Applications of Industry 4.0 in Supply Chain Management: A Systematic Literature Review

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Abstract

In 2011, the German government introduced "Industry 4.0" as part of its high-tech strategy to maintain the competitiveness of the country's manufacturing sector and meet new challenges. This fourth industrial revolution relies on the Internet of Things (IoT), new technological advancements, real-time data transmission between products, customers, and manufacturing facilities, and the blending of virtual and physical worlds. End-to-end engineering and the integration of information and communication technologies are considered fundamental concepts and significant advancements in Industry 4.0. While the business sector plays a vital role in economic growth, the introduction of new technology and increased product and production complexity impact industrial companies and their workers. Critics of Industry 4.0 emphasize its technocratic focus on digitalization and new technology, despite its potential to increase economic values, competitiveness, productivity, and revenue growth. The integration of Industry 4.0 impacts all corporate operations, from purchasing and production to customer management, leading to significant changes in processes, communication, and relationships. Industry 4.0 introduces uncertainties, hazards, feedback cycles, and dynamics that pose challenges to modern production and logistics systems, supply chains, and Industry 4.0 networks. This study critically examines current applications and classifications of Industry 4.0 and proposes potential directions for future research. It suggests that interdisciplinary supply chain optimization methodologies must continue evolving, and collaboration between supply chain specialists and control engineers could enhance the realism of dynamic planning and modeling and the efficiency of supply chains, Industry 4.0 networks, and production and logistics systems. Lastly, this study examines developments in digital supply chain management and the trend toward the intellectualization of Industry 4.0.

Keywords
Industry 4.0, Supply Chain Management, Industrial Revolution, Sustainable Manufacturing, and Smart Manufacturing.

1. Introduction
Researchers and practitioners are driven to develop strategies and supply chain capabilities that address the challenges and contribute to achieving sustainable development goals, driven by the increasing concern for sustainability. It is essential to establish a comprehensive model that facilitates understanding the interrelationships between supply chain practices, Industry 4.0 technology, and supply chain performance metrics. Consequently, this study examines the impact of Industry 4.0 technologies on supply chain management strategies and supply chain performance indicators. Structural equation modeling (SEM) was utilized for data analysis. This study makes several contributions. Firstly, the findings demonstrate that the adoption of Industry 4.0 technology is influenced by supply chain management techniques. Secondly, the results indicate significant improvements in supply chain performance metrics due to Industry 4.0 technologies. Moreover, Industry 4.0 technology mediates the relationship between supply chain management techniques and supply chain performance measurements. The outcomes also offer valuable insights into the underlying principles for the successful adoption and effective utilization of Industry 4.0 technologies. The ecology of supply chains (SCs) is recognized as the foundation for societal, economic, and environmental development. It relies heavily on the interactions and feedback among the various entities within SCs, as well as society, the economy, and nature (Ivanov et al., 2021a; Ivanov et al., 2021b).

Industry 4.0 emphasizes the integration of cutting-edge technologies into business and supply chain activities, resulting in a more resilient supply chain, particularly in terms of disruptions. Among the most challenging disruptions is the disruption of the distribution center. Luong et al. provide a mathematical approach to capture and mitigate this type of risk, benefiting from the real-time data offered by Industry 4.0 for decision-making (Luong et al., 2022).

Industry 4.0, also known as smart manufacturing, refers to the digital transformation achieved through technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Cloud Computing (CC), Machine Learning (ML), and Data Analytics (DA), among others. These concepts are based on connecting machines and systems to self-correct and adapt in response to changing environmental conditions. Smart manufacturing progresses from simple digitalization and automation of individual machines to interconnecting machines using IoT technology and leveraging data from connected systems for real-time decision-making.

