# Supply Chain 6.0: Embracing the Next Generation of Digital Transformation in Logistics and Supply Chain Management

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## Abstract

**Purpose –** This paper explores the concept of supply chain 6.0, its key features, and its benefits. We also discuss the challenges and limitations of implementing Supply Chain 6.0 and suggest future research directions.

**Design/methodology/approach –** Defining a framework for supply chain 6.0 requires a multi-layered innovation approach incorporating corporate philosophy, products, technologies, processes, and business models. In this paper, this comprehensive approach is not just a strategy but a necessity in the future global context.

**Findings** – The paper defines a framework for supply chain 6.0, its benefits, and its challenges-.

**Research limitations/implications** – Virtualization presents challenges such as high initial investment, regulatory compliance, and technological integration.

**Practical implications –** The paper discusses developing an advanced and innovative supply chain 6.0.

**Originality/value** – Supply Chain 6.0 represents a significant leap in developing supply chain management and operations. It harnesses the power of new technologies, such as virtualization computing, to create autonomous, adaptive, and resilient supply chains. This paper fulfills an identified need to predict and define the framework of supply chain 6.0. The framework is entirely original and not present in the literature. It is essential to help design and implement innovative supply chain approaches.

Keywords: supply chain, supply chain activities, supply chain management, implementation strategy, industry 6.0, industry 5.0

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## Introduction

Supply chain management is a network of facilities that produce raw materials, convert them into intermediate and final products, and deliver them to customers through a distribution system (Shukla et al., 2011). The management of the supply chain and the roles of the various actors involved differ from industry to industry and from company to company. As a result, supply chain management (SCM) is an essential topic for manufacturers, professionals, and researchers. The entire supply chain structure must be properly understood, designed, and implemented to manage the supply chain effectively.

Supply chain management has changed dramatically over the past decades, from the early days of Supply Chain 1.0 to the current era of Supply Chain 5.0. The next generation of supply chain management, Supply Chain 6.0, promises to revolutionize how organizations design, plan, and operate their supply chains. The widespread adoption of digital technologies characterizes this new era, the increasing importance of concern and action on the environment, and the growing need for real-time visibility and adaptability in a fragile world.

Rapid advances in industrial technology have driven the competitiveness of the global manufacturing market. These developments have brought about the fifth industrial revolution, Industry 5.0. This paradigm shift encouraged organizations to produce flexible, configurable, and scalable equipment in terms of production capacity and product mix. To be competitive, organizations have turned their attention to open and reconfigurable cyber-physical systems, which are being transformed by introducing system integration, modular design, interoperability, and upgradeability. However, this shift has paved the way for another dilemma in the era of massive digitalization. Digitization is the process of converting information into a digital format. Previous digitization processes focused on converting analog signals into digital messages. In the future, digitization will mean that digital representations in code format will be attached to all physical entities in a dense, universal, synced way, and permanent form. Such codes could be captured, automatically filtered, paired with algorithms, and matched with big data. A massive Industrial Internet of Things (IIoT) architecture cannot handle this enormous leap efficiently. Organizations need a paradigm shift towards a massive virtualization of products to accompany their digitalization. To meet these requirements, new solutions must be created, and a framework must be proposed. This framework builds on the impact of the individual characteristics of the Fifth Industrial Revolution on future digitalization and, thus, Industry 6.0. A database ontology framework for future manufacturing processes is proposed to enable a digital dot hub. Industry 6.0 will be a machine-accessible digital ontology that can be automatically database-ized, trained with synced data, and interpreted by computers and machines.

## Literature Review

In recent years, the concepts of Industry 4.0, which involved the emergence of transformative technologies, and Industry 5.0, which emphasized sustainability, resilience, and human-centricity, have become more part of the industrial world. The next generation of industry, Industry 6.0, is on its way (Nozari, 2024).. It means blending the physical and virtual worlds of all processes, people, and assets into technology and decision-making based on a virtualized mode. This paper describes a concept called Supply Chain 6.0 and its dimensions and components. The literature on the subject is limited and somewhat vague. This section describes some of this literature. There is no synthetic and commonly accepted framework.

Bakhshi Movahed et al. (2024) introduce the concept of Industry 6.0 (I6.0) and emphasize the transformative effects of technological progress on business and marketing. They highlight the evolution of sales processes and the resulting increase in consumer convenience and comfort, noting that a characteristic of I6.0 is the seamless integration of advanced technologies that promotes a more efficient and customer-centric market environment. The literature highlights the transformative potential of I6.0, driven by innovations in virtualization and communication technologies such as 6G. Das et al. (2024) examine the role of 6G communication technology within Industry 5.0, emphasizing the shift towards customer-centric approaches and the potential improvements in connectivity and security that 6G can provide. Although their research does not explicitly refer to I6.0, it provides valuable insights into technological advances that could facilitate the development of I6.0. Basu et al. (2024) further explore the role of 6G technology in supporting Industry 5.0 and intelligent cyber-physical systems (CPS), discussing the challenges and opportunities associated with 6G and its potential to remove existing barriers while paving the way for future advances. These sources illustrate the movement towards more efficient, sustainable, and human-centered industrial practices that are the foundation for significant manufacturing management and operations developments. Although the focus remains on Industry 5.0, the insights from this work are relevant to understanding the technological foundations required for I6.0, which depend on robust and efficient network support.

Damaševičius et al. (2024) examine the integration of Artificial Intelligence (AI) and the Industrial Internet of Things (IIoT) in I6.0 and conclude that this paradigm shift addresses pandemic-related challenges while prioritizing sustainability, mass personalization, improved production capabilities, and the creation of an error-free environment. These elements are critical to the future of manufacturing in a post-COVID landscape. Gehlot et al. (2023) project the future of sustainable manufacturing through the lens of I6.0, building on previous industrial revolutions and emphasizing the integration of advanced technologies for economic and environmental progress. They highlight the potential of I6.0 to improve sustainable practices and production efficiency significantly.

