaining specific environmental conditions is critical for product quality and safety. With real-time monitoring enabled by 5G, companies can continuously track conditions such as temperature and humidity during transportation and storage. This improves control over logistics processes and reduces the risk of product damage or loss [95].

The growth of digital supply chains is closely connected with the capabilities of 5G technology. By enabling seamless communication between different systems and platforms, 5G supports the integration of logistics operations into unified digital environments. This allows companies to manage supply chain activities more efficiently and respond quickly to customer demands. As a result, supply chains become more agile and customer-oriented [91].

Recent experimental studies further demonstrate how 5G supports the practical transformation of digital supply chains through the deployment of private 5G-enabled Automated Guided Vehicle (AGV) testbeds. Such platforms integrate autonomous mobile robots, high-definition video streaming, Mobile Edge Computing (MEC) and real-time communication within smart factory environments to evaluate advanced logistics applications under realistic operating conditions. Beyond improving operational flexibility and wireless connectivity, these testbeds enable teleoperation, continuous monitoring, autonomous material handling and seamless interaction between logistics equipment and manufacturing systems. The findings indicate that 5G-based AGV platforms provide an effective technological foundation for intelligent, resilient and flexible supply chains while also supporting the digital transformation of small and medium-sized manufacturing enterprises (SMEs) [227].

In addition, 5G supports the development of new business models and supply chain structures. Traditional supply chains are evolving into more dynamic and interconnected networks, where different stakeholders collaborate in real time. This transformation creates new opportunities for innovation and allows companies to improve service quality and customer satisfaction [200].

The integration of 5G into industrial environments further enhances supply chain performance. In sectors such as manufacturing and smart logistics, 5G enables better coordination between production processes and logistics operations. This integration improves efficiency across the entire value chain and supports the development of more advanced and intelligent supply chain systems [140].

Moreover, 5G contributes to the digital transformation of logistics companies by improving operational efficiency and reducing costs. By enabling faster communication and better coordination, it helps companies optimize their processes and improve service delivery. This transformation is essential for companies that want to remain competitive in modern markets characterized by high demand and rapid technological change [182].

Another important aspect of 5G-enabled supply chains is the ability to support complex decision-making processes. With access to real-time data and advanced analytics, companies can make more informed decisions and respond quickly to changes in the market. This improves the overall performance of supply chain operations and enhances their ability to adapt to uncertainty [218].

The research has further demonstrated that the integration of 5G with Vehicular Edge Computing (VEC) and Artificial Intelligence enables more intelligent decision-making in connected logistics systems. By employing meta-reinforcement learning, computational tasks generated by connected autonomous vehicles can be dynamically offloaded to nearby edge servers according to network conditions and processing requirements. This adaptive task offloading reduces communication latency, improves resource utilization and enhances the responsiveness of logistics operations. As a result, 5G-enabled edge intelligence supports more efficient transportation management, autonomous vehicle coordination and real-time operational decision-making, contributing to the development of highly adaptive and intelligent supply chain ecosystems [256].

At the same time, 5G facilitates the connection between physical and digital systems, creating a more integrated and intelligent supply chain environment. This allows companies to monitor and control operations more effectively, improving both efficiency and reliability. The combination of physical logistics systems with digital technologies leads to the development of next-generation supply chains [147].

The role of 5G in supply chain transformation is also evident in global logistics networks. As supply chains become more complex and interconnected, the need for reliable and high-speed communication increases. 5G provides the necessary infrastructure to support global logistics operations, enabling better coordination between different regions and improving the overall performance of international supply chains [140].

Furthermore, the adoption of 5G technology supports the transition toward more sustainable supply chain systems. By improving efficiency and reducing waste, 5G contributes to more environmentally friendly logistics operations. This is particularly important in modern supply chains, where sustainability is becoming a key priority for companies and policymakers [200].

Finally, the impact of 5G on supply chain management extends beyond operational improvements. It also influences strategic decisions and long-term planning. Companies must adapt their business models and supply chain structures to take full advantage of 5G capabilities. This requires investment in new technologies, infrastructure and skills, but also creates opportunities for innovation and growth [207].

In conclusion, 5G technology plays a central role in transforming supply chain and logistics systems into more intelligent, connected and efficient networks. By enabling real-time communication, supporting automation and improving data-driven decision-making, 5G helps companies enhance their operational performance and adapt to the challenges of modern markets. As the adoption of 5G continues to expand, its impact on supply chain transformation will become even more significant, shaping the future of logistics and global supply networks.

5.3.4 5G-Driven Innovation and Emerging Business Models

The introduction of 5G technology is not only improving communication systems, but it is also creating new opportunities for innovation and new business models in logistics and supply chain management. With its ability to provide very fast data transmission, very low latency and high reliability, 5G enables companies to redesign how services are created, delivered and managed. As a result, logistics systems are moving from traditional models to more flexible, digital and service-oriented structures [213].

One of the key drivers of innovation in 5G environments is the ability to support a large number of connected devices and systems at the same time. This allows companies to collect and process large amounts of data in real time, which is essential for improving operational efficiency and decision-making. In logistics, this leads to better coordination between different actors in the supply chain and supports the development of more intelligent and automated systems [213].

A very important concept introduced with 5G is the idea of Network Applications (NetApps). These applications act as modular building blocks that simplify the development and deployment of services in logistics systems. Instead of dealing with the complexity of the network infrastructure, developers can focus on creating applications that directly support logistics operations. This reduces development time, lowers costs and allows faster innovation in the market [74].

Recent research further expands the NetApp concept by describing NetApps as modular, virtualized 5G-enabled applications that can be dynamically deployed, scaled, monitored and combined to create complex logistics and transportation services. Unlike traditional applications, NetApps are designed to interact directly with IoT sensors, cameras, gateways, Automated Guided Vehicles (AGVs) and other operational devices while remaining independent from the underlying network complexity. This abstraction enables logistics providers and service developers to create innovative digital services without requiring detailed knowledge of network slicing, virtualization mechanisms, or infrastructure management. Practical implementations in port logistics demonstrate how NetApps can integrate real-time sensor data, high-definition video streams and AI-based analytics to support assisted navigation, operational monitoring, safety improvements and logistics optimization. Such architectures illustrate how 5G enables the creation of flexible, service-oriented logistics ecosystems built around reusable digital service components [54].

At the same time, NetApps help bridge the gap between different stakeholders, such as network providers, software developers and logistics companies. By providing a common platform for service development, they enable better collaboration and integration across the entire ecosystem. This is particularly important in logistics, where many different systems and organizations must work together efficiently [203].

Another important innovation enabled by 5G is the use of edge computing and Edge Network Applications (EdgeApps). These applications process data closer to where it is generated, instead of sending everything to central cloud systems. This reduces delays and improves system responsiveness, which is critical for time-sensitive logistics operations such as transportation control and real-time monitoring. EdgeApps also help reduce network congestion and improve overall system performance [186].

The use of 5G testbeds and experimental platforms is also playing a key role in innovation. These platforms allow companies to test new applications and services in real environments, such as ports, warehouses and logistics hubs. By experimenting with different use cases, companies can better understand how 5G can improve their operations and identify new business opportunities. This accelerates the adoption of 5G technologies and supports the development of innovative logistics solutions [196].

In addition, 5G supports the creation of new business models based on digital services. Instead of focusing only on physical product delivery, companies can offer value-added services such as real-time tracking, predictive analytics and remote system management. These services improve customer experience and create new revenue streams for logistics providers. As a result, the role of logistics companies is evolving from simple service providers to digital solution providers [213].

Another important change introduced by 5G is the shift toward more flexible and scalable business models. With technologies such as network slicing, companies can create customized communication services tailored to specific logistics needs. This allows businesses to adapt quickly to changing requirements and operate more efficiently in dynamic environments. It also supports the development of specialized logistics services for different industries and applications [106].

5G also plays a key role in supporting innovation ecosystems. By enabling collaboration between different industries, technologies and stakeholders, it creates an environment where new ideas can be developed and implemented more easily. This includes collaboration between telecommunications companies, logistics providers, software developers and research institutions. Such ecosystems are essential for driving continuous innovation and technological progress in logistics systems [226].

At the same time, the adoption of 5G requires companies to rethink their strategies and invest in new capabilities. Factors such as infrastructure development, technology awareness, workforce skills and regulatory support play an important role in the successful implementation of 5G-based solutions. Without these elements, it becomes difficult for companies to fully benefit from the opportunities offered by 5G technology [71].

Another important aspect of 5G-driven innovation is the transformation of the telecommunications supply chain itself. Technologies such as Open RAN allow the creation of more open and flexible network architectures, where multiple vendors can collaborate. This reduces dependency on single suppliers and promotes competition and innovation in the market. It also improves the resilience and security of communication networks, which is critical for logistics operations [225].

Furthermore, 5G supports the development of more agile and adaptive production and logistics systems. Companies can respond more quickly to changes in demand, optimize resource usage and improve overall efficiency. This is particularly important in modern supply chains, where uncertainty and rapid changes are common. By enabling real-time communication and coordination, 5G helps companies become more resilient and competitive [225].

In the broader context, 5G is a key enabler of the hyper-connected digital economy. It connects different technologies such as artificial intelligence, cloud computing and advanced analytics, creating new possibilities for innovation. This leads to the development of new products, services and business models that were not possible before. As a result, industries including logistics are undergoing significant transformation and modernization [226].

Finally, the integration of intelligent systems, such as multi-agent systems, further enhances the impact of 5G on business models. These systems allow different components of the supply chain to operate autonomously while still coordinating with each other. This improves decision-making, increases efficiency and supports the development of fully automated logistics systems. 5G provides the communication infrastructure needed to connect and coordinate these intelligent systems effectively [262].

In conclusion, 5G is a key driver of innovation and new business models in logistics and supply chain management. It enables the development of advanced applications, supports real-time data processing and improves system integration and collaboration. By transforming how services are designed and delivered, 5G allows companies to create more efficient, flexible and intelligent logistics systems. As the technology continues to evolve, its role in shaping the future of supply chains and business models will become even more significant.

5.3.5 Security, Sustainability and Future Perspectives of 5G Supply Chains

The rapid development of 5G technology has significantly transformed modern supply chains, especially in logistics and industrial systems. While 5G enables high-speed communication, real-time data exchange and automation, it also introduces new challenges related to security, sustainability and long-term system evolution. These challenges arise from the increasing complexity of digital infrastructures, the integration of multiple technologies and the large number of connected devices within supply chain ecosystems [230].

One of the most important issues in 5G-enabled supply chains is data security and privacy. Logistics systems rely heavily on sensitive data such as customer information, delivery routes and operational processes. As shown in recent research, the use of fog computing and distributed systems increases the risk of data leakage and unauthorized access. highlights that logistics platforms must implement strong encryption, access control mechanisms and smart contract-based security solutions to protect data during transmission and processing. These approaches ensure that only authorized users can access critical information, reducing the risk of cyberattacks and data misuse [182].

ecent studies also emphasize the importance of integrating blockchain technology with RFID systems to strengthen security in 5G-enabled supply chains. Blockchain provides a decentralized and immutable ledger where RFID-generated information can be securely stored and shared among supply chain partners. This approach enhances traceability, prevents unauthorized modification of transaction records and improves trust between manufacturers, distributors and retailers. Furthermore, blockchain-based authentication protocols enable secure identification of RFID devices while reducing dependence on centralized authentication servers, making supply chain communications more resilient against cyberattacks and data manipulation [183].