Lean manufacturing, focused on enhancing customer service and eliminating process waste (Womack et al., 2003), is widely recognized as one of the most employed process management techniques (Tortorella et al., 2017). The role of Industry 4.0 technology in effectively implementing existing supply chain strategies (such as lean, agile, resilient, green, and sustainable practices) remains a critical question. Accordingly, we investigate how Industry 4.0 technologies interact with current supply chain practices to influence supply chain performance (Shadravan et al., 2022).

Based on a thorough examination of the literature, we present a conceptual framework and a set of research hypotheses. The conceptual framework comprises seven independent variables, including lean, agile, resilient, green, sustainable practices, Industry 4.0 technologies, and supply chain performance (Shadravan et al., 2023). The dependent variables are supply chain performance, encompassing operational performance and sustainability (economic, social, and environmental), while the mediating variables are Industry 4.0 technology (Figure 1) (Sharma et al., 2022).

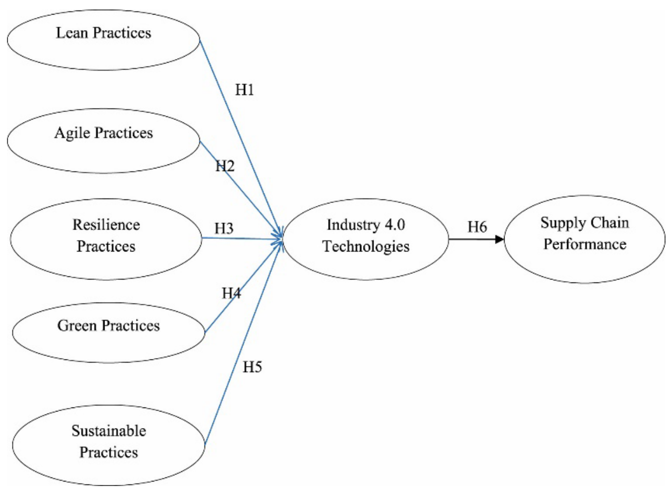

Figure 1. Conceptual framework and hypothesis grounded (Sharma et al. 2022).

Supply chains (SCs) are susceptible to unforeseen interruptions and failures arising from various interactions. Recently, SCs have faced significant issues caused by natural and artificial disturbances, bringing operations to a standstill. The resulting damage extends beyond any single entity, impacting the economy, communities, and the environment on a large scale (Khan et al., 2022b; Ivanov et al., 2021a; Ivanov et al., 2021b).

Furthermore, 193 nations have endorsed seventeen Sustainable Development Goals (SDGs), aiming to create a wealthier, more inclusive, sustainable, and resilient world by 2030 (United Nations, 2019). The opportunities associated with these goals vary across industries. For instance, in the energy, natural resources, and chemicals sectors, the focus is on universal access to energy, zero-carbon energy, sustainable production, and community development (KPMG and United Nations, 2016a). In the transportation industry, the emphasis is on inclusive mobility, resource efficiency, safety and security, and transportation infrastructure (KPMG and United Nations, 2016b). Similarly, the manufacturing industry aims for sustainable products, sustainable production, affordable goods, and enterprise development (KPMG and United Nations, 2016c). Consequently, to meet management expectations and contribute to the SDGs while remaining competitive, SCs must enhance their flexibility, responsiveness, and sustainability (Yu et al., 2022c; Ivanov et al., 2021a; Ivanov et al., 2021b).

According to Alicke et al. (2017), the proper implementation of Industry 4.0 technology can lead to a 30% reduction in operational expenses, as well as a 75% decrease in lost sales and inventory. Similarly, Küpper et al. (2017) estimated that combining lean techniques with Industry 4.0 technologies can result in cost reductions of up to 40%, whereas implementing lean alone reduces costs by 15-20%, and Industry 4.0 alone reduces costs by 10-15%. Despite notable progress and practical implementations in each framework, industries remain hesitant to adopt Industry 4.0 technology in conjunction with existing supply chain methods (Küpper et al., 2017) due to a lack of available material on the integration of Industry 4.0 with existing SC techniques (Raut et al., 2021; Sharma et al., 2021; Ivanov et al., 2021a).