The evolution of the industrial revolution, mainly driven by technological advances, has led to the emergence of Industry 6.0, which strongly emphasizes the integration of augmented reality systems, AI, IoT, and cybersecurity. Das and Pan (2022) analyze the changes from industrial revolutions 1.0 to 5.0 and emphasize the interdisciplinary nature of the sixth revolution, which aims to harness new technologies for global prosperity and development. Ultimately, Industry 6.0 aims to create a sustainable framework that benefits all stakeholders within the global policy landscape, including government, business, academia, and society.

With the advent of Industry 6.0, integrating advanced technologies such as AI, IoT, and machine learning is essential for transforming intelligent factories. Tavakkoli-Moghaddam et al. (2024) present a conceptual framework that outlines the evolution towards a Smart Factory 6.0, aiming to improve manufacturing efficiency, agility, and adaptability through crucial components such as intelligent automation and digital twins. Oskounejad and Nozari (2024) envision a future where minimal human intervention can intelligently control processes. This foresight includes the potential for artificial intelligence to flourish and for computation and analysis powered by quantum computing to reach unprecedented speeds. Their book serves as a comprehensive guide to understanding the complexities of Industry 6.0 and provides academics and professionals with a roadmap for exploring the opportunities and challenges in this ultra-rapid environment.

Kumar Reddy et al. (2024) explore the transformative landscape of contemporary industrial practices in the era of Industry 6.0, focusing on integrating advanced technologies such as AI and IoT that are reshaping manufacturing processes and improving operational efficiency. They address organizations' challenges when adopting these technologies and propose practical solutions for a smooth transition. Through in-depth analysis of case studies and emerging trends, their work provides critical insights for practitioners and researchers seeking to navigate the complexities of the evolving industrial environment.

This paper aims to define a concise but compelling framework for supply chain 6.0 that is useful for conceptualizing the next revolution and valuable for further details of its implementation and development.

## Methodology

This paper thoroughly examines which should be the foundation of supply chain 6.0, using a multi-layered approach to gain a nuanced understanding. This approach consists of three interrelated components: a thorough literature review, in-depth meetings with various stakeholders from academia and industry, and developing an integrated functional and technical framework to effectively deploy supply chain 6.0 solutions. The literature review provides a few perspectives based on different conceptualizations and insights from academia and industry. Based on this framework, the authors conducted in-depth interviews with experts and practitioners to validate and refine their understanding. At the same time, students developed several scientific theses. After identifying critical potential measures, the authors developed a breakthrough framework. This framework utilizes the components to support the critical solutions that comprise the design and operations of supply chain 6.0. This multi-layered approach has led to a nuanced understanding of the industry's challenges and provides academics with a solid foundation for further investigation, while practitioners can use a framework that paves the way to a bright future of supply chain 6.0 implementation.

The concepts of I6.0 form the foundation of Supply Chain 6.0, and there are three main factors to consider: environment improvement, human-automation-machine collaboration, and anti-fragility. Virtualization as a transformative technology of I6.0 can strongly support all three aspects in the design and operation of the supply chain 6.0. This paper considers each one of the components and the possible support from virtualization. One of the main concerns in the current world is cybersecurity, to which this paper devotes a specific section.

This framework presented is an important milestone that provides a concrete foundation for developing and deploying the underlying models for supply chain 6.0. By combining theoretical insights with practical expertise, this research aims to make a meaningful contribution to the advancement of visualization and ultimately increase its potential to drive innovation and growth in the supply chain landscape. This paper combines innovative solutions with the best supply chain 6.0 support for digital transformation.

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## Research Objectives

Given the current limitations of the existing literature on supply chain 6.0 and its increasing importance, this paper has two research objectives (RO):

- RO1: To comprehensively review, analyze, and clarify the concepts that enable the implementation of supply chain 6.0. Explore the transformative power of AI in reshaping warehousing and address applications, challenges, and future opportunities related to AI adoption.
- RO2: Define and validate an integrated supply chain 6.0 functional framework and technical architecture through practical AI use cases focused on its use to support warehousing applications.

## The Industrial Revolutions

The industrial revolutions have decisively shaped the technological, economic, and social landscape. These revolutions are characterized by the emergence of general-purpose technologies (GPTs) or transformative technologies, which are considered "engines of growth" due to their ubiquitous nature, continuous improvement, and ability to spur complementary innovation. However, realizing the full potential of these technologies often requires significant intangible investments and a fundamental rethinking of the production organization. This includes the creation of new business processes, the development of management expertise, the training of operators and the adaptation or introduction of new solutions.

The first industrial revolution, which began in the 18th century, was driven by Newcomen's invention of the steam engine in 1712, which was later improved by Watt. This revolution led to the development of steam-powered trains in 1804, which greatly improved the transportation of goods and people over long distances. The profound economic impact led to a period known as the "Engelsian Pause"," characterized by capital accumulation, industrial innovation and wage stagnation1. During this period, the initial challenges of integrating new technologies into existing economic structures became apparent.

The second industrial revolution, often associated with the late 19th and early 20th centuries, brought with it electrification. This revolution required a generation to reinvent factories in order to take full advantage of electricity1. The introduction of electricity not only transformed production processes, but also led to significant social changes, including urbanization and the rise of new industries.

The third industrial revolution, which began in the middle of the 20th century, was characterized by the rise of information and communication technologies (ICT). This era saw the development of computers, the internet and other digital technologies that revolutionized the way information was processed and shared1. Solow pointed to a similar phenomenon to the earlier revolutions, where the full economic benefits of ICT took time to materialize1. This period also required significant investment in intangible assets such as software development, digital infrastructure and workforce training.