At the same time, the increasing connectivity of devices in 5G networks expands the attack surface of supply chains. Modern ICT supply chains are global, complex and highly dependent on multiple stakeholders, including hardware manufacturers, software providers and network operators. explains that this complexity introduces vulnerabilities at different stages, such as design, manufacturing and distribution. Cyber threats may include malware injection, hardware tampering and supply chain attacks, which can compromise the reliability and integrity of the entire system. As a result, securing the entire lifecycle of the supply chain has become a critical requirement [230].

27Figure : ICT Supply Chain processes [230].

Another key challenge is legal and regulatory compliance. The adoption of 5G in supply chains is closely linked to cybersecurity laws and policies, especially in regions such as the European Union. shows that governments are increasingly focusing on risk assessment of suppliers, data protection regulations and national security considerations. These legal frameworks aim to ensure that 5G infrastructures are secure and resilient, but they also create challenges for companies that must comply with complex and evolving regulations [219].

In addition to security concerns, privacy protection in logistics operations is becoming increasingly important. 5G enables highly accurate tracking and positioning, which improves efficiency but also raises privacy risks. For example, trajectory data of vehicles and shipments can reveal sensitive business information, such as routes and operational strategies. explains that advanced techniques like differential privacy and data anonymization are required to protect such information while still allowing useful data analysis. This balance between data utility and privacy is essential for modern supply chains [211].

Another important aspect is the security of communication networks and user devices. In 5G environments, user equipment (such as sensors, vehicles and mobile devices) plays a critical role in data collection and communication. shows that these devices can become targets for cyberattacks, including spoofing, data interception and unauthorized access. The use of threat modeling frameworks helps identify vulnerabilities and develop countermeasures, ensuring that communication remains secure across the entire network [229].

Studies have also demonstrated the growing importance of Artificial Intelligence for protecting 5G-enabled cyber-physical supply chain systems against Distributed Denial of Service (DDoS) attacks. As modern logistics infrastructures increasingly rely on interconnected sensors, autonomous vehicles and industrial control systems, conventional intrusion detection techniques are often unable to cope with the large volumes and dynamic nature of 5G network traffic. To address this challenge, deep learning-based frameworks combining Point-Wise Activations, Steerable Convolutional Networks (PSCNs) and Circulatory System-Based Optimization (CSBO) have been proposed to identify malicious traffic patterns in real time. Experimental evaluation showed detection accuracy approaching 99.9%, demonstrating that AI-driven intrusion detection can significantly improve the security, resilience and operational continuity of 5G-enabled cyber-physical supply chain environments by rapidly detecting and mitigating evolving cyber threats [270].

As supply chains evolve towards Beyond 5G (B5G) and 6G systems, new challenges emerge related to software security and network integration. highlights that future networks will integrate technologies such as Low Earth Orbit (LEO) satellites, artificial intelligence and advanced communication protocols. While these technologies improve performance and global connectivity, they also introduce risks such as software vulnerabilities, fake nodes and data interception. Ensuring secure software development and end-to-end encryption becomes essential for maintaining system reliability [234].

Beyond security, sustainability has become a major concern in 5G-enabled supply chains. The increasing use of digital technologies leads to higher energy consumption, especially in data centers, communication networks and automated logistics systems. explains that smart logistics systems must include mechanisms for monitoring and reducing carbon emissions. By using data analytics and optimization models, companies can improve energy efficiency, reduce waste and minimize environmental impact [157].

Sustainability in supply chains is not limited to energy consumption but also includes resource optimization and lifecycle management. Modern logistics systems aim to reduce unnecessary transportation, improve route planning and optimize storage processes. These improvements are supported by 5G connectivity, which enables real-time monitoring and decision-making. As a result, supply chains become more efficient and environmentally friendly [170].

Another important trend is the use of machine learning and intelligent algorithms in 5G networks. These technologies help optimize network performance, reduce latency and improve resource allocation. For example, machine learning can be used to predict user behavior, optimize handovers between network cells and improve quality of service. shows that such approaches can significantly reduce network inefficiencies and improve overall performance [222].

Similarly, predictive algorithms can improve mobility management and communication efficiency in supply chains. demonstrates that logistic regression models can be used to optimize paging procedures and reduce signaling overhead in 5G networks. This leads to more efficient communication and lower energy consumption, which is important for large-scale logistics operations [218].

In advanced logistics applications, high-precision positioning and real-time communication are critical. shows that 5G signals can be used for accurate positioning even in environments where traditional GPS systems are not available. This capability is especially useful for autonomous delivery systems and UAV-based logistics, where precise navigation is required [240].

Moreover, the development of ultra-reliable low-latency communication (URLLC) supports critical logistics operations such as remote control, automation and real-time monitoring. explains that 5G networks must meet strict requirements in terms of latency, reliability and availability, especially in industrial environments. These requirements are essential for ensuring safe and efficient operations in modern supply chains [241].

Looking at the future, 5G supply chains are expected to evolve into fully integrated digital ecosystems. These ecosystems will combine communication networks, cloud computing, artificial intelligence and automation technologies. The goal is to create intelligent supply chains that can adapt to changing conditions, optimize operations in real time and provide high levels of efficiency and flexibility [173].

However, achieving this vision requires addressing several challenges, including security, interoperability and scalability. As systems become more complex, ensuring compatibility between different technologies and stakeholders becomes more difficult. At the same time, maintaining high levels of security and performance requires continuous innovation and investment [230].

In conclusion, 5G technology plays a key role in transforming supply chains, but it also introduces significant challenges. Security remains a critical issue, requiring advanced solutions such as encryption, access control and threat detection. Sustainability is equally important, as companies must reduce energy consumption and environmental impact. Finally, future developments in B5G and 6G technologies will create new opportunities but also new risks. Understanding and addressing these challenges is essential for building secure, efficient and sustainable supply chains in the digital era.

5.4 Interaction of 5G with UAV

5.4.1 UAV-Based Logistics and Supply Chain Applications

The integration of 5G technology with Unmanned Aerial Vehicles (UAVs) represents a major advancement in modern logistics and supply chain systems. UAVs require reliable, high-speed and low-latency communication to operate effectively, especially in applications such as autonomous delivery, real-time monitoring and remote coordination. Traditional communication networks, such as 4G, are often insufficient to support these requirements, particularly in scenarios involving high mobility and large-scale connectivity. In contrast, 5G networks provide enhanced data rates, ultra-low latency and the ability to support a massive number of connected devices, making them ideal for UAV-based logistics systems [178].

One of the key aspects of the interaction between 5G and UAVs is the ability to support high-speed drone operations. UAVs operating in logistics environments often move at high speeds, which introduces challenges such as Doppler shifts and signal interference. According to the analysis presented in, 5G communication systems must address these issues through advanced signal processing techniques, such as improved channel estimation and interference cancellation. These mechanisms ensure stable communication even under dynamic flight conditions, enabling drones to maintain reliable connections with base stations during high-speed movement [178].

In logistics applications, UAVs are increasingly used for autonomous delivery and transportation systems. These systems rely on continuous communication with control centers to receive navigation instructions, avoid obstacles and coordinate with other vehicles. The low latency of 5G networks allows real-time decision-making, which is critical for safe and efficient UAV operation. Furthermore, 5G enables the aggregation of data from multiple UAVs, supporting coordinated fleet management and improving overall logistics efficiency [178].

Another important application of 5G-enabled UAVs is in real-time monitoring and tracking within supply chains. UAVs can be equipped with sensors and communication modules to collect and transmit data related to location, environmental conditions and operational status. For example, in cold chain logistics systems, 5G connectivity supports continuous monitoring of temperature and humidity during transportation. As shown in, the use of advanced communication technologies enables real-time data transmission to centralized platforms, allowing better control and supervision of logistics processes [99].

The role of 5G is also critical in enabling intelligent and automated logistics infrastructures. UAVs can operate as part of a larger digital ecosystem that includes warehouses, transportation systems and control centers. Through 5G connectivity, data collected by UAVs can be processed in real time, enabling automated decision-making and dynamic optimization of logistics operations. This leads to improved efficiency, reduced operational costs and enhanced service quality [251].

Beyond logistics operations, 5G also supports the integration of UAVs into industrial production systems. As presented in, 5G-based architectures enable seamless communication between UAV production lines, manufacturing systems and supply chain components. Technologies such as network slicing and edge computing allow customized communication environments for different applications, ensuring reliable and efficient data exchange across all stages of the UAV lifecycle. This integration improves production efficiency, supports real-time quality control and enhances traceability in supply chain processes [251].

Number	Production status	Takt Time	Number of operators	One aircraft working hours	Efficiency improvement%
Branch-line vertical takeoff and landing (VTOL) unmanned aerial vehicle					
1	Previous homework methods	16h/ frame	8	128 person-hours	—
2	Conventional production mode after application of achievements	8h/ frame	6	48 person-hours	62.5%
3	Full speed production mode after application of achievements	2h/ frame	11	22 person-hours	82.8%
Tail-rotor unmanned aerial vehicles(UAVs)					
1	Previous homework methods	8h/ frame	2	16 person-hours	—
2	Conventional production mode after application of achievements	2.5h/ frame	4	10 person-hours	37.5%
3	Full speed production mode after application of achievements	0.2h/ frame	12	2.4 person-hours	85%

28Figure : Research Application Effects UAV [251].

In addition to industrial and logistics applications, UAVs supported by 5G are increasingly used in large-scale monitoring and distributed operations, such as agriculture and environmental management. The combination of UAVs with 5G networks enables real-time data collection over wide geographical areas, supporting applications that require fast response times and continuous monitoring. According to the paper with number [260], 5G provides the necessary communication infrastructure to support intelligent UAV operations, including real-time data processing, autonomous decision-making and efficient resource management. These capabilities can be transferred to logistics systems, where similar requirements exist for large-scale monitoring and coordination.

A key advantage of 5G in UAV-based supply chains is its support for massive connectivity and scalability. Modern logistics systems may involve large numbers of UAVs operating simultaneously. 5G networks are designed to handle such scenarios by supporting massive machine-type communications (mMTC), enabling efficient communication between multiple UAVs and control systems. This capability is essential for the development of drone fleets and large-scale autonomous logistics networks [260].

Moreover, the integration of 5G with UAVs enhances operational flexibility and responsiveness. Supply chains are often affected by dynamic conditions such as demand fluctuations, traffic congestion and environmental factors. UAVs, supported by 5G connectivity, can quickly adapt to these changes by rerouting deliveries, adjusting schedules and responding to real-time data. This level of flexibility improves the resilience and efficiency of supply chain operations [178].

Despite these advantages, the interaction between 5G and UAVs also introduces several challenges. Communication reliability must be maintained in highly dynamic environments, where signal conditions may change rapidly due to movement, obstacles, or interference. Additionally, ensuring secure communication between UAVs and network infrastructure is critical to prevent unauthorized access and cyberattacks. These challenges highlight the need for continuous research and development in 5G-enabled UAV systems [251].

In conclusion, the interaction between 5G and UAV technologies plays a crucial role in the evolution of modern logistics and supply chain systems. 5G provides the necessary communication infrastructure to support high-speed, reliable and scalable UAV operations. Through applications such as autonomous delivery, real-time monitoring and industrial integration, 5G-enabled UAVs contribute to more efficient, flexible and intelligent supply chains. At the same time, addressing technical and security challenges remains essential for the successful deployment of these systems in real-world environments [178].