To address the research gaps mentioned above, we aim to answer the following research questions:
Q1: To what extent do current supply chain practices influence the transition of supply chains to Industry 4.0 technologies?
Q2: How do Industry 4.0 technologies impact supply chain performance? What is the magnitude of this influence?
Q3: Does Industry 4.0 technology mediate the relationship between existing supply chain practices and supply chain performance?

2. Literature Review

2.1 Smart Manufacturing

Various terminologies have been used interchangeably when assessing written literature, including data-driven production, Industry 4.0 technologies, advanced manufacturing, factories of the future, and the fourth industrial revolution (Buchi et al., 2020). These concepts refer to the future of manufacturing by leveraging linked and networked technologies to create value for companies and society (Roblek et al., 2016). The general term refers to machines equipped with data-gathering devices that can interface with other machines and systems to achieve specific goals. Smart manufacturing, which focuses on integration, interoperability, and bridging the gap between the physical and virtual worlds, has gained significant attention in recent studies (Chen et al., 2008; Tang et al., 2016).

Interoperability establishes linkages between systems to enable sharing of knowledge and skills. It involves the ability of different systems to understand and function together in various situations. For machines, it means accessing the resources of other machines, while in a networked environment, it refers to the interaction among the enterprise's systems. Initially, research focused more on the component-level application of interoperability, considering specific technologies such as cloud services and big data. However, recent articles have explored the integrative features of these technologies in areas like design, planning, production, and human resource management.

Smart manufacturing aims to utilize data from the product lifecycle in intelligent systems to enhance all production processes positively. According to Frank et al. (2019), the concept of Industry 4.0 consists of underlying technologies and the front end. The front-end technology dimension includes initiatives related to smart working, smart products, smart supply chains, and smart manufacturing. Fundamental components of technology include IoT, big data, analytics, and cloud services. Wang et al. (2016) proposed a multi-layered view of production environments, including the physical layer (shop floor and visible activities), data layer (uploading data to the cloud), intelligence layer (software and tools for analysis), and control layer (human supervision).

Data-driven smart manufacturing comprises manufacturing modules, data-driven problem processing, real-time monitoring, and the utilization of big data for tasks like material assessment, energy efficiency management, and predictive maintenance. It enables intelligent decision-making and reduces human interaction in smart factories (Wuest et al., 2016). Big data support activities such as monitoring, optimization, and simulation in smart manufacturing (Tao et al., 2018). By collecting and analyzing data, smart manufacturing enhances process efficiency and product performance. It involves data collection from the production environment, analysis in cloud-based data centers, monitoring for quality control and process adjustment, and using data to anticipate issues and suggest solutions (Tao et al., 2018).

Smart manufacturing projects have shown improvements in production flexibility, performance, error reduction, efficiency, and setup time (Buchi et al., 2020). Adoption of smart technologies can lead to higher efficiency and production capacity (Buchi et al., 2018). Product development uses consumer data to determine important features and requirements, while network optimization and resource allocation can be enhanced by utilizing data. Machine data aids in predicting equipment defects and enables proactive maintenance (Tao et al., 2018). Augmented reality empowers end-users to minimize interruptions on the shop floor (Van Lopik et al., 2020), and data mining approaches improve production processes and quality in small manufacturing businesses (Oliff and Liu, 2017). IoT helps lower costs as well as increase quality, efficiency, and predictive maintenance services (Aheleroff et al., 2020).

2.2 Emerging Technologies

Numerous researchers have discussed smart manufacturing, also known as Industry 4.0 technologies, in relation to various aspects such as augmented and virtual reality (Kolberg and Zühlke, 2015), additive manufacturing (Chan et al., 2018), the internet of things (Wu et al., 2017), and big data analytics (De Mauro et al., 2015; Addo-T).