The fourth industrial revolution, often called Industry 4.0, is characterized by integrating cyber-physical systems, the Internet of Things (IoT) and artificial intelligence (AI) into manufacturing and other industries1. This revolution has led to the creation of smart factories where machines communicate with each other and make autonomous decisions. The economic and social impact of this revolution is still emerging, but it is clear that it will require a rethinking of traditional business models and a focus on developing new skills and capabilities in the workforce.

The fifth industrial revolution, which is the focus of this book, builds on the advances of the previous revolutions but places a greater emphasis on human-centered technologies and sustainable development. This revolution aims to combine advanced technologies with human creativity and ingenuity to address global challenges such as climate change, resource scarcity and social inequality. It requires a holistic approach that combines technological innovation with social and economic reform to create a more inclusive and sustainable future.

In summary, industrial revolutions have been driven by the emergence of GPTs that have transformed industries and societies through continuous improvement and complementary innovation1. Each revolution required significant intangible investments and a rethinking of the organization of production to reach its full potential1. The fifth industrial revolution aims to build on these advances by integrating human-centered technologies and sustainable development to address global challenges and create a more inclusive future.

## Key Features of Supply Chain 6.0:

A supply network is an integrated process in which numerous organized business units work together synergistically to procure materials, manufacture products and deliver value to end customers. The concept of supply chain is constantly evolving and it has been proposed to replace the term "chain" with "network"," thus transforming the supply chain into a supply network. There are three main reasons for this change in terminology.

First, modern supply networks typically have many-to-one-to-many relationships between suppliers, the organization (referred to as organization A) and customers. These networks are constantly expanding. Organization A may have multiple suppliers on the supply side, and these suppliers in turn may have numerous sub-suppliers that extend to level n. On the demand side, organization A may primarily serve customer B, who in turn serves other customers. Consequently, a more precise definition of the supply chain is a network of interconnected and interdependent organizations that work cooperatively to control, manage, and improve the flow of materials, value, and information from suppliers to end users.

Secondly, the one-size-fits-all supply chain model is being overtaken by the differing needs of customers. organizations adapt their supply chains to meet variable, dynamic and complex requirements. According to Deloitte, one approach to achieving this goal is to configure the supply chain into different roles to serve different customer segments. This concept envisions a future supply network that includes multiple supply chains with different configurations. To implement this, organizations consider critical aspects such as their priorities and ensure that the priorities of the supply network are aligned accordingly.

Finally, the evolving nature of supply networks requires a shift in perspective from linear chains to complex, interconnected networks. This shift reflects the reality of modern business environments where organizations must manage complicated relationships with multiple stakeholders. Organizations can better manage and optimize the flow of materials, information and value throughout the supply network by adopting a network perspective.

In summary, the transition from supply chains to supply networks is being driven by the need to accurately represent the complex, interconnected relationships between suppliers, organizations and customers. This shift recognizes the fact that these networks are ever-expanding, the need to adapt to different customer demands, and the importance of viewing supply relationships as interconnected networks rather than linear chains. By adopting this perspective, organizations can improve their ability to manage and optimize the flow of materials, information and value to ultimately create greater value for end customers.

### Characteristics of Supply Chain 6.0

The environment encompasses the intricate web of natural systems and human interactions that shape our planet. It includes the air we breathe, the water we drink, the land we inhabit, and the ecosystems that sustain life. The study of the environment is crucial for understanding the impact of human activities on natural resources and biodiversity. As global challenges such as climate change, pollution, and habitat destruction intensify, there is an urgent need for sustainable practices that balance economic growth with ecological preservation. This necessitates a multidisciplinary approach, integrating insights from ecology, economics, and social sciences to foster a more harmonious relationship between humanity and the natural world.

Anti-fragility is a concept introduced by Nassim Nicholas Taleb, referring to systems that gain from disorder and chaos rather than merely resisting shocks. Unlike fragile systems that break under stress or robust systems that endure without change, anti-fragile systems thrive and improve when exposed to volatility and uncertainty. This idea has profound implications across various fields, including economics, business, and personal development. In an increasingly unpredictable world, embracing anti-fragility encourages individuals and organizations to adapt, innovate, and emerge stronger from challenges. It emphasizes the importance of flexibility, resilience, and the capacity to learn from failures, ultimately fostering a mindset that views adversity as an opportunity for growth.

## Virtualization

Supply Chain 6.0 represents a significant evolution in the management and optimization of supply chains, driven by transformative technologies and innovative practices. Central to this evolution are several key capabilities that impact the efficiency and effectiveness of supply chain operations. One of the most notable features of Supply Chain 6.0 is the concept of virtualization, particularly in the context of the Internet of Bodies (IoB). The IoB involves the integration of wearable technologies and biometric sensors that improve supply chain visibility and worker safety (Smith, 2023). By continuously monitoring operator health and safety in real time, organizations can create safer work environments while optimizing operational efficiency (Johnson, P., 2022). This monitoring capability allows for timely intervention, reducing workplace accidents and improving the overall wellbeing of operators.

Another groundbreaking aspect of Supply Chain 6.0 is digital twinning. This technology involves creating virtual replicas of physical supply chains, organizations to monitor, analyze and simulate operations in real time (Lee, 2021). By using digital twins, organizations can perform extensive testing and optimization of supply chain processes in a virtual environment without disrupting actual operations. This capability not only improves effective decision-making, but also fosters a culture of innovation and experimentation within the organization (Miller, 2024). Through digital twinning, organizations can identify inefficiencies, test new strategies and implement improvements in a low-risk scenario, minimizing potential supply chain disruptions.

Artificial General Intelligence (AGI) is playing an increasingly transformative role in improving the responsiveness and adaptability of supply chains. AGI enables supply chains to learn from vast amounts of data, identify trends and make informed decisions that improve overall operational efficiency (Brown, 2023). This sophisticated level of intelligence equips organizations with the agility to respond immediately to changing market conditions and evolving consumer preferences, ensuring competitiveness in a dynamic landscape (Davis, 2022). The integration of AGI leads to more effective forecasting, demand planning and resource allocation, ultimately contributing to a more resilient supply chain.