5.4.2 UAV Systems, Digital Twins and Optimization Models

The integration of UAV systems with digital twin technologies and optimization models represents a significant advancement in modern logistics and supply chain management. In 5G-enabled environments, these technologies work together to provide real-time monitoring, predictive analysis and efficient decision-making. Digital twins allow the creation of virtual representations of physical logistics systems, while UAVs act as data collection and execution agents within these systems. The combination of these technologies enables more intelligent, adaptive and efficient logistics operations [104].

A key application of this integration is found in warehouse management systems supported by UAVs and digital twin platforms. In such systems, UAVs are used to collect real-time data related to inventory, storage conditions and operational activities. This data is transmitted through 5G networks to cloud platforms, where it is processed and reflected in a digital twin environment. The digital twin platform maintains a synchronized virtual model of the physical warehouse, allowing managers to monitor operations remotely and in real time. This bidirectional communication enables both visualization and control, significantly improving operational efficiency and reducing manual workload [104].

The use of 5G technology is essential in these systems, as it ensures low-latency and high-speed communication between UAVs, cloud platforms and digital twin environments. The rapid transmission of sensor data allows the digital twin to accurately reflect the current state of the warehouse, including UAV position, cargo status and system performance. Additionally, control commands can be sent back to UAVs in real time, enabling remote operation and automated task execution. This creates a closed-loop system where physical and virtual environments continuously interact [104].

Another important aspect of digital twin integration is the ability to support real-time visualization and anomaly detection. UAVs equipped with sensors can identify inconsistencies in inventory or operational errors during warehouse inspections. These anomalies are immediately reflected in the digital twin platform, allowing operators to respond quickly. For example, incorrect cargo placement or missing items can be highlighted visually in the virtual model, improving accuracy and reducing operational risks. This capability enhances both efficiency and reliability in logistics processes [2].

Beyond warehouse environments, digital twins play a critical role in complex UAV-based scenarios requiring cooperation and coordination. In advanced frameworks, UAVs collaborate to collect data and construct both local and global virtual models. These models are organized into multiple layers, including small-scale and large-scale digital twins, allowing for detailed local analysis as well as broader system-level optimization. This layered approach improves both the accuracy and responsiveness of digital twin systems [202].

A key advantage of cooperative digital twin systems is their ability to support real-time decision-making and adaptive optimization. UAVs can share data with neighboring units and cloud or edge computing systems, enabling continuous updates of digital models. Through mechanisms such as parameter adjustment and model transfer, the system can adapt to changing conditions, such as moving objects or dynamic environments. This allows UAVs to optimize their operations, including path planning, sensing strategies and task allocation [202].

Optimization models also play a crucial role in UAV-based logistics, particularly in route planning and delivery efficiency. The combination of UAVs and ground vehicles introduces new opportunities for optimizing logistics operations, especially in complex or emergency scenarios. Hybrid delivery systems that combine drones and vehicles can significantly reduce delivery time and improve service efficiency. These systems rely on mathematical optimization techniques to determine the most efficient routes and task allocation strategies [214].

One widely used approach in such optimization problems is the application of heuristic algorithms, such as simulated annealing. These algorithms are particularly effective in solving complex logistics problems where exact solutions are difficult to obtain due to computational constraints. By iteratively improving candidate solutions, simulated annealing can identify near-optimal delivery routes that minimize total travel time while considering constraints such as payload capacity and distance limitations. This approach is especially useful in emergency logistics scenarios, where fast and efficient delivery is critical [214].

The integration of optimization models with 5G-enabled UAV systems further enhances operational performance and flexibility. Real-time data collected by UAVs can be used to continuously update optimization models, allowing logistics systems to adapt to changing conditions. For example, route planning algorithms can adjust delivery paths based on real-time traffic, environmental conditions, or system constraints. This dynamic optimization capability improves both efficiency and responsiveness in supply chain operations [214].

Another important benefit of combining digital twins with optimization models is the ability to support predictive analytics and simulation-based decision-making. Digital twins can simulate different operational scenarios, allowing decision-makers to evaluate potential strategies before implementing them in the real world. This reduces risks and improves planning accuracy. UAVs contribute to this process by providing real-time data that enhances the accuracy of simulations and predictions [202].

Despite these advantages, the integration of UAV systems, digital twins and optimization models also introduces several challenges. One major challenge is the computational complexity associated with large-scale digital twin models and optimization algorithms. Managing and processing large volumes of data in real time requires significant computational resources, which may exceed the capabilities of individual UAVs. This issue is often addressed through cloud and edge computing solutions, but it remains an important consideration in system design [202].

Additionally, ensuring reliable communication and synchronization between physical and virtual systems is critical. Any delay or inconsistency in data transmission can reduce the accuracy of the digital twin and affect decision-making processes. The use of 5G networks helps mitigate these issues by providing high-speed and low-latency communication, but maintaining system reliability in complex and dynamic environments remains a challenge [104].

In conclusion, the integration of UAV systems with digital twins and optimization models represents a powerful approach to enhancing logistics and supply chain operations. 5G technology plays a central role in enabling real-time communication, data processing and system coordination. Through applications such as intelligent warehouse management, cooperative UAV systems and optimized delivery models, these technologies contribute to more efficient, flexible and intelligent logistics systems. At the same time, addressing challenges related to computational complexity and system reliability is essential for the successful implementation of these advanced solutions [104].

5.4.3 Communication, Network Performance and Infrastructure

The communication infrastructure that supports UAV operations in modern logistics systems is strongly dependent on the capabilities of 5G and beyond networks. These networks are designed to provide high data rates, low latency and reliable connectivity, which are essential for UAV-based applications such as delivery, monitoring and real-time coordination. However, achieving efficient communication between UAVs and ground networks requires careful design of network architecture, positioning strategies and performance optimization mechanisms [243].

One of the key approaches to improving network performance in UAV-assisted systems is the use of drones as dynamic communication nodes. UAVs can act not only as delivery agents but also as relay nodes within the network, helping to offload traffic from congested base stations. By adjusting their position and altitude, UAVs can establish better line-of-sight communication links with base stations and users, thereby increasing network throughput and reducing interference. This flexible positioning capability makes UAVs valuable components of next-generation communication infrastructures [103].

The optimization of UAV placement in three-dimensional space is a critical factor in enhancing network performance. Advanced algorithms, such as trajectory and altitude optimization methods, enable UAVs to dynamically adapt their position based on network conditions. These algorithms consider factors such as congestion levels, signal strength and energy consumption to determine optimal flight paths. As a result, UAVs can improve both communication efficiency and logistics performance simultaneously, creating a dual-function system that supports both data transmission and physical delivery [103].

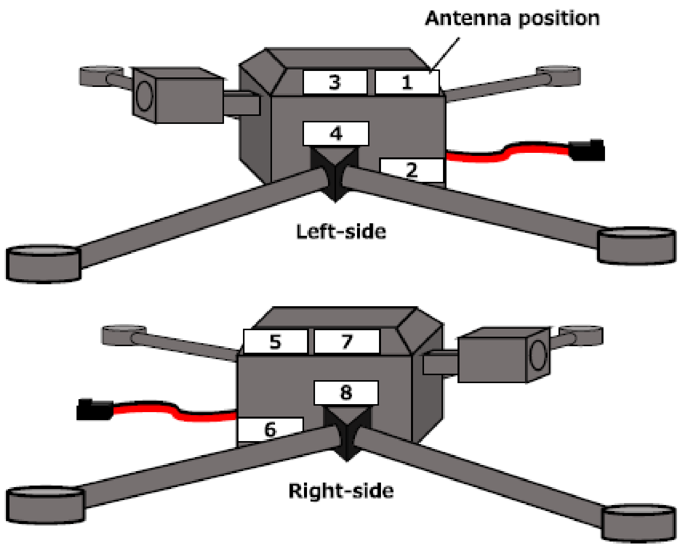
In addition to outdoor communication, indoor UAV operations introduce additional challenges, particularly in terms of localization and signal coverage. While 5G networks provide strong outdoor connectivity, their performance may degrade in indoor environments due to obstacles and signal attenuation. To address this issue, hybrid communication architectures have been proposed, combining 5G with Wi-Fi-based systems. These systems use strategically placed Wi-Fi access points to enhance indoor positioning accuracy and maintain reliable communication for UAV navigation [250].

The integration of multiple radio access technologies (multi-RAT) allows UAVs to seamlessly switch between communication systems depending on the environment. For example, UAVs may rely on 5G networks during outdoor flight and transition to Wi-Fi-based systems when operating indoors. This approach ensures continuous connectivity and accurate localization throughout the UAV's mission. The performance of such systems depends heavily on the optimal placement of access points, as poor geometric configurations can significantly reduce positioning accuracy [250].

Another important aspect of UAV communication systems is the impact of electromagnetic interference (EMI) on network performance. UAVs contain multiple electronic components that can generate emission noise, which may interfere with communication signals. Studies have shown that this noise can significantly degrade receiver sensitivity, reducing the quality and reliability of wireless communication. In some cases, the performance degradation can be substantial, affecting both LTE and 5G communication systems [248].

Electromagnetic shielding, while intended to protect internal components, can also negatively affect signal transmission by attenuating communication signals. This creates a trade-off between protecting

UAV electronics and maintaining strong communication links. As a result, careful design and testing of UAV hardware are required to ensure that communication performance is not compromised. Addressing EMI-related challenges is essential for safe and reliable UAV operations, especially in urban and industrial environments where signal conditions are already complex [248].



29Figure : Antenna points for evaluation of EMI with LTE communication systems [248].

Beyond physical communication challenges, the integration of UAVs into 5G and B5G networks introduces new requirements for advanced communication technologies. These include the use of smart antennas, beamforming techniques and high-frequency communication such as millimeter-wave (mmWave). These technologies improve spectral efficiency, increase data rates and enable more precise signal transmission. However, they also introduce new challenges, such as sensitivity to mobility and alignment issues, which must be carefully managed in UAV applications [243].

Machine learning and artificial intelligence are increasingly used to enhance communication performance in UAV networks. These technologies enable UAVs to make autonomous decisions regarding routing, resource allocation and interference management. By analyzing real-time data, AI-based systems can optimize communication parameters and improve overall network efficiency. This is particularly important in dynamic environments where network conditions change rapidly [243].

Security and privacy are also critical concerns in UAV communication systems, especially in B5G networks. UAVs collect and transmit large amounts of data, including sensitive information related to logistics operations and user activities. This makes them vulnerable to cyber-attacks, data breaches and unauthorized access. Ensuring secure communication requires the implementation of advanced security mechanisms, such as encryption, authentication protocols and blockchain-based solutions [257].

Moreover, the use of AI and machine learning in UAV systems introduces additional security risks, such as adversarial attacks and data manipulation. Attackers may exploit vulnerabilities in AI models to disrupt UAV operations or gain access to sensitive information. Therefore, secure AI frameworks and robust data protection mechanisms are necessary to ensure the reliability and safety of UAV communication systems [257].

The overall performance of UAV communication networks depends on the integration of multiple factors, including infrastructure design, communication technologies and system optimization strategies. A well-designed network must balance coverage, capacity, latency and energy efficiency while ensuring reliability and security. This requires a holistic approach that considers both the physical and digital aspects of UAV systems [103].

In conclusion, communication and network performance play a central role in the successful deployment of UAV-based logistics systems. 5G and B5G technologies provide the necessary foundation for high-performance communication, while advanced optimization techniques and hybrid network architectures enhance system efficiency. At the same time, challenges related to interference, localization and security must be addressed to ensure reliable and scalable UAV operations. The continuous evolution of communication technologies will further strengthen the role of UAVs in future smart logistics and supply chain systems [243].