Wu et al. (2013) used Azuma's work (1997) to explain virtual reality as a technology that provides real-time interactions and three-dimensional representations of relevant objects. Additive manufacturing, on the other hand, utilizes digital data, specialized polymeric materials, and a layer-by-layer manufacturing process (Wu et al., 2013). The Internet of Things (IoT) enables the detection and remote control of autonomous objects and devices (Wu et al., 2017; Ketzenberg and Meters, 2020). Big data, referring to the gathering and analysis of large amounts of data, enhances decision-making capabilities (Astill et al., 2020).

Chiarello et al. (2018) explained the fourth industrial revolution by outlining enabling technologies, including additive manufacturing, augmented reality, virtual reality, 3D printing, computing, programming languages, protocols and architecture, the internet of things, communication networks and infrastructures, production and identification technologies, digital transactions, and big data. They provided descriptions of these technologies for those familiar with Industry 4.0. Osterrieder et al. (2020) emphasized eight key perspectives—cyber-physical systems, IT infrastructure, human-machine interface, cloud manufacturing and services, decision making, and data handling—as crucial to the development of smart manufacturing. Pacchini et al. suggested that to accelerate the adoption of Industry 4.0, eight enablers, including artificial intelligence, additive manufacturing, the internet of things, cyber-physical systems, cloud computing, big data, augmented reality, and collaborative robots, were empirically tested in the Brazilian auto manufacturing industry. Kusiak et al. (2019) provided detailed descriptions of the characteristics of smart manufacturing, covering prediction technologies, agents, data storage, cloud computing, automation and processes, and digitization.

2.3 Supply Chains and Smart Manufacturing

Smart manufacturing refers to the collaborative functioning of interconnected devices within a Cyber-Physical System (CPS), creating an environment capable of adapting to changes and suggesting optimal alternatives. It is crucial to recognize that the success of smart manufacturing relies on the collective efforts of multiple entities. If one entity fails to adopt smart manufacturing concepts, it hinders the achievement of global optimal outcomes. Each entity contributes on an individual level to shape the journey from raw materials to end consumers. Similar to interconnected physical assets in a smart environment, smaller individual entities must operate as interconnected platforms to enable the entire supply chain to function effectively as a whole (Nasiri et al., 2020).

Existing literature focuses on the digital transformation of the industrial sector's supply chain. The integration of physical processes or devices with various digital platforms is referred to as smart technology. The incorporation of smart technologies into the current supply chain can lead to significant improvements in a company's internal and external performance (Nasiri et al., 2020). Fig. 2 provides a visual representation that helps readers better understand the key differences between traditional supply networks and digital supply chains.

Preindl et al. (2020) demonstrated how Industry 4.0 and digital transformation can facilitate the establishment of a fully digital supply chain by enhancing operational transparency through centralized operations. However, achieving this level of transparency requires the implementation of appropriate information-sharing standards. It is important to emphasize that information sharing across the supply chain is essential for enhancing process efficiency and effectiveness. In line with this perspective, Ding's (2018) research revealed that the innovations and technologies of the fourth industrial revolution enable autonomous decision-making throughout the entire supply chain (Figure 2).