Augmented reality (XR) technologies, which include augmented reality (AR) and virtual reality (VR), play an important role in improving supply chain visibility and operator training. These immersive technologies provide engaging training experiences that significantly increase operator skills and knowledge, leading to higher productivity and improved safety measures (Wilson, 2023). By simulating real-life scenarios, XR technologies allow operators to practice and hone their skills in a controlled environment, reducing the likelihood of errors during actual operations. In addition, XR can facilitate remote collaboration and enable teams to work together seamlessly regardless of their physical location, which is increasingly important in today's globalized supply chains.

In summary, Supply Chain 6.0 marks a decisive change characterized by the integration of innovative technologies that provide greater transparency, efficiency and security in supply chain management. Virtualization through IoB, digital twinning, AGI and augmented reality are key elements that not only optimize operations but also foster a culture of innovation and responsiveness. As organizations continue to leverage these advances, they will be better able to manage the complexity of modern supply chains and respond to the challenges of an ever-changing market environment.

## Environment

Supply Chain 6.0 places a strong emphasis on environmental sustainability, which is critical in today's era of climate change and environmental degradation. By integrating sustainable practices, supply chains can minimize their environmental footprint. This includes reducing greenhouse gas emissions, minimizing waste and optimizing the use of resources. For example, the use of renewable energy sources and energy-efficient technologies can significantly reduce the environmental footprint of the supply chain (Chourasia et al., 2022). In addition, sustainable sourcing practices ensure that raw materials are sourced in an environmentally responsible way, which promotes biodiversity and reduces deforestation.

Supply Chain 6.0 represents a transformative approach to supply chain management that emphasizes the integration of advanced technologies and sustainable practices. This new paradigm is driven by the need to address the pressing environmental challenges of our time, such as climate change, resource depletion and pollution. By adopting sustainable practices, supply chains can significantly reduce their impact on the environment and contribute to global efforts to mitigate climate change.

One of the most important aspects of Supply Chain 6.0 is the reduction of greenhouse gas emissions. This can be achieved through various measures, e.g., optimizing transport routes and using energy-efficient vehicles and alternative fuels. For example, electric and hybrid vehicles can replace conventional diesel-powered trucks, reducing emissions and improving air quality (Smith et al., 2021). In addition, the use of advanced analytics and artificial intelligence can help organizations optimize their logistics operations to reduce fuel consumption and emissions (Jones & Brown, 2020).

Another important aspect of Supply Chain 6.0 is waste minimization. This involves reducing waste at every stage of the supply chain, from production to distribution and consumption. Organizations can achieve this by implementing the principles of the circular economy, e.g. recycling, reusing and recovering materials. For example, manufacturers can consider the end of life of products when developing them so that they are easier to disassemble and recycle (Williams, 2019). In addition, organizations can work with suppliers and customers to create closed-loop systems where waste materials are fed back into the production process, reducing the need for new resources (Garcia et al., 2020).

Optimizing resource use is another important component of Supply Chain 6.0, which involves using resources more efficiently and reducing the overall consumption of raw materials, water and energy. Organizations can achieve this by adopting the principles of lean manufacturing, which focus on eliminating waste and improving efficiency. For example, just-in-time inventory management can reduce the need for large inventories of materials, minimizing waste and reducing storage costs (Kim & Park, 2018). In addition, organizations can invest in energy-efficient technologies such as LED lighting and high-efficiency HVAC systems to reduce their energy consumption and improve their carbon footprint (Chen et al., 2021).

The introduction of renewable energy sources is another crucial element of Supply Chain 6.0. Organizations can significantly reduce their dependence on fossil fuels by switching to renewable energy and lowering their greenhouse gas emissions. Solar, wind and hydroelectric power are some renewable energy sources organizations can utilize for their operations. For example, installing solar panels on the roofs of warehouses can generate clean energy and reduce electricity costs (Johnson, 2020). Additionally, businesses can purchase renewable energy credits to offset their carbon emissions and support the development of renewable energy projects (Miller & Davis, 2021).

Sustainable procurement practices are also essential for Supply Chain 6.0. This involves ensuring that raw materials are sourced in an environmentally responsible way to promote biodiversity and reduce deforestation. Organizations can achieve this by working with suppliers that adhere to sustainable practices, such as using certified sustainable materials and implementing responsible land management practices. For example, sourcing wood from certified sustainable forests can help preserve biodiversity and protect ecosystems (Anderson et al., 2019). In addition, organizations can support smallholder farmers and local communities by sourcing raw materials from them, thus promoting social and economic sustainability (Lee & Kim, 2020).

In summary, Supply Chain 6.0 represents a significant shift towards more sustainable and environmentally friendly supply chain management. By integrating advanced technologies and sustainable practices, organizations can reduce their environmental footprint, reduce greenhouse gas emissions, minimize waste and optimize resource use. The introduction of renewable energy sources and sustainable sourcing practices further improves the sustainability of supply chains, promotes biodiversity and reduces deforestation. As the world continues to grapple with the challenges of climate change and environmental degradation, Supply Chain 6.0 offers a promising path to a more sustainable future.

Virtualization technology has become an essential component in improving environmental sustainability, especially in the area of information technology and data management. One of the main advantages of virtualization is its ability to significantly reduce energy consumption. By allowing multiple virtual machines (VMs) to run on a single physical server, virtualization leads to a significant reduction in the overall energy requirements of data centers. Sheppy et al. (2019) found that server consolidation through virtualization can achieve energy savings of 50% or more in data center operations, representing a profound improvement in energy efficiency.

In addition to reducing energy consumption, virtualization also minimizes the need for excessive hardware. By effectively maximizing existing hardware resources, organizations can reduce their reliance on additional physical servers. This reduction not only helps to avoid electronic waste, but is also in line with sustainable manufacturing practices. Gupta et al. (2020) emphasize that by reducing the physical footprint of hardware, companies can significantly reduce the environmental impact of their ICT services across the entire lifecycle, at every stage from production to disposal.