5.5 Interaction of 5G with AI

5.5.1 AI Applications in Supply Chain and Logistics

The integration of Artificial Intelligence (AI) with 5G technology is transforming modern supply chain and logistics systems by enabling smarter decision-making, real-time data processing and higher levels of automation. 5G provides the communication infrastructure, while AI acts as the "intelligence layer" that analyzes data and optimizes operations. Together, they create highly responsive and adaptive logistics systems that can operate efficiently even in complex and dynamic environments [95].

One of the most important applications of AI in logistics is the ability to process large volumes of real-time data. Through 5G connectivity, data from different parts of the supply chain—such as transportation, warehousing and distribution—can be collected instantly. AI algorithms analyze this data to support decision-making processes such as route optimization, demand forecasting and inventory management. This combination allows supply chains to become more flexible and responsive to changes in demand or disruptions [95].

In logistics operations, AI is widely used to improve monitoring and control systems. For example, in cold chain logistics, AI-based systems can track temperature, humidity and product conditions in real time. These systems use data collected from sensors and communication technologies to ensure product quality and reduce losses during transportation. The integration of intelligent monitoring systems allows companies to detect problems early and take corrective actions, improving both efficiency and reliability [25].

AI also supports the development of advanced tracking and identification mechanisms in supply chains. By combining data from multiple sources, AI can create a complete view of the product lifecycle, from production to delivery. This enables better traceability and transparency, which are critical for industries such as food logistics and pharmaceuticals. Real-time tracking systems can also help optimize logistics processes and reduce delays [25].

Another important application of AI is in the optimization of last-mile delivery, especially in rural or hard-to-reach areas. The use of AI together with 5G-enabled UAVs (drones) allows for intelligent route planning and delivery scheduling. These systems can analyze factors such as distance, terrain and demand patterns to determine the most efficient delivery method. This helps solve the "last mile" problem, which is one of the biggest challenges in logistics systems [209].

In such scenarios, AI algorithms can evaluate multiple variables and select the best delivery strategy. For example, decision-making models such as the Analytic Hierarchy Process (AHP) can be used to analyze different factors that affect logistics performance, including infrastructure, cost and environmental conditions. By combining these models with real-time data from 5G networks, logistics systems can become more adaptive and efficient [209].

AI also plays a key role in enabling intelligent service management in logistics systems. In modern 5G environments, large amounts of data must be processed quickly and efficiently. Edge computing, combined with AI, allows data to be processed closer to where it is generated, reducing latency and improving system performance. This is particularly important in time-sensitive logistics operations, where delays can lead to significant losses [170].

One advanced approach in this area is the use of federated learning and collaborative caching mechanisms. These technologies allow multiple edge nodes to share data and learn from it without transferring sensitive information to a central system. As a result, logistics systems can improve data processing efficiency while maintaining data privacy and security. This approach also reduces network congestion and improves overall system scalability [170].

In addition, AI techniques such as machine learning and predictive analytics are used to improve logistics service quality. By analyzing historical data and real-time information, AI systems can predict future demand, identify potential disruptions and optimize resource allocation. This leads to better planning and more efficient use of logistics infrastructure [95].

Another important benefit of combining AI with 5G is the ability to support autonomous and semi-autonomous systems. These include autonomous vehicles, drones and robotic systems used in warehouses and transportation. AI enables these systems to make decisions independently, while 5G ensures fast and reliable communication between devices. This creates highly automated logistics systems that require minimal human intervention [209].

Furthermore, AI contributes to improving customer experience in logistics services. By analyzing customer data and preferences, AI systems can provide personalized services, optimize delivery times and improve service reliability. Real-time communication through 5G networks allows customers to track their orders and receive updates instantly, increasing transparency and satisfaction [95].

However, the integration of AI and 5G also introduces challenges. These include the need for high computational resources, data privacy concerns and the complexity of managing large-scale intelligent systems. Ensuring the security and reliability of AI-driven logistics systems is essential, especially when dealing with sensitive data and critical operations [170].

In conclusion, the interaction between 5G and AI is a key factor in the development of modern intelligent logistics systems. 5G provides the necessary connectivity and speed, while AI enables advanced data analysis and decision-making. Together, they support real-time monitoring, automation and optimization across the entire supply chain. As these technologies continue to evolve, they will play an even more important role in shaping the future of logistics and supply chain management [95].

5.5.2 AI Models and Optimization in 5G-Enabled Systems

Artificial Intelligence (AI) models play a critical role in optimizing the performance of 5G-enabled systems, particularly in complex environments such as logistics networks and real-time communication infrastructures. The combination of AI techniques with 5G connectivity enables the development of intelligent systems that can analyze large datasets, predict system behavior and optimize decision-making processes in real time.

One of the fundamental applications of AI in 5G-enabled logistics systems is predictive modeling. In modern supply chains, demand and transportation volumes are highly dynamic and influenced by various factors such as seasonal changes, unexpected disruptions and customer behavior. AI-based forecasting models, such as ARIMA and probabilistic methods, are used to predict traffic volumes across logistics routes. These predictions allow logistics operators to plan transportation and resource allocation more efficiently, reducing delays and improving operational performance [180].

In addition to prediction, optimization models are essential for managing logistics networks. AI algorithms such as genetic algorithms, simulated annealing and multi-objective optimization techniques are widely used to determine optimal routing strategies, load balancing and resource allocation. These models consider multiple constraints, including transportation capacity, cost and service quality and aim to find solutions that improve overall system efficiency. In 5G environments, where real-time data is available, these optimization processes can be continuously updated, enabling adaptive and dynamic logistics management [180].

A key advantage of using AI in 5G-enabled systems is the ability to support multi-objective decision-making. In logistics networks, decisions often involve trade-offs between different objectives, such as minimizing cost, reducing delivery time and maintaining service reliability. Multi-objective optimization models allow these competing factors to be analyzed simultaneously, providing balanced solutions that improve overall system performance. For example, optimization models can determine whether to open or close specific logistics routes based on demand patterns and network conditions, ensuring efficient flow of goods across the network [180].

Another important aspect of AI in 5G systems is network performance optimization. Machine Learning (ML) models are used to analyze network Quality of Service (QoS) parameters such as latency, throughput and packet loss and to predict the Quality of Experience (QoE) perceived by users. By learning from historical data, these models can estimate user satisfaction levels and adapt network behavior accordingly. This is particularly important in applications such as video streaming, real-time communication and remote logistics operations, where maintaining high service quality is critical [261].

ML-based models also enable intelligent resource management in 5G networks. By analyzing real-time network conditions, AI systems can dynamically allocate bandwidth, adjust transmission parameters and optimize traffic flows. This ensures efficient utilization of network resources and reduces congestion, especially in high-demand scenarios. The ability to predict network conditions and adapt accordingly is a key advantage of integrating AI into 5G systems [261].

Furthermore, AI models contribute to improving system reliability and robustness. In dynamic environments such as logistics networks, disruptions can occur due to equipment failures, network congestion, or external events. AI-based optimization models can quickly identify alternative routes and adjust system parameters to maintain normal operation. This adaptability is essential for ensuring continuous service in critical logistics applications [180].

Another significant contribution of AI in 5G-enabled systems is the evaluation and ranking of system components. Techniques such as entropy-based weighting and multi-criteria decision-making models (e.g., TOPSIS) are used to assess the importance of different logistics nodes and routes. These methods help identify critical components within the network and support better planning and optimization strategies. By understanding which parts of the system are most important, operators can prioritize resources and improve overall system efficiency [180].

In addition, AI supports the development of intelligent control systems that can operate autonomously. These systems use real-time data and predictive models to make decisions without human intervention. For example, AI-driven logistics systems can automatically adjust transportation routes, manage inventory levels and coordinate operations across multiple nodes. The integration of these capabilities with 5G networks enables fast and reliable communication, which is essential for real-time decision-making.

However, the implementation of AI models in 5G-enabled systems also introduces challenges. These include the need for high computational power, efficient data processing and reliable communication infrastructure. Ensuring the accuracy and reliability of AI models is also critical, as incorrect predictions or decisions can negatively impact system performance. Additionally, the integration of AI with 5G requires careful system design to ensure scalability and interoperability.

In conclusion, AI models and optimization techniques are key enablers of efficient and intelligent 5G-enabled systems. By combining predictive analytics, optimization algorithms and real-time data processing, these technologies support improved decision-making, enhanced system performance and greater operational flexibility. As 5G networks continue to evolve, the role of AI in optimizing logistics and communication systems will become increasingly important, enabling the development of more advanced and autonomous supply chain solutions [261].

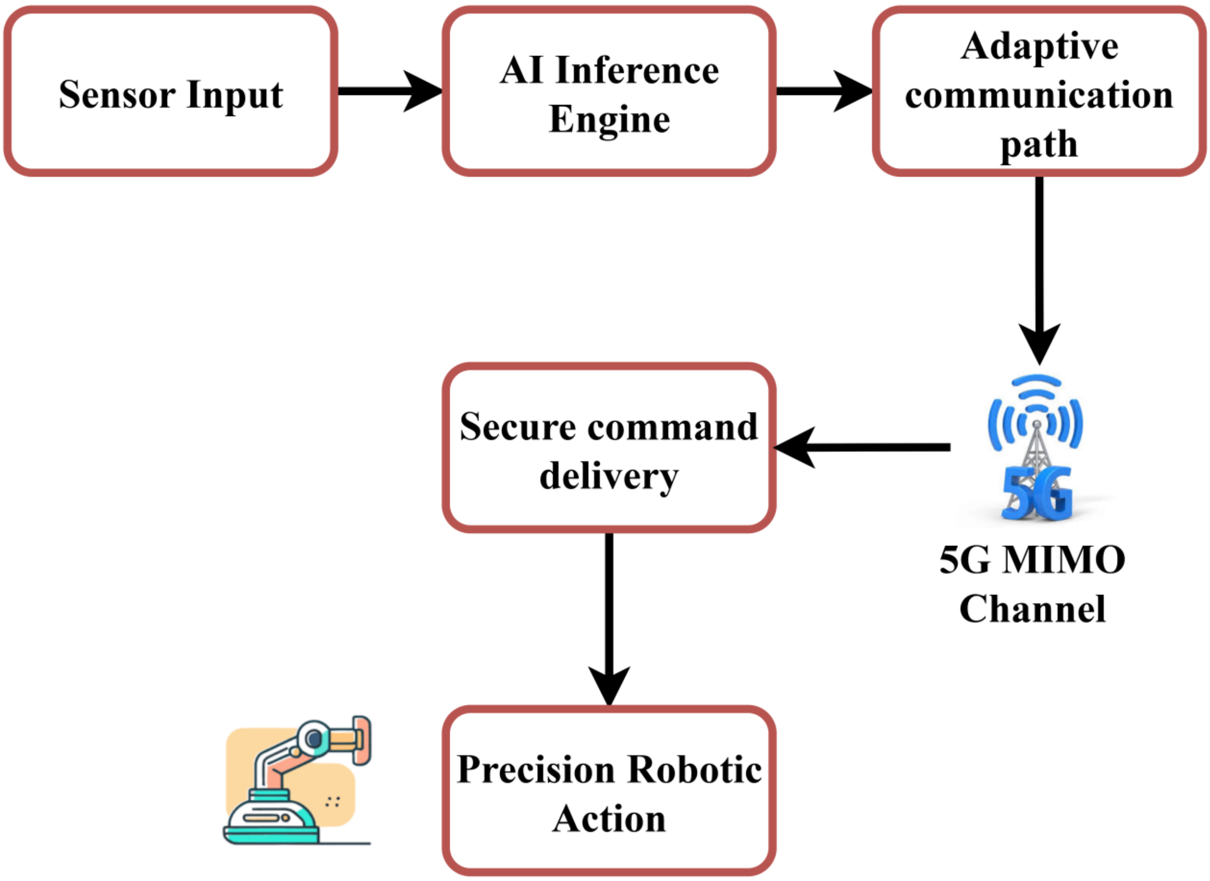
5.5.3 Smart Systems, Architecture and Future AI Integration

The integration of Artificial Intelligence with 5G networks leads to the development of smart systems that are capable of autonomous operation, real-time decision-making and efficient resource management. These systems are built on advanced architectures that combine communication infrastructure, data processing capabilities and intelligent algorithms. The combination of these elements enables the creation of highly adaptive and scalable environments that support modern logistics, industrial automation and smart agriculture.