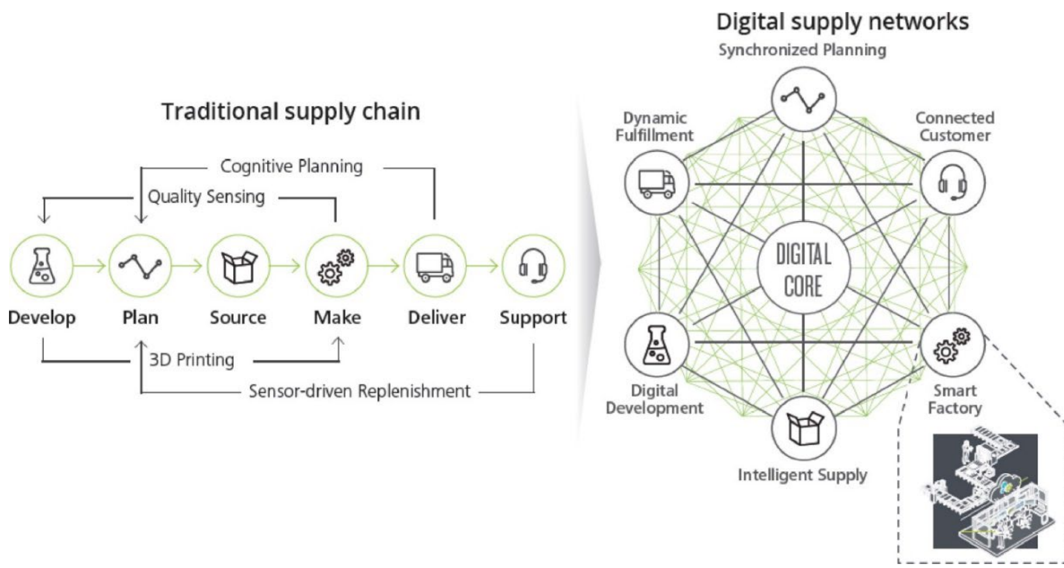

Figure 2. Schematic of traditional supply chain and digital supply networks (Shao et al. 2021).

3. Methods

To address the lack of systematic studies on the implementation of the Industry 4.0 concept in the supply chain, this research employs an exploratory case study model focusing on the packaging supply chain in Pakistan. According to Eisenhardt (1989), qualitative data often contributes to understanding the underlying dynamics of phenomena. Case study research is particularly useful in exploring management difficulties and capturing emergent theories (Yin, 2009; Eisenhardt and Graebner, 2007). Additionally, inter-organizational relationships are thoroughly investigated to generate qualitative, interpretive, and exploratory data (Maanen, 1998). Exploratory investigations, which shed light on novel subject matters, are also employed (Brown and Brown, 2006).

The objective of this study is to use exploratory and qualitative research techniques to identify potential innovative approaches to integrating supply chain and smart technologies, enhancing our understanding of the impact of such initiatives on smart organizations (Zikmund et al., 2013). The single-case approach is utilized to examine the evolving phenomenon of Industry 4.0 deployment across the supply chain and uncover the dynamics that arise during the implementation process (Siggelkow, 2001). This approach is particularly helpful in describing the evolution of a business or phenomenon (Siggelkow, 2002), especially when the goal is to replicate the adopted procedure (Leonard-Barton and Deschamps, 1988).

The organization chosen for this study was selected through theoretical sampling, considering its potential to document the development of Industry 4.0 implementation across a supply chain that includes the focal firm, its supplier, and a downstream customer (Eisenhardt, 1989; Siggelkow, 2007). A specific procedure was designed to guide the process of conducting semi-structured interviews with the team members directly involved in the implementation process. These interviews took place in person at the facilities of the collaborating organizations. The interview data were transcribed and shared with the team for additional feedback. The information gathered from the interviews was verified using three sources: project data, interviews, and additional feedback. After analyzing the case data, an implementation framework was proposed and shared with implementing managers and Industry 4.0 researchers to validate the results.

4. Discussion

Recent technological advancements have initiated the development of smart factories, which aim to optimize the flow of information between the physical infrastructure and the internet within an integrated and networked system known as Industry 4.0. To achieve peak performance, these smart factories rely on advanced data management and analytics technologies. However, the full potential of Industry 4.0 can only be realized when the concept of the smart factory is extended throughout the entire supply chain, resulting in smart supply chains. Both large and small businesses, including those in the automotive, electrical, and pharmaceutical industries, are embracing smart manufacturing (Müller, 2019).