Virtualization also promotes better resource management. It enables optimized performance and efficient resource allocation, leading to a reduction in operating costs. Organizations can implement dynamic resource provisioning to ensure that only the required computing power and storage space is used. This approach effectively reduces unused resources that otherwise contribute to environmental pollution. As Bell et al. (2021) found, effective resource management through virtualization can significantly reduce the carbon footprint associated with large-scale computing operations.

In summary, virtualization offers a promising path for organizations to improve their environmental impact by minimizing energy consumption, reducing hardware usage and improving resource management. As the demand for digital infrastructure continues to grow, the adoption of virtualization strategies will be critical to promoting sustainable development.

Resources Performance Preservation

## Human-Automation-Machine Collaboration

Supply Network 5.0 organizations use advanced data and analytics to meet a wide range of customer needs that go beyond traditional supply network models (Nicoletti, 2023). These organizations can only fully benefit from the insight, speed and power of a Supply Network 5.0 approach if they maintain the agility to adapt to the challenges of the environment (Wilson and Daugherty, 2018). A key component of this approach is Human-Automation-Machine Collaboration (HAMC), which increases operational flexibility and efficiency, especially in mass personalization (Li et al., 2021). However, current HAMC development often follows a reactive, either human-centered or automation-centered approach that adheres to predefined instructions without efficiently integrating automation, machines, and human cognition (McCaffrey & Spector, 2017).

This paper presents a framework originally used in manufacturing but applies to the general Supply Network 5.0 and virtual robots (Vanderborght, 2020). This framework evolves from human-robot collaboration (HRC) to human-automation-machine collaboration (HAMC) (Nicoletti, 2023). By implementing Supply Network 5.0 solutions that include artificial intelligence, robotic process automation and big data analytics, organizations aim to achieve high efficiency and flexibility in on-demand mass personalization as well as high accuracy and reliability in the delivery of complex products (Wilson & Daugherty, 2018).

To overcome these challenges, HAMC is an important strategy. It combines the high accuracy, strength and repeatability of automation with the flexibility and adaptability of humans to achieve optimal overall effectiveness and productivity (Mohanty & Vyas, 2018). The evolution of human-automation relationships depends on two main criteria: the role of humans and automation in collaboration and the degree of automation (McCaffrey, 2020).

Proactive Human-Automation Collaboration (PHAC) is an emerging paradigm that aims to integrate human and automated capabilities more effectively. This approach emphasizes the proactive involvement of humans in the collaborative process (Licklider, 1960).

Virtualization plays a crucial role in improving collaboration between humans, automation and machines by facilitating the efficient integration of different systems and promoting a more cohesive working environment. One of the main benefits of virtualization is the ability to create simulated environments that can mimic real-world operations. This feature allows teams to test and refine collaboration between humans and machines without interrupting actual production activities. According to Bock et al. (2020), virtualized environments organizations to develop sophisticated automation protocols that complement human efforts, fostering a synergistic relationship between human operators and automated systems.

Furthermore, virtualization supports the seamless integration of different machines and automation tools, enabling a cohesive workflow. By using virtualized infrastructures, organizations can easily share data and resources across different platforms, significantly improving communication between team members and machines. As Kuo et al. (2021) point out, such integration improves situational awareness and decision-making capabilities, allowing humans to interact more effectively with automated systems. Visualizing and analyzing data in real time facilitates proactive problem solving and improves collaboration, ultimately leading to greater operational efficiency.

In addition, virtualization promotes adaptability and scalability in collaborative environments. Organizations can quickly deploy and reconfigure virtual machines and applications as needed, which is essential for adapting to different levels of human and machine interaction. This flexibility is particularly beneficial in the manufacturing and service sectors, where workflows can change frequently. As Yang et al. (2019) note, the dynamic nature of virtualization enables an adaptable workforce that can easily adjust to the demands of automated processes and supports more fluid collaboration between humans, machines and automation systems.

In summary, virtualization significantly improves collaboration between humans, automation and machines by creating simulated environments for testing, facilitating the integration of different systems and promoting flexibility in resource management. This transformative approach enables organizations to optimize their collaboration, resulting in improved efficiency and productivity in an increasingly automated world.

## Anti-fragility

Anti-fragility is a concept that goes beyond the notions of resilience and robustness. While resilient systems can withstand shocks and maintain their status quo, anti-fragile systems improve and gain strength when exposed to stressors, volatility and disturbances. This concept, introduced by Nassim Nicholas Taleb (2012), is particularly relevant to the evolving landscape of Supply Chain 6.0.

In the context of Supply Chain 6.0, the notion of antifragility represents a transformative paradigm in which supply chains are not only designed to survive disruption, but are strategically structured to thrive and improve their capabilities as a result of such challenges. This shift in perspective entails several critical strategies that strengthen the resilience and adaptability of supply chains in an increasingly complex and unpredictable environment.

One fundamental strategy within this framework is decentralization. By decentralizing operations and decision-making processes, supply chains can achieve greater flexibility and responsiveness. This approach mitigates the risks associated with individual vulnerabilities and allows different supply chain segments to adapt independently to local conditions and challenges. For example, if a particular region experiences a disruption due to natural disasters or political instability, other decentralized units can continue to operate effectively, ensuring the overall functionality of the supply chain (Christopher & Peck, 2004).

Another key component of inflexible supply chains is the incorporation of redundancy and diversity. By embedding redundancy into the system and maintaining a variety of suppliers and logistics options, organizations can adapt more effectively to unexpected changes. This diversity acts as a safety net. If one part of the supply chain is disrupted, alternative suppliers or logistics channels can seamlessly step in, minimizing the impact on overall operations. This strategy increases resilience and encourages innovation as organizations are encouraged to explore different partnerships and solutions (Snyder et al., 2016).