A key characteristic of smart systems is the use of advanced architectural frameworks that integrate 5G connectivity with AI-driven services. In such architectures, different system components—including sensors, drones, robots and control platforms—are connected through a unified communication network. The use of private and public 5G networks allows for flexible deployment, especially in remote or complex environments. These architectures are designed to support real-time data collection, processing and analysis, enabling systems to respond quickly to changing conditions. For example, smart agricultural architectures combine drones, robots and edge computing to create intelligent environments where decisions are based on real-time data and AI analysis.

Another important element of smart system architecture is the use of edge computing. Instead of sending all data to centralized cloud servers, data processing is performed closer to the data source, reducing latency and improving system responsiveness. This is particularly important in applications that require immediate decision-making, such as autonomous vehicles, robotics and real-time logistics operations. Edge computing, combined with 5G, enables ultra-low latency communication and supports time-critical applications where delays can negatively affect system performance [233].

Artificial Intelligence plays a central role in these architectures by enabling intelligent data processing and automation. AI models analyze large volumes of data collected from sensors, drones and other devices and generate insights that support decision-making. For example, AI can be used to monitor environmental conditions, detect anomalies and optimize operational processes. In smart agriculture, AI models process images and sensor data to evaluate crop health, optimize irrigation and improve resource utilization. This combination of AI and 5G enables systems to operate more efficiently and with higher accuracy [269].



30Figure : Flow of intelligence: from perception to precision [269].

In addition to decision-making, AI also enhances communication performance within 5G networks. Advanced frameworks integrate AI with technologies such as MIMO (Multiple-Input Multiple-Output) to improve signal transmission, reduce interference and optimize network performance. AI-driven signal processing techniques dynamically adjust communication parameters, ensuring reliable and efficient data transmission even in complex environments. This is especially important in industrial and robotic systems, where precise and stable communication is required for safe and effective operation.

Furthermore, AI contributes to the development of secure and resilient systems. In 5G environments, cybersecurity is a major concern due to the large number of connected devices and the complexity of network architectures. AI-based security mechanisms can detect anomalies in network traffic, identify potential threats and respond to cyber-attacks in real time. These capabilities enhance system reliability and protect critical operations from disruptions. The integration of AI with secure 5G communication frameworks ensures that smart systems can operate safely even in dynamic and unpredictable environments [269].

Another important aspect of smart systems is automation. AI-enabled systems can operate autonomously, reducing the need for human intervention. For example, robotic systems connected through 5G networks can perform complex tasks such as transportation, monitoring and maintenance. These systems rely on real-time data and AI algorithms to make decisions and adapt to changing conditions. The combination of automation and 5G connectivity enables faster and more efficient operations, particularly in industrial and logistics environments.

The integration of AI with 5G also supports the development of sustainable systems. Smart architectures are designed to optimize resource usage, reduce energy consumption and minimize environmental impact. In Agriculture 4.0, for example, 5G-enabled systems support efficient irrigation, precision farming and real-time monitoring of environmental conditions. AI models help optimize these processes by analyzing data and providing recommendations that improve efficiency and sustainability. This leads to reduced waste, lower energy consumption and more environmentally friendly operations.

Moreover, future AI integration in 5G systems will focus on increasing system intelligence and autonomy. Emerging technologies such as machine learning, deep learning and generative AI will enable systems to learn from data, adapt to new conditions and improve their performance over time. These technologies will support more advanced applications, including autonomous logistics networks, smart cities and intelligent industrial systems. The continuous evolution of AI and 5G will lead to more complex and capable systems that can operate with minimal human intervention [260].

Finally, the combination of AI, 5G and advanced system architectures creates new opportunities for innovation. Smart systems can support new business models, improve operational efficiency and enable the development of new services. The integration of these technologies will continue to transform industries such as logistics, manufacturing and agriculture, leading to more intelligent, connected and sustainable systems in the future.

6. Technology 6G

6.1 Introduction to 6G

6G technology represents the next stage in the evolution of wireless communication systems, aiming to significantly extend the capabilities introduced by 5G. While 5G focuses on high-speed connectivity and reduced latency, 6G is designed to create a fully integrated digital ecosystem where communication, computing and intelligence operate together. This new generation of networks is expected to support not only human communication but also seamless interaction between machines, digital systems and physical environments, enabling more advanced and autonomous operations across multiple industries [178].

A fundamental vision of 6G is the convergence of the physical, digital and human worlds into a unified environment. In this context, communication networks will evolve from simple data transmission infrastructures into intelligent systems capable of real-time sensing, processing and decision-making. Technologies such as Digital Twins play a key role in this transformation, as they enable the creation of virtual representations of physical systems that can be monitored, analyzed and controlled continuously. This allows organizations to improve operational efficiency, predict system behavior and optimize resource utilization in real time [110].

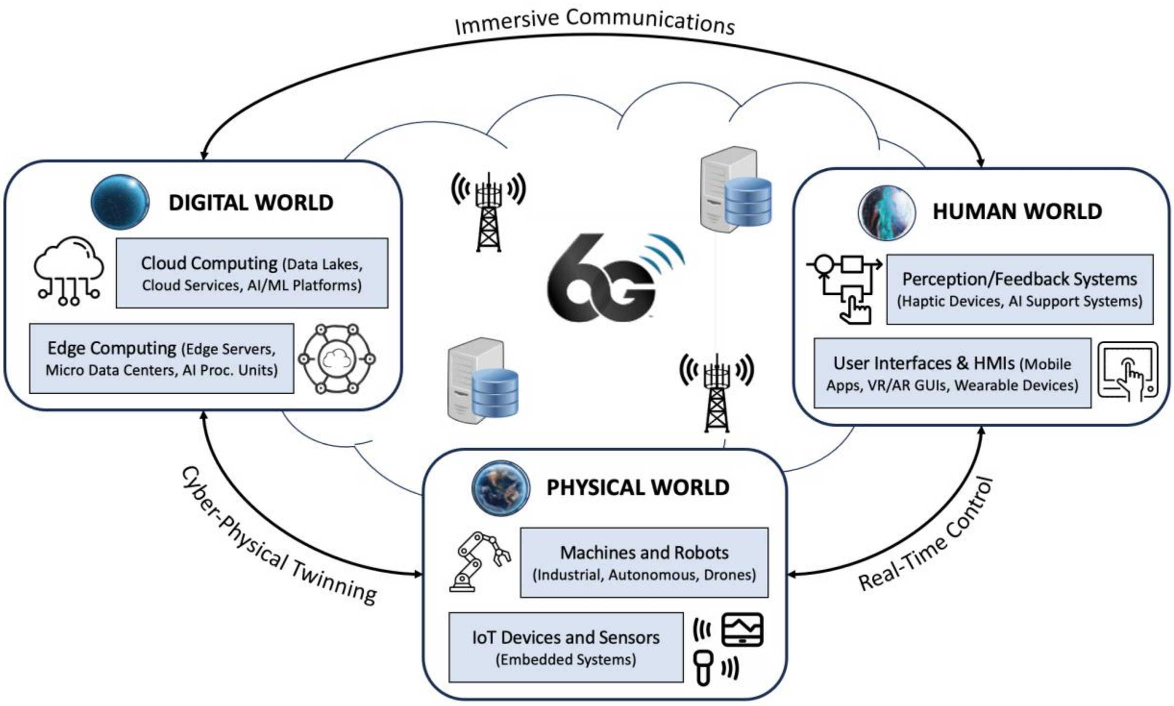


Figure 31: conceptual diagram based on the Hexa-X 6G vision of interconnected worlds, now also encompassing Digital Twins, IoT and Edge and Cloud computing components [110].

Compared to previous generations, 6G is expected to deliver significantly improved performance characteristics. These include ultra-high data rates, extremely low latency at microsecond levels and the ability to support a massive number of connected devices. Such capabilities are essential for real-time applications in complex environments, including logistics, industrial automation and smart infrastructure systems. In addition, 6G integrates advanced technologies such as Artificial Intelligence and blockchain, enhancing system intelligence, security and flexibility, while enabling more efficient and autonomous network operations [178].

Another important aspect of 6G is its role in supporting intelligent and automated systems in sectors such as logistics and supply chain management. By enabling real-time data exchange and advanced analytics, 6G allows the development of intelligent logistics systems that improve decision-making, reduce operational costs and increase system efficiency. These systems rely on the integration of communication technologies with data-driven approaches, supporting better coordination across all stages of the supply chain [168].

In addition to these capabilities, 6G is closely linked with emerging digital environments such as the industrial metaverse. These environments combine physical and virtual systems, allowing users to interact with digital representations of real-world processes. Technologies such as virtual reality, augmented reality and Digital Twins are expected to become essential components of future industrial systems, enabling immersive interaction, improved monitoring and more efficient system control. This transformation is expected to create new business opportunities and innovative service models across industries [159].

A key technological pillar of 6G is the integration of distributed computing architectures, including Edge and Cloud computing, into a unified system. Instead of relying solely on centralized processing, data will be processed across multiple layers closer to where it is generated. This approach reduces latency, improves system responsiveness and supports real-time applications that require immediate decision-making. Furthermore, the use of Artificial Intelligence for resource orchestration enables dynamic allocation of computational resources, ensuring optimal system performance under varying conditions. [110].

Moreover, the evolution toward 6G is strongly connected with the development of Web 3.0 technologies, which introduce decentralized and secure data management mechanisms. In large-scale industrial environments, where massive amounts of data are generated by interconnected devices, ensuring data security, privacy and trust becomes critical. Web 3.0 technologies, such as blockchain and smart contracts, enable transparent and tamper-resistant data exchange, improving supply chain transparency and operational efficiency. At the same time, decentralized identity systems enhance data control and privacy, encouraging wider data sharing and collaboration across organizations [204].

Finally, 6G is expected to play a central role in the digital transformation of modern industries. By enabling high-speed communication, intelligent automation, real-time data processing and secure data exchange, it supports the development of highly connected and efficient systems. These capabilities are particularly important for logistics and supply chain management, where real-time coordination, visibility and adaptability are essential for improving performance and maintaining competitiveness in a global environment [168].

6.2 Characteristics of 6G

6G technology introduces a new paradigm in wireless communication systems, where the focus shifts from simple data transmission to the integration of communication, sensing, positioning and intelligence into a unified framework. Unlike previous generations, which primarily aimed at improving data rates and connectivity, 6G is designed to support complex digital ecosystems where physical and digital environments are closely interconnected. This evolution allows communication networks to act not only as transmission platforms but also as intelligent systems capable of supporting advanced applications and real-time decision-making processes.