This study focuses on the application of Industry 4.0 concepts to connect different layers of the supply chain from start to finish. The interaction between various entities was triggered by a requirement or issue that emerged at the downstream end of the value chain. Positioned as the central partner, the firm took the initiative and assumed a dominant role due to its understanding of sophisticated management tools and its status as a significant corporation in the field. The case data demonstrate the existence of several stages in the adoption process of Industry 4.0 throughout the value chain. These stages include the visualization phase, first-level linkage phase, linked supply chain phase, and the final smart supply chain phase.

4.1 The Visualization level

The initial phase that marks the beginning of connected supply chains is referred to as the trigger phase, also known as the visualization level. However, it's important to note that in this context, the term "connected" supply chain does not have the same meaning as typically used in supply chain collaboration literature. According to research on supply chain cooperation, collaboration is facilitated by mutual trust, which leads to activities such as information exchange, planning, and product creation. These collaborative activities enhance efficiency across the entire value chain (Chopra and Meindl, 2016).

In this context, the term "connected" is used more literally, indicating a foundation of connectivity that enables intelligent systems to make automatic decisions within the framework of Industry 4.0. While traditional supply chain connections aim for visibility and collaborative planning (Simchi-Levi et al., 2003), the connection in the Industry 4.0 context facilitates automated physical planning, information exchange processes, control, and tasks (Pereira and Romero, 2017), as well as end-to-end visibility across the value chain (Miragliotta et al., 2018), thus improving supply chain efficiency.

In the case discussed, the focal firm, positioned in the middle of a three-tier supply chain, assumed the role of the champion and oversaw the journey. When a problem was identified at the downstream end, the focal firm took the initiative to lead the project. Ideally, the champion firm possesses the necessary resources, vision, and leadership capabilities to drive the visualization process (Tangpong et al., 2008). The firm's dominance in the category, advanced management techniques employed, and significant product ownership all supported this role. Within the champion firm, the initial step involved forming a project team to examine the issue and develop a practical strategy. The focal firm already had experience with cross-functional Kaizen initiatives and had achieved an advanced level of implementation of the World Class Manufacturing (WCM) principle. It had also been internally working on the digitization concept and had an internal roadmap aligned with the implementation of the WCM principle at a higher level.

4.2 Connected Supply Chain

The team proceeded to gather the necessary specifications at their facility using the data obtained from the supplier. However, additional data needed to be collected to supplement the existing information. The team set up equipment and used sensors to collect data on the crease profiles, which also revealed process issues at the focus firm's level. Subsequently, the team aimed to connect this data with the data recorded at the supplier's end (Barratt, 2011). To accomplish this, data science professionals assisted in mapping the data from both sources.

The next step in this phase involved connecting with the third partner in the value chain. However, there was a challenge in coding the product's external appearance, particularly in identifying dents that would appear in the finished product. There were no criteria or measuring devices available to assess this quality. Additionally, the high production pace of 24,000 packs per hour made it difficult for a human to count defects in real-time. Human inspection could only be implemented after the production process, leading to associated expenses and delays. In order to address this, the team explored alternative options to automatically detect the presence of dents. They installed a camera equipped with artificial intelligence that could identify dents, with the assistance of data experts (Pang et al., 2020). The camera provided data to determine which dents should be counted and which should be ignored. The subsequent step involved connecting the dent data with the paper board data flowing from the lower levels of the supply chain.

4.3 Smart Supply Chain

Finally, the data were successfully linked together, enabling the system to take corrective action at the appropriate level based on the identified defects. However, it's important to recognize that this achievement should not be seen as the endpoint of the smart technology implementation process within supply chain operations, as envisioned by industry 4.0. Instead, it marks the beginning of a journey that aims to uncover numerous areas for interconnected development. This journey will require ongoing investments in both the relationship and technological aspects of the problem.