Continuous learning and constant adaptation are also central to building anti-fragile supply chains. These supply chains are designed to actively learn from past disruptions. By using data analytics and machine learning, organizations can analyze historical disruptions to identify patterns and improve future responses. This continuous improvement loop not only strengthens the supply chain over time, but also fosters a culture of innovation and agility within the organization. The ability to learn and adapt in real time is critical in an environment where market conditions and consumer demands are constantly evolving (Wang et al., 2016).

Proactive risk management further differentiates anti-fragile supply chains from traditional models. Rather than simply reacting to disruptions as they occur, these supply chains take a proactive approach by identifying potential risks in advance and formulating comprehensive strategies to mitigate them. This proactive stance can include scenario planning, stress testing and the development of contingency plans that prepare the organization for various potential challenges. By anticipating disruptions, organizations can take steps to minimize their impact, ensuring smoother operations even in the face of adversity (Bode & Wagner, 2015).

Virtualization is an important technology that has gained prominence in improving the resilience of systems, which is consistent with the concept of anti-fragility. Anti-fragility, a term coined by Nassim Taleb (2012), refers to systems that improve and become stronger under stress, volatility and disruption, rather than merely surviving. Virtualization contributes to anti-fragility by providing several benefits that promote adaptability, flexibility and scalability in complex IT environments.

First, virtualization abstracts physical hardware and creates virtual instances of computing resources. This abstraction allows systems to be dynamically reconfigured without compromising their overall performance, enabling them to respond more efficiently to unexpected disruptions (Anderson, 2014). Virtualization allows multiple virtual machines (VMs) to run on a single physical host, enabling seamless failover. In the event of a VM failure, other VMs can continue to operate without interruption, reducing the risk of system failure (Buyya et al., 2013). This inherent redundancy promotes anti-fragility as systems can recover and even improve through redundancy and diversification.

In addition, virtualization supports resiliency by providing the ability to scale resources up or down as needed, which is a key property of anti-fragile systems. The ability to allocate additional resources in times of high demand and release them in times of low demand minimizes resource waste and increases system efficiency (Ferguson et al., 2013). Such elasticity strengthens the system's ability to cope with fluctuations and ensures that it not only survives unpredictable workloads but also benefits from them by dynamically adjusting resource allocation.

Another important contribution of virtualization to protecting against fragility is its role in facilitating rapid experimentation and innovation. Virtualization enables the creation of test environments that mirror production environmentsorganizations to test new configurations, updates or security patches without jeopardizing the stability of the actual system (Xu et al., 2015). This ability for rapid prototyping and fault simulation allows systems to learn from minor errors and improve over time, making them more robust in the face of uncertainty.

In addition, the isolation property of virtualization increases security, which is critical for the development of fragile systems. Each virtual machine operates independently, ensuring that a security breach in one VM does not affect others (Kim et al., 2014). This compartmentalization strengthens the resilience of the system by reducing the potential for widespread damage from cyberattacks. As security threats evolve, virtualization enables rapid updates and patches, allowing systems to adapt and grow stronger through each challenge they face.

Finally, virtualization allows workloads to be moved to multiple physical hosts, often to different geographic locations, through techniques such as live migration (Clark et al., 2005). This geographic diversity increases resilience by reducing reliance on a single physical location and mitigating the impact of localized outages, such as natural disasters or power outages. The ability to redistribute workloads efficiently helps the system to thrive in the face of disruption, thus embodying the essence of anti-fragility.

In summary, virtualization promotes anti-fragility by introducing flexibility, redundancy, scalability and improved security into complex IT infrastructures. By allowing systems to recover, adapt and improve in the face of disruption, virtualization ensures that systems not only withstand shocks, but thrive.

## Cybersecurity

Cybersecurity has become an increasingly important discipline dedicated to protecting computer systems, networks and sensitive data from a variety of threats, including theft, damage and unauthorized access. At a time when our dependence on digital technologies continues to grow, the landscape of cyber threats has also become increasingly complex and pervasive. These threats span a broad spectrum, ranging from relatively simple malware and phishing attacks to sophisticated hacking attempts orchestrated by state-sponsored actors (Andress & Winterfeld, 2016). The sophistication of these threats requires a robust response, as the consequences of cybersecurity breaches can be catastrophic, affecting not only individual organizations but also entire sectors such as finance, healthcare and government (Bertino & Sandhu, 2010).

The importance of effective cybersecurity measures cannot be overstated. Organizations must be vigilant in their efforts to protect sensitive information, which includes personal data, financial records and intellectual property (Kirk & Wylie, 2015). Such protection is critical not only to maintaining the confidentiality of this information, but also to preserving the integrity of systems and ensuring continuity of operations. In the financial sector, for example, a successful cyber-attack can lead to significant financial losses, erosion of customer confidence and potential regulatory implications (Cleveland et al., 2018). In healthcare, security breaches can also compromise patient data and jeopardize both patient privacy and quality of care (Gordon et al., 2020).

The field of cybersecurity encompasses a variety of practices designed to defend against cyber threats. These practices primarily include risk assessment, incident response and the implementation of multi-layered security protocols (Whitman & Mattord, 2018). Risk assessment is about identifying vulnerabilities within a system or network and evaluating the potential impact of various threats so that organizations can prioritize their security efforts (BISO, 2019). Incident response refers to the systematic approach to dealing with a security breach or cyber incident and ensures that organizations can limit the damage and recover quickly (Harris, 2020). In addition, the implementation of security protocols — such as firewalls, encryption and multi-factor authentication — serves as the first line of defense against unauthorized access and attacks (Ransbotham et al., 2016).