A defining characteristic of 6G is the seamless integration of communication and sensing functionalities. In this context, networks are expected to continuously collect and process environmental data, enabling real-time awareness of surrounding conditions. This capability transforms communication systems into sensing platforms that can support applications such as industrial monitoring, autonomous navigation and logistics tracking. The ability to combine sensing with communication enhances system efficiency and enables more accurate and reliable operations in dynamic environments [237].

Another important feature of 6G is the advancement of positioning technologies. Future systems are expected to provide highly accurate localization capabilities, extending beyond traditional positioning methods to support full 6D localization, including both spatial position and device orientation. This level of precision is essential for applications that require detailed spatial awareness, such as robotics, autonomous vehicles and immersive digital environments. The use of advanced signal processing techniques, combined with high-frequency communication and large antenna arrays, allows for improved estimation of angles, distances and propagation characteristics, leading to enhanced positioning performance [249].

In addition to improved positioning, 6G networks are characterized by extremely low latency and high reliability, which are critical for supporting time-sensitive applications. Real-time control systems, such as industrial automation and remote operations, require immediate data transmission and consistent network performance. 6G is expected to meet these requirements by minimizing communication delays and ensuring stable connectivity, even in complex or high-demand environments. These capabilities enable the development of systems that can respond quickly to changes and maintain efficient operation under varying conditions [247].

The use of higher frequency bands is another fundamental characteristic of 6G. Technologies operating in sub-Terahertz and Terahertz ranges provide significantly larger bandwidths compared to previous generations, allowing for extremely high data transmission rates. These frequency bands also enable finer resolution in signal measurements, which contributes to improved sensing and positioning capabilities. However, the use of such high frequencies requires advanced techniques, including beamforming and adaptive transmission strategies, to address challenges related to signal attenuation and limited coverage [237].

6G systems are also expected to support advanced network architectures that integrate terrestrial and non-terrestrial components into a unified infrastructure. This includes the use of aerial platforms such as UAVs, as well as satellite systems, to extend network coverage and provide services in areas where traditional infrastructure is not available. These hybrid architectures enhance flexibility and scalability, allowing networks to adapt to different environments and application requirements. For example, UAV-based communication systems can provide on-demand coverage and support positioning services in remote or disaster-affected areas [239].

Another key characteristic of 6G is the emphasis on energy efficiency and sustainable operation. As the number of connected devices increases significantly, efficient resource management becomes essential.

6G networks are designed to optimize the use of energy and communication resources, reducing operational costs and environmental impact. Techniques such as intelligent resource allocation and adaptive network management contribute to the development of more sustainable communication systems, which are essential for long-term deployment at a global scale [247].

Artificial Intelligence plays a central role in the operation of 6G networks, representing another important characteristic of this technology. AI is expected to be integrated across all layers of the network, enabling automated decision-making, predictive analysis and dynamic optimization of system performance. This allows networks to respond to changing conditions in real time, improving efficiency and reliability. AI-driven mechanisms can also enhance network security and support the management of complex systems with minimal human intervention [237].

Furthermore, 6G supports the development of new types of applications and digital environments that require high levels of interaction and data processing. These include immersive technologies such as augmented reality, virtual reality and extended reality, as well as advanced industrial applications and smart infrastructure systems. The combination of high-speed communication, accurate positioning and intelligent processing enables the creation of integrated digital environments where physical and virtual systems operate together. This opens new opportunities for innovation and supports the evolution of modern industries [247].

Finally, 6G is characterized by its ability to support large-scale and complex systems with diverse requirements. It is designed to handle a wide range of applications, from low-power devices to high-performance industrial systems, ensuring flexibility and scalability. By combining advanced communication technologies with intelligent system design, 6G enables the development of highly connected and adaptive environments. These characteristics make it a fundamental technology for future digital transformation and the evolution of next-generation communication systems [237].

6.3 The Role of 6G in Supply Chain & Logistics

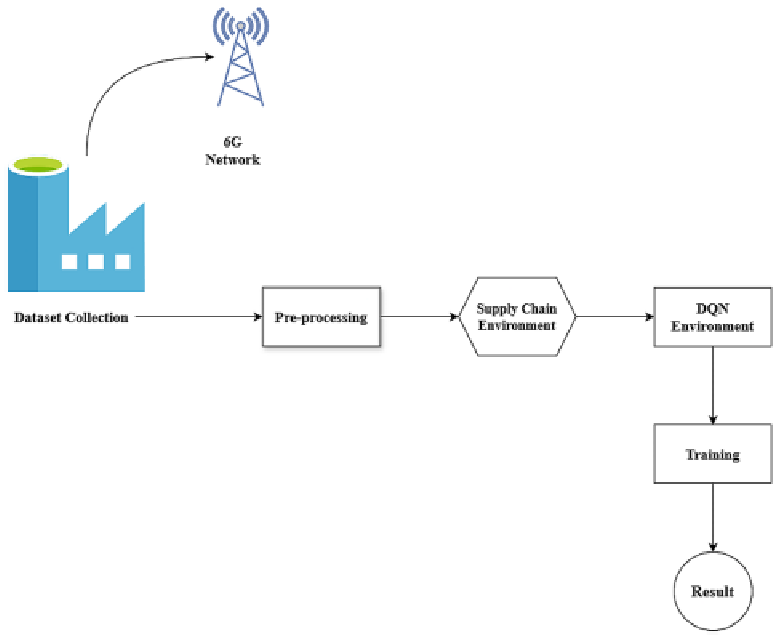
6.3.1 Transformation of Supply Chain through 6G Technologies

The emergence of 6G technology is expected to fundamentally transform supply chain management by enabling highly connected, intelligent and adaptive systems. Unlike previous generations, which primarily focused on improving communication speed and reliability, 6G introduces a new paradigm where communication, computing and intelligence are deeply integrated. This transformation allows supply chains to operate as dynamic and data-driven systems, capable of responding in real time to changes in demand, disruptions and market conditions. As a result, organizations can improve operational efficiency, reduce delays and enhance coordination across all stages of the supply chain [76].

Recent studies further suggest that the transformation enabled by 6G will extend beyond improvements in communication performance toward the creation of fully integrated vertical ecosystems. Unlike previous mobile generations, where telecommunications providers were the primary stakeholders, future 6G environments are expected to combine communication networks with information technology (IT), operational technology (OT), artificial intelligence (AI), cloud services and data platforms within a collaborative ecosystem. This approach promotes interoperability among telecom operators, digital service providers, governments, equipment manufacturers and supply chain organizations, allowing the development of intelligent logistics platforms capable of real-time coordination, distributed decision-making and end-to-end digital integration across supply chain operations [198].

A key role of 6G in supply chains is the enhancement of visibility and transparency. Through high-speed communication and advanced data processing capabilities, companies can monitor the movement of goods, materials and information continuously. This real-time visibility enables better decision-making and allows organizations to quickly identify and respond to disruptions, such as delays in transportation or changes in supplier performance. In addition, the ability to access accurate and up-to-date information supports improved planning and forecasting, leading to more efficient and reliable supply chain operations [169].

Another important contribution of 6G is the support of intelligent and automated supply chain systems. By integrating technologies such as Artificial Intelligence and machine learning, 6G enables advanced analytics and predictive capabilities. These systems can analyze large volumes of data to identify patterns, predict future demand and optimize logistics processes. For example, companies can use predictive models to anticipate changes in customer demand and adjust production and distribution strategies accordingly. This leads to improved efficiency, reduced costs and better resource utilization across the supply chain.



32Figure : Architecture of proposed method [169].

In addition, 6G supports the development of cyber-physical supply chain systems, where physical operations are closely connected with digital technologies. These systems enable continuous interaction between machines, sensors and digital platforms, allowing real-time monitoring and control of logistics operations. The integration of cyber-physical systems enhances operational flexibility and enables automated decision-making processes, which are essential for managing complex supply chain networks. Furthermore, these systems improve the ability to detect and respond to potential issues before they impact operations, increasing overall system reliability [275].

The ability of 6G to support massive connectivity is another critical factor in supply chain transformation. Modern supply chains involve a large number of interconnected devices, including sensors, vehicles and production systems. 6G enables seamless communication between these devices, allowing efficient data exchange and coordination. This connectivity supports advanced applications such as real-time tracking, automated inventory management and intelligent logistics planning. By enabling the efficient handling of large amounts of data, 6G enhances the overall performance and scalability of supply chain systems [169].

Moreover, 6G contributes to the development of more resilient and flexible supply chains. By enabling real-time communication and predictive analytics, organizations can better manage risks and respond to unexpected disruptions. For example, supply chains can quickly adjust production schedules or reroute shipments in response to changes in market conditions or supply availability. This level of adaptability is essential for maintaining continuity and efficiency in complex and uncertain environments.

Finally, the integration of 6G technology supports the evolution of supply chains toward more sustainable and efficient systems. By optimizing resource allocation and reducing operational inefficiencies, 6G enables organizations to minimize waste and improve energy efficiency. In addition, real-time monitoring and data-driven decision-making support more sustainable practices across the supply chain, contributing to long-term environmental and economic benefits [76].

6.3.2 Advanced Logistics Systems and Emerging 6G Applications

6G technology plays a central role in the development of advanced logistics systems that rely on intelligent communication and automation. One of the most important applications is in e-commerce logistics, where 6G enables real-time tracking, predictive analytics and automated decision-making. These capabilities allow companies to optimize delivery processes, reduce delays and improve customer satisfaction. By combining high-speed communication with advanced analytics, logistics systems can dynamically adjust to changes in demand and operational conditions, improving overall performance [275].

Another significant application of 6G is the support of autonomous and intelligent logistics systems. Technologies such as autonomous vehicles, drones and robotic systems require reliable and low-latency communication to operate effectively. 6G provides the necessary infrastructure to support these systems, enabling continuous communication between devices and control systems. This improves coordination and efficiency in logistics operations, while also reducing the need for human intervention. In addition, these systems enhance safety and reliability, particularly in complex or hazardous environments [185].

The integration of 6G with advanced communication technologies further expands the capabilities of logistics systems. For example, optical wireless communication technologies provide additional bandwidth and support high-capacity data transmission, which is essential for applications that require large amounts of data. These technologies enable communication in challenging environments, including air, space and underwater systems, supporting the development of multi-layer logistics networks. This multi-dimensional connectivity enhances the flexibility and scalability of logistics operations [266].

Security is another critical aspect of 6G-enabled logistics systems. As supply chains become more interconnected and dependent on digital technologies, they become more vulnerable to cyber threats. Advanced security frameworks are required to protect data and ensure the reliability of communication systems. Technologies such as artificial intelligence, blockchain and advanced encryption methods are integrated into 6G networks to enhance security and resilience. These solutions help prevent unauthorized access, detect potential threats and ensure the integrity of data across the supply chain.

In addition, 6G supports the development of integrated logistics ecosystems that connect multiple domains, including air, space, ground and maritime environments. This multi-domain connectivity enables efficient coordination of logistics operations across different regions and infrastructures. For example, drones, satellites and ground transportation systems can work together to ensure efficient delivery and resource distribution. This approach improves the efficiency and reliability of logistics operations, particularly in large-scale and complex supply chain networks [194].

Furthermore, 6G enables the use of advanced data analytics and optimization techniques in logistics operations. By processing large amounts of data in real time, organizations can improve forecasting accuracy, optimize routes and manage inventory more effectively. These capabilities are essential for improving operational efficiency and reducing costs in logistics systems. In addition, data-driven decision-making supports continuous improvement and innovation in supply chain management [258]. Recent studies further suggest that 6G will support the development of highly intelligent logistics systems through technologies such as Digital Twins, smart shipments, intelligent routing and edge artificial intelligence. In these environments, products, vehicles and logistics assets can continuously generate real-time data through embedded sensors and communication modules. The collected information can be processed at the network edge, allowing dynamic route optimization, automated shipment management, predictive logistics planning and real-time monitoring of supply chain activities. Furthermore, Digital Twin platforms provide virtual representations of logistics operations, enabling simulation, performance optimization and proactive decision-making. These emerging applications are expected to improve operational efficiency, visibility, responsiveness and automation across future logistics ecosystems [75].

Finally, 6G technology supports the development of new business models and innovative services in logistics and supply chain management. The ability to process and analyze data in real time allows companies to offer more flexible and customer-oriented services. For example, logistics providers can offer personalized delivery options and real-time tracking services, improving customer satisfaction and competitiveness. This transformation supports the evolution of supply chains into more intelligent, efficient and responsive systems [76].

6.4 Interaction of 6G with UAV

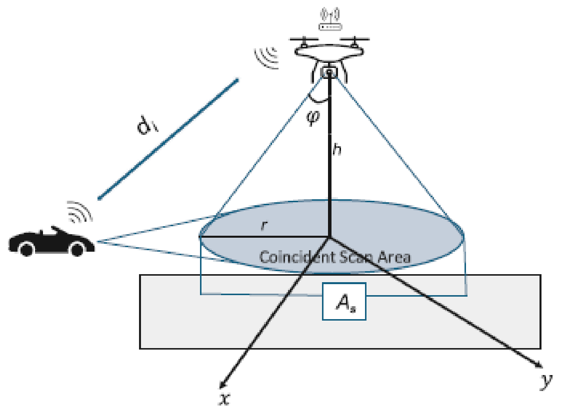
The interaction between 6G technology and Unmanned Aerial Vehicles (UAVs) represents a critical component of next-generation communication systems, especially in logistics and supply chain environments. 6G enables UAVs to operate as intelligent and fully connected nodes within a broader digital ecosystem, supporting real-time communication, advanced data processing and autonomous decision-making. Compared to previous communication technologies, 6G provides enhanced coverage, ultra-low latency and massive connectivity, allowing UAVs to perform complex tasks more efficiently and reliably.

One of the most important roles of 6G in UAV systems is the enhancement of communication capabilities. In traditional systems, UAV communication is limited by network coverage and latency constraints. However, 6G enables continuous and seamless connectivity between UAVs, ground stations and other network components. This is particularly important in scenarios where UAVs operate in dynamic environments, such as logistics delivery or urban monitoring. The ability to maintain stable communication links ensures efficient coordination and improves the overall performance of UAV networks [238].

Another key aspect of this interaction is the use of UAVs as aerial communication platforms within 6G networks. UAVs can act as flying base stations or relay nodes, extending network coverage to areas where traditional infrastructure is not available. This is especially useful in remote or disaster-affected regions, where communication infrastructure may be limited or damaged. By dynamically adjusting their position, UAVs can provide on-demand connectivity and support critical communication services.

In addition, 6G enables advanced UAV-based positioning and sensing capabilities. UAVs equipped with communication and sensing technologies can provide accurate location information and environmental data in real time. These capabilities are essential for applications such as logistics tracking, emergency response and smart city operations. The integration of sensing and communication functions allows UAVs to support intelligent services at the network edge, improving system efficiency and decision-making processes [243].

The combination of 6G and UAVs also supports the development of cooperative and autonomous systems. UAVs can operate as part of a coordinated network, sharing information and collaborating to achieve common objectives. For example, multiple UAVs can work together to monitor large areas, collect data, or perform delivery tasks. The use of 6G communication enables efficient data exchange and coordination between UAVs, improving system performance and reliability [273].



33Figure: UAV coverage area on flat terrain [273].

Another important feature of this interaction is the integration of Artificial Intelligence in UAV operations. AI-based algorithms can be used to optimize UAV trajectory, resource allocation and communication strategies. For example, trajectory optimization techniques can improve energy efficiency and reduce operational costs by determining optimal flight paths based on environmental conditions and system requirements. These capabilities are particularly important in logistics applications, where efficient routing and energy management are critical [199].

Energy efficiency and resource management are also key challenges in UAV systems and 6G provides solutions to address these issues. UAVs have limited battery capacity, which restricts their operational time and performance. By using advanced optimization algorithms and communication techniques, 6G enables more efficient use of energy and communication resources. This allows UAVs to operate for longer periods and perform more complex tasks, improving the overall effectiveness of UAV-based systems [238].

Furthermore, the integration of 6G with UAV systems supports the development of intelligent logistics and warehouse environments. UAVs can be used to provide dynamic communication coverage and support the operation of automated systems such as autonomous guided vehicles (AGVs). By adjusting their position and transmission power, UAVs can ensure efficient communication between different components of the logistics system. This improves coordination, reduces delays and enhances overall system performance [210].

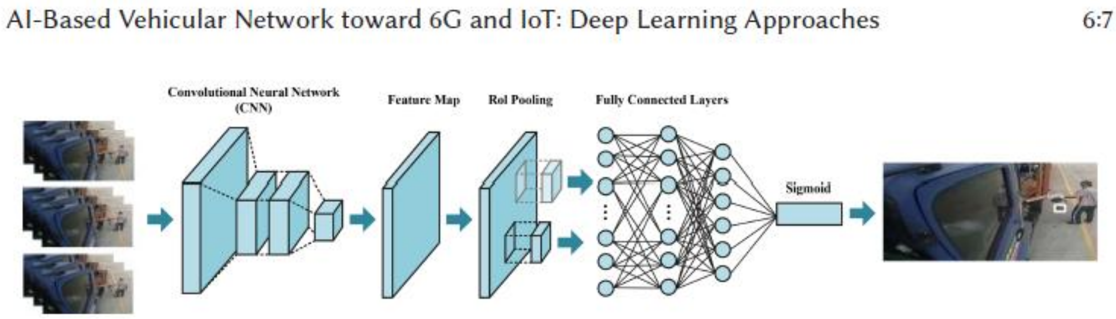
Another important aspect is the use of edge computing in 6G-enabled UAV systems. Instead of relying on centralized cloud infrastructure, data can be processed at the network edge, closer to where it is generated. UAVs can act as mobile edge nodes, supporting real-time data processing and reducing communication delays. This approach improves system responsiveness and enables faster decision-making, which is essential for time-critical applications such as autonomous navigation and emergency response [235].

Finally, the interaction between 6G and UAVs enables the development of fully integrated and intelligent communication systems. These systems combine communication, sensing and computing capabilities to support a wide range of applications, including logistics, smart cities and industrial automation. By leveraging the advanced capabilities of 6G, UAVs can operate more efficiently, adapt to changing conditions and support the development of next-generation digital ecosystems [273].

6.5 Interaction of 6G with AI

The interaction between Sixth Generation (6G) communication systems and Artificial Intelligence (AI) represents one of the most transformative developments in next-generation networks. Unlike previous generations, where AI was mainly used as a supporting tool, 6G is designed to be inherently AI-driven. This integration enables intelligent, adaptive and autonomous network operations, supporting complex applications across multiple domains such as logistics, transportation and smart cities.

One of the primary roles of AI in 6G networks is to enhance network intelligence and automation. 6G systems are expected to operate in highly dynamic and heterogeneous environments, requiring real-time decision-making and self-optimization capabilities. AI techniques, particularly deep learning, enable networks to learn from data, predict network conditions and optimize resource allocation. This allows 6G networks to achieve improved performance in terms of latency, reliability and efficiency, meeting the demanding requirements of emerging applications [194].



34Figure : CNN model training process [194].

Another important aspect of the interaction between 6G and AI is the ability to process massive amounts of data generated by modern systems. Technologies such as IoT devices, sensors, drones and autonomous vehicles produce large volumes of heterogeneous data. 6G networks provide the high bandwidth and ultra-low latency required for real-time data transmission, while AI algorithms analyze this data to extract meaningful insights. For example, deep neural networks can process historical and real-time data to optimize resource allocation, scheduling and system operations in complex environments [223].

In addition, 6G enables the deployment of AI models across distributed environments, including cloud, edge and device levels. This distributed AI architecture allows data processing to occur closer to the data source, reducing latency and improving system responsiveness. Edge computing plays a critical role in this context, enabling real-time decision-making for time-sensitive applications. However, deploying large AI models on resource-constrained devices remains a challenge, requiring the development of lightweight and adaptive AI solutions.

The integration of AI with 6G also supports advanced content generation and intelligent services. Artificial Intelligence Generated Content (AIGC), based on large language models and deep learning techniques, enables the automatic creation of text, images and other multimedia content. In 6G environments, these capabilities can be used in applications such as smart logistics, automated communication systems and real-time data interpretation. However, these applications introduce challenges related to data privacy, model security and access control, which must be addressed through advanced encryption and security mechanisms [174].

Another key feature of the 6G-AI interaction is the enhancement of intelligent applications such as autonomous vehicles and smart transportation systems. AI techniques are used to analyze sensor data, recognize patterns and support decision-making processes in real time. For example, deep learning models can detect abnormal driving behavior and with this way avoiding accidents. 6G networks enable the real-time transmission of high-quality data, such as images and videos, allowing AI systems to operate effectively even in highly dynamic environments.

Furthermore, AI plays a crucial role in enabling self-organizing and self-learning networks in 6G. These networks can automatically adapt to changing conditions, optimize their performance and recover from failures without human intervention. This level of automation is essential for managing the complexity of future communication systems, which will involve billions of connected devices and diverse applications. The combination of AI and 6G creates a foundation for fully autonomous network management and intelligent service delivery [194].

Despite its advantages, the integration of AI with 6G also introduces several challenges. These include issues related to data privacy, security, computational complexity and energy consumption. AI models often require large amounts of data and computational resources, which can be difficult to manage in distributed environments. Additionally, ensuring the security and reliability of AI-driven systems is critical, especially in applications involving sensitive data or safety-critical operations [174].

Finally, the interaction between 6G and AI is expected to drive the development of intelligent digital ecosystems. By combining advanced communication capabilities with powerful data analysis and decision-making tools, 6G-AI systems can support a wide range of applications, from smart logistics and industrial automation to healthcare and smart cities. This synergy will play a key role in shaping the future of technology, enabling more efficient, adaptive and intelligent systems across various sectors [223].