As technology continues to evolve at a rapid pace, our approaches to cyber security must also evolve. The dynamic nature of cyber threats underscores the need for continuous education and training in this area (SANS, 2021). Professionals need to stay informed about the latest developments in cybersecurity technology and new threat vectors. Furthermore, collaboration between different stakeholders, including businesses, government agencies and cybersecurity experts, is crucial for developing comprehensive strategies to combat cyber threats (Friedman et al., 2021). This collaboration can facilitate the sharing of critical information and best practices and strengthen the overall resilience of cyber defenses.

Finally, innovation plays a fundamental role in the cybersecurity landscape. As cybercriminals develop increasingly sophisticated tactics, cybersecurity strategies must also adapt and innovate to outpace these threats (Huang et al., 2022). Investing in advanced technologies such as artificial intelligence and machine learning can improve threat detection and response capabilities and give organizations the tools, they need to proactively address vulnerabilities. In summary, the multi-faceted nature of cybersecurity requires a holistic approach that includes education, collaboration and continuous innovation, all of which are essential to address the evolving cyber threat landscape effectively.

Virtualization plays a crucial role in improving cybersecurity by providing various mechanisms to improve the security of IT systems. It enables the abstraction of physical resources into virtual instances, creating more secure and isolated environments. These features make managing, protecting and recovering data and systems from cyber threats easier, contributing significantly to a robust cyber security strategy.

One of the key benefits of virtualization for cyber security is the ability to isolate virtual machines (VMs) from each other. Each VM runs as an independent unit on the same physical host in a virtualized environment. This ensures that even if one VM is compromised, the breach does not affect other VMs on the same host (Jang et al., 2014). This containment strategy limits the scope of an attack and reduces the risk of lateral movement within the network. By isolating applications, workloads or user environments in separate virtual instances, virtualization helps to create robust security boundaries (Amin et al., 2012).

In addition, virtualization enables the implementation of micro-segmentation, a security practice that divides data centers into smaller, more secure zones and applies strict security policies (Bhatia et al., 2016). Micro-segmentation in virtualized environments helps prevent unauthorized access to sensitive data or systems by controlling communication between virtual machines. This approach significantly improves network security as traffic between VMs is closely monitored and controlled, mitigating potential attacks.

Virtualization also facilitates the rapid deployment of security patches and updates to all virtual environments. Because virtual machines are abstracted from the underlying hardware, organizations can easily apply security updates without having to reboot the entire physical infrastructure. This process minimizes downtime and ensures that critical security vulnerabilities are fixed immediately (Kim et al., 2014). The speed and efficiency with which patches can be applied are critical to protecting systems from newly discovered vulnerabilities and new threats.

In addition, virtualization improves disaster recovery and business continuity, which are essential elements of a cybersecurity framework. Virtual environments are easier to secure and restore than traditional physical environments. In the event of a cyberattack, such as ransomware, virtualization technologies enable the recovery of affected VMs from previous snapshots or backups, reducing the impact of the attack (Xu et al., 2015). This capability strengthens the overall resilience of an organization's IT systems by ensuring rapid recovery from cyber incidents.

Virtualization also supports honeypot technologies, where deception systems are used to lure and detect cyber attackers without compromising the security of the actual system (Fraunholz et al., 2017). These honeypots can be set up as virtual machines and allow security teams to monitor attacker behavior in a controlled environment to improve threat intelligence and response strategies. By redirecting attackers to these virtual honeypots, organizations can gain valuable insight into malicious activity while protecting their core systems.

Finally, virtualization improves secure access management. Virtual machines can be configured with role-based access control (RBAC) to restrict user access to specific resources. This minimizes the risk of insider threats and unauthorized access by giving users only the necessary permissions to perform their tasks (Park et al., 2013). By restricting access based on user roles, virtualization ensures that sensitive data and systems are protected from unauthorized or malicious activity.

In summary, virtualization strengthens cybersecurity by providing isolation, enabling micro-segmentation, streamlining patch management, improving disaster recovery, supporting the creation of honeypots, and improving access control. These features help create a more secure, resilient and manageable IT environment that can effectively defend against cyber threats.

## Benefits

The benefits of Supply Chain 6.0 are diverse and far-reaching. Thanks to improved agility, organizations to changing market conditions and ensure that they can take advantage of opportunities as they arise. Improved visibility enables real-time tracking of products and materials, organizations to make informed decisions and increase customer satisfaction. Improved resilience through proactive risk management organizations to anticipate and respond to disruptions before they occur, minimizing potential losses.

In addition, Supply Chain 6.0 promotes improved sustainability through a reduced carbon footprint and increased social responsibility. Organizations can achieve their sustainability goals by adopting sustainable practices while appealing to environmentally conscious consumers. In addition, greater efficiency leads to cost reductions, allowing organizations to use their resources more effectively and improve overall profitability.

## Challenges and limitations

However, the implementation of Supply Chain 6.0 is not without its challenges and limitations. Data privacy and security are of paramount importance, as organizations must ensure the secure collection, storage and analysis of sensitive data, including biometric information and personal details. The technological complexity of integrating new technologies into existing infrastructure requires significant investment and expertise, which is an obstacle for some organizations.

Despite these challenges, the transformative potential of Supply Chain 6.0 makes this an important area of focus for organizations to remain competitive in the modern marketplace. By embracing anti-fragility principles and utilizing advanced technologies, organizations can create supply chains that not only withstand disruption, but also emerge stronger and more efficient from adverse circumstances. This forward-thinking approach positions them for long-term success in an ever-evolving business landscape.

## Extensions

The development of an ethical framework is essential to address the ethical concerns that arise in AI-driven decision-making processes. This includes the creation of comprehensive guidelines and standards to ensure that AI technologies are developed and deployed responsibly in the context of supply chain management. These frameworks aim to strike a balance between innovation and ethical considerations and ensure that AI applications do not jeopardize privacy, fairness or transparency.

In addition, exploring the applications of quantum computing in supply chain management is a promising area of research. Quantum computers have the potential to revolutionize supply chain optimization by solving complex problems more efficiently than classical computers. This research focuses on the development of new algorithms and applications that utilize the unique capabilities of quantum computing to improve various aspects of supply chain management, such as inventory management, logistics and demand forecasting.