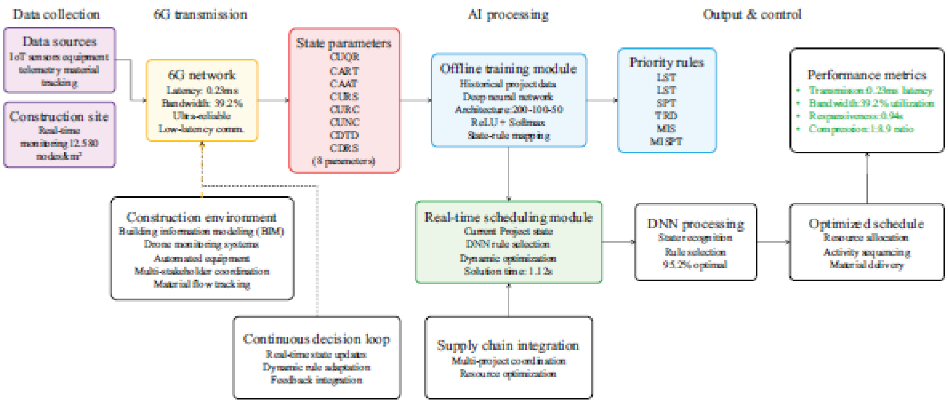
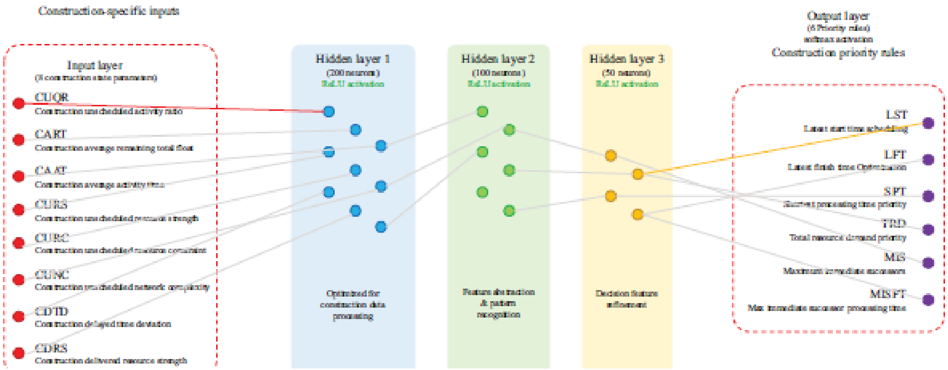


FIGURE 1 | DRDS algorithm framework for CSCs with 6G integration.



35Figure : DNN architecture for CSC optimization [223].

6.6 Comparison of 5G, B5G & 6G

5G and 6G represent two important stages in the evolution of wireless communication systems. 5G has already introduced major improvements in speed, latency, reliability and device connectivity, making it a key technology for Industry 4.0, smart logistics, autonomous systems and real-time monitoring. In logistics, 5G supports applications such as automated warehouses, connected vehicles, real-time tracking and supply chain visibility. However, 6G is expected to go beyond these capabilities by integrating Artificial Intelligence, ultra-high data rates, advanced sensing and deeper automation into the network itself [108].

Feature	5G	6G
Data Rate	Up to 20 Gbps	Upto 1 Tbps
Latency	Millisecond (ms)	<1 ms
Frequency	Sub-6 GHz, mmWave	Sub-THz, THz
Energy Efficiency	1000x compared to 4G	10x compared to 5G
Mobility	350 km/h	>1000 km/h
Traffic density	10Tb / s / sqkm	>100Tb / s / sqkm
Spectrum efficiency	3-5x compared to 4G	>3x compared to 5G

36Figure : Comparison between 5G & 6G [108].

A key difference between 5G and 6G is their performance level. 5G provides high-speed communication, low latency and the ability to connect a very large number of devices. These features are already useful for logistics systems that require real-time communication between sensors, vehicles, AGVs, drones and warehouse systems. 6G, however, is expected to provide even higher speeds, potentially reaching terabit-per-second levels, with even lower latency and more reliable communication. This makes 6G more suitable for applications that require instant response, such as autonomous logistics, digital twins, remote control and intelligent decision-making [108].

In terms of logistics and supply chain operations, 5G mainly improves connectivity and automation. It enables real-time tracking of goods, better warehouse management, predictive maintenance and communication between smart devices. B5G and 6G extend this role by supporting embedded AI, ultra-fast data transmission and more advanced automation. This means that logistics systems will not only collect and transmit data, but also analyze it and react automatically in real time. As a result, 6G is expected to create more intelligent, flexible and autonomous logistics systems [172].

Another important difference is the role of Artificial Intelligence. In 5G, AI is mostly used as an external tool to optimize network performance or logistics processes. In 6G, AI is expected to become a native part of the network architecture. This means that 6G networks will be able to manage themselves, predict traffic demand, allocate resources dynamically and support autonomous decision-making. This is especially important for vertical industries, where different applications require different levels of latency, reliability and bandwidth [190].

5G has also introduced important technologies such as network slicing, edge computing, private campus networks and Open RAN. These technologies allow industries to create customized communication environments for specific needs. For example, a logistics company can use a private 5G campus network to support warehouse automation, AGVs and real-time monitoring. These 5G campus networks are also considered an important step toward 6G, because they create the technical foundation for more open, flexible, AI-driven and software-based networks [165].

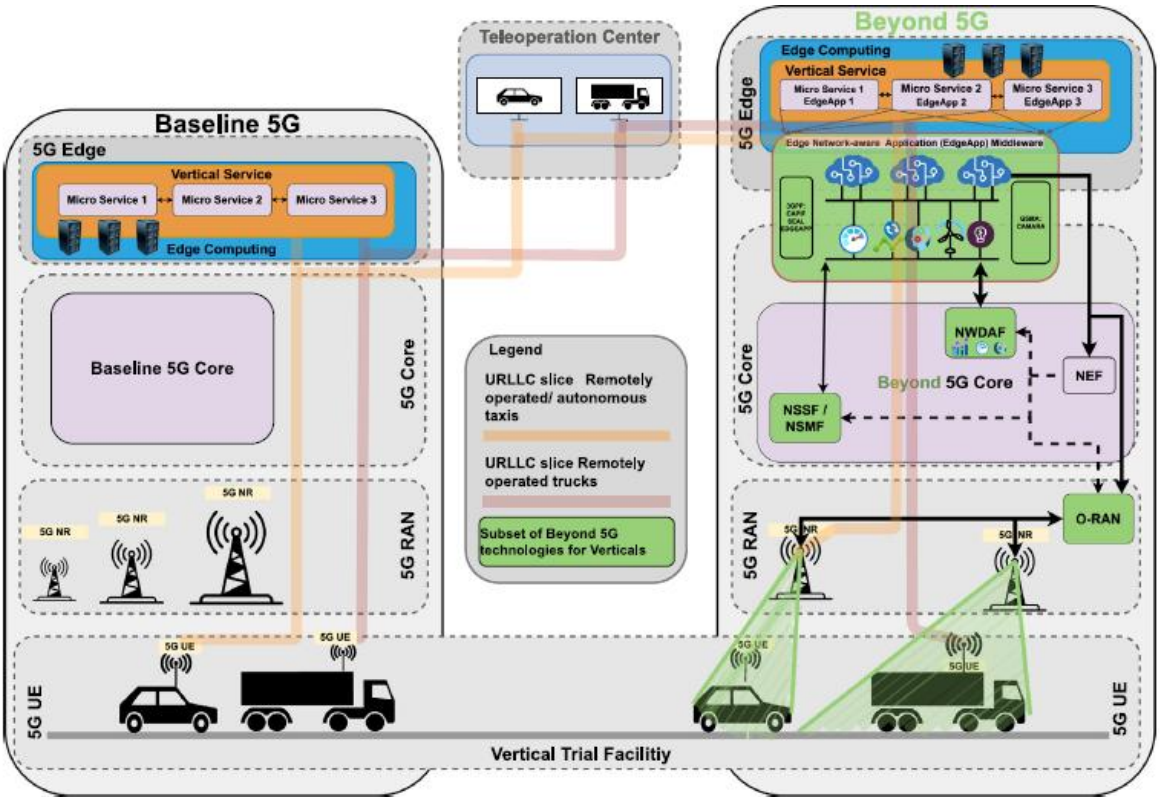
6G is expected to expand this architecture by integrating more advanced technologies, such as intelligent network slicing, network exposure, AI-based orchestration and stronger edge-cloud coordination. While 5G provides the first practical framework for digital transformation in industries, 6G will focus more on creating a complete digital ecosystem where communication, computing, sensing and intelligence work together. This will be important for future logistics systems that depend on real-time data, autonomous vehicles, drones and digital twins [190].

Resource optimization is another area where the difference between 5G and 6G becomes clear. In 5G networks, resource management is already a major challenge due to spectrum congestion, latency requirements and energy consumption. Technologies such as RFID can help improve real-time resource allocation, spectrum utilization and load balancing. These methods are useful for 5G but also prepare the transition to 6G, where networks will need even more intelligent and adaptive resource management due to the massive number of connected devices and applications [163].

From a business perspective, 5G has already created new opportunities in manufacturing, healthcare, smart cities, logistics and transportation. It supports automation, real-time cloud computing, IoT applications and improved operational efficiency. 6G is expected to create even more advanced business models by enabling real-time digital twins, AI-driven services, immersive applications and global intelligent connectivity. Therefore, while 5G supports digital transformation, 6G is expected to accelerate the development of fully intelligent and autonomous business ecosystems [108].

In logistics specifically, 5G improves the movement of products by making tracking, monitoring and automation more accurate. It supports AGVs, smart warehouses, connected assets and real-time data collection. In comparison, 6G is expected to support more advanced automated logistics systems with embedded AI, ultra-low latency and stronger connectivity between vehicles, robots, drones and warehouse management platforms. This will allow logistics systems to become more predictive, autonomous and resilient [172].

Overall, 5G can be understood as the foundation of modern digital logistics and industrial connectivity, while 6G represents the next step toward intelligent, autonomous and fully integrated systems. 5G enables real-time communication and automation, whereas 6G will combine communication with intelligence, sensing and advanced computing. For supply chain and logistics, this means that 5G improves current operations, while 6G will reshape future operations by enabling more adaptive, secure and intelligent supply chain ecosystems [190].



37Figure : Empowering Vertical Industries with next-gen technologies and facilities, from Baseline 5G towards B5G technologies (example vertical services teleoperation and autonomous driving) [190].

7. Conclusions

This dissertation examined the role of digital technologies in modern supply chain management and logistics, with a particular focus on 5G and emerging 6G communication technologies. The literature review showed that supply chains have become increasingly digital, interconnected and data-driven, requiring organizations to adopt new technologies to improve efficiency, flexibility and operational performance.

The findings highlighted the importance of digital transformation in supply chain operations. Technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, Blockchain, Digital Twins and cloud-based systems have significantly improved visibility, information sharing and decision-making across supply chain networks. These technologies help organizations manage complex operations more effectively and respond faster to changing market conditions.

The study also demonstrated the importance of risk management, resilience and sustainability in modern supply chains. Digital technologies support these capabilities by improving visibility, monitoring and communication throughout the supply chain.

Particular attention was given to the role of 5G technology. The reviewed literature showed that 5G provides high-speed communication, low latency and reliable connectivity, making it suitable for smart logistics, real-time monitoring, warehouse automation and large-scale IoT applications. The integration of 5G with technologies such as Artificial Intelligence, Digital Twins and UAV systems creates new opportunities for improving supply chain operations and logistics performance.

The dissertation also explored the future potential of 6G technology. Although 6G is still under development, the literature suggests that it will offer even greater levels of connectivity, intelligence and automation. The combination of 6G, Artificial Intelligence and advanced digital technologies is expected to support the development of highly intelligent supply chain ecosystems capable of operating with greater autonomy and efficiency.

Overall, the literature indicates that advanced communication technologies will play an increasingly important role in the future of supply chain management and logistics. Organizations that successfully adopt and integrate these technologies are likely to improve operational performance, strengthen resilience, increase flexibility and support innovation. As digital transformation continues to evolve, 5G and future 6G technologies are expected to become key enablers of smart and sustainable supply chains.

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