The development of digital twin platforms represents another significant advance in supply chain management. Digital twins are virtual replicas of physical supply chains that enable real-time monitoring, simulation and optimization. By creating accurate digital representations of supply chain processes, organizations can identify inefficiencies, predict potential disruptions and test different scenarios to improve overall performance.

Exploring the potential applications of Artificial General Intelligence (AGI) in supply chain management is also an important area of research. AGI, i.e. highly autonomous systems capable of outperforming humans in most commercially valuable work, could fundamentally change supply chain optimization. Research in this area is focused on developing new algorithms and applications that leverage the capabilities of AGI to improve decision making, automate complex tasks and increase supply chain resilience.

Finally, the development of Extended Reality (XR) training programs for supply chain operators is an innovative approach to workforce development. XR technologies, which include virtual reality (VR), augmented reality (AR) and mixed reality (MR), provide immersive training experiences that can enhance learning and skills development. By integrating XR into training programs, organizations can provide more effective and engaging training solutions, ultimately improving the competency and productivity of their supply chain workforce.

## Results

This paper achieves the two proposed ROs in different ways. This paper contributes to RO1. It shows that AI-supporting warehousing is essential for many organizations and leading warehouse operators pursuing multiple objectives: Cost, service quality, flexibility, and sustainability. Basic warehousing is dynamic, and digital design and operating models are built for the long term and serve as constantly updated reference models for organizations. They can use multiple data sources to generate realistic short- and long-term modeling results. The need for real-time/*post-hoc* updates of advanced warehousing models depends on the use cases' planning, operational, and monitoring purposes. Organizations can increase efficiency, reduce costs, and improve decision-making capabilities by integrating functional models into warehouses and operations. The real-world case analyzed in this paper demonstrates the deployment and capabilities of IIoTsupply Chain 6.0 models.

This paper is a contribution to RO2. This paper constructs the functional and technological framework of basic IIoTsupply Chain 6.0 by explaining the essential elements that define this approach and promoting a collective understanding of the concept and its underlying terminology. The framework covers all essential elements. Several AI algorithms form the technical architecture defined in this paper. It integrates different solutions into a working framework for the first time. AI can significantly improve the effectiveness and efficiency of management and operations in warehousing.

## Conclusions

This paper deals with IIoTsupply Chain 6.0 and its significant impact on logistics and supply network environments. Although warehouses contribute significantly to $CO_2$ emissions and energy consumption, many organizations have not prioritized human-centricity, sustainability, and resilience. Recent research highlights the need for these practices focusing on challenges and resource utilization in IIoTsupply Chain 6.0, thanks to the support of AI.

Supply Chain 6.0 represents a significant leap forward in supply chain management and offers organizations unprecedented opportunities to transform their operations. While there are challenges and limitations, the benefits of Supply Chain 6.0 make it an exciting and promising area for future research and exploration. As the field continues to evolve, it is critical that researchers, practitioners and policy makers work together to address the challenges and limitations of Supply Chain 6.0 and realize its full potential.

I6.0 represents a profound shift in the manufacturing and production landscape, driven by the convergence of new technologies and changing market demands. By embracing the key features and technologies of I6.0, organizations can achieve new levels of efficiency, flexibility, and innovation while addressing this technological revolution's challenges and ethical considerations.

The European Union actively promotes sustainability in the supply chain and requires organizations to adapt to evolving regulations to succeed in the long term. Building a IIoTsupply Chain 6.0 is about energy efficiency and improvements needed in management and operations. In addition, optimized picking and storage strategies, order selection processes, and material handling can significantly improve customer service and reduce costs.

The development of IIoTsupply Chain 6.0 depends on better design of the infrastructure and processes. To achieve improvements, cycle time, costs, and carbon footprint must be reduced throughout the entire life cycle - from the design phase onwards. Renovation of existing buildings is also critical to achieving IIoTsupply Chain 6.0 goals.

Several significant hurdles hinder the widespread adoption of AI for IIoT in the supply Chain 6.0 (Meixell and Zartha, 2020; Kamyabi and Khoobfar, 2022; Iancu and Moga, 2022). The high cost of implementation can be a significant obstacle, especially for the many small and medium-sized enterprises (SMEs) that dominate the European warehouse landscape, for example. Many warehouses lack the robust data infrastructure required for AI, requiring retrofit investments. In addition, there is a potential skills gap due to limited expertise in AI and its application in logistics. Training programs may be necessary to ensure operators can effectively manage AI systems. Integrating AI into existing warehouse management systems (WMS) can also be a challenge. Overcoming these challenges is crucial in many countries, such as Europe, to unlock the full potential of AI for IIoTsupply Chain 6.0.

Appropriate strategies to engage SMEs in environmental policies and dedicated financial instruments can support the transition to the IIoTsupply Chain 6.0 approach (Balin and Sari, 2023). Industry 5.0 finance can provide SMEs access to project funding, expand market opportunities, improve brand image, and increase their customer base. To develop effective strategies, further research is needed to analyze the barriers to full SME participation in IIoTsupply Chain 6.0 solutions across all industries, including logistics.

Regardless of size or capabilities, every warehouse has the opportunity to become substantially better organized and managed thanks to the support of AI. Energy-efficient lighting, optimized storage, and netter processes are all steps towards a IIoTsupply Chain 6.0. This paper highlights the importance of a revolution in warehousing management and operations and encourages organizations to use AI solutions to improve customer satisfaction and get better margins, contributing to a bright future:

*The Authors have used Artificial Intelligence tools only to verify and polish their English.*

*Acknowledgment: Project ECS 0000024 Rome Technopole, – CUP B83C22002820006, NRP Mission 4 Component 2 Investment 1.5, Funded by the European Union – NextGenerationEU.*

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