To facilitate this continuous improvement, it is essential to invest in IoT devices for real-time information exchange among supply chain participants, RFID sensors for real-time vehicle tracking, and centralized manufacturing execution systems through cloud computing (Almada-Lobo, 2015). Furthermore, it is crucial to acknowledge that the experimentation and exploration of cutting-edge technologies will demand ongoing commitments of time and financial resources. Consequently, the team's profile may need to be significantly expanded to continually explore the usage of advanced technology (Ghadimi et al., 2019).

Figure 3 illustrates the levels of collaboration, along with a summary of their technological components and the organizational enablers required to progress towards more advanced stages. This visual representation provides a clear overview of the collaboration levels and the key factors necessary for advancing the implementation of industry 4.0 technologies within the supply chain.

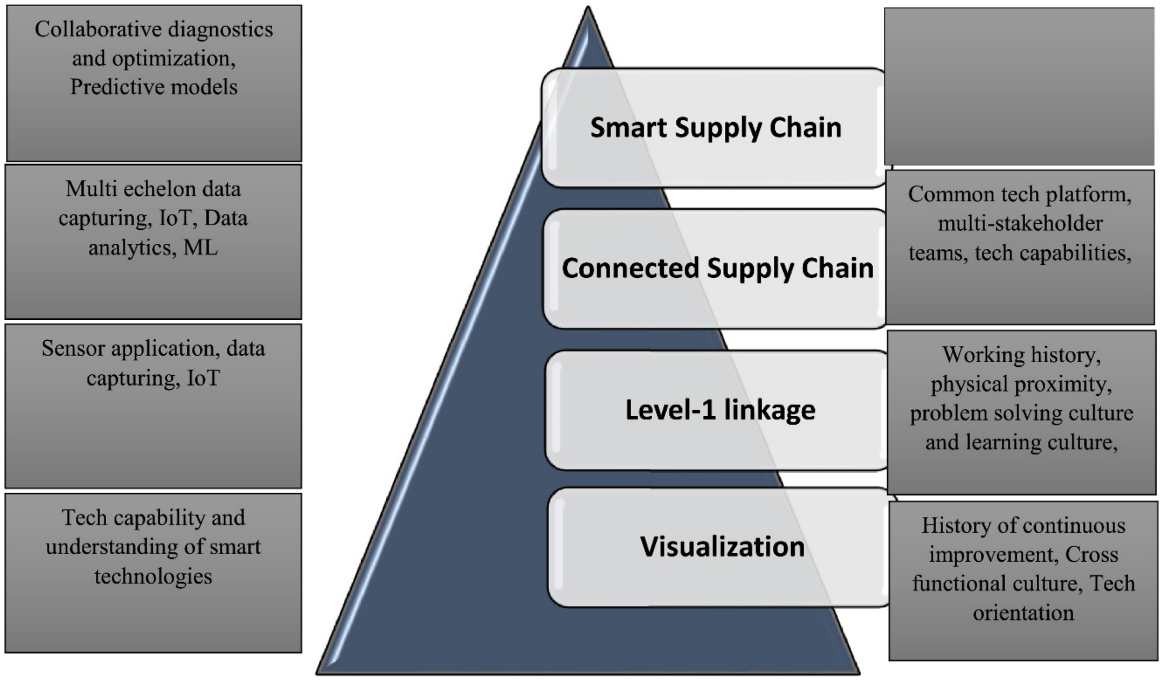

Figure 3. Implementation phases for Industry 4.0 across the supply chain (Shao et al. 2021).

5. Conclusion

The introduction of the Industry 4.0 concept has led to increased adoption of cutting-edge technologies like IoT, cloud computing, big data analytics, smart sensors, and robotics in various industries. Enterprises are beginning to experience the benefits of implementing these technologies in their manufacturing systems, leading to improved process efficiencies. However, from a supply chain perspective, it is essential to consider two key factors. Firstly, it is important to avoid adopting the concept of smart factories in isolation, as this may result in compatibility issues when implementing it in larger supply chains later on. Taking an end-to-end approach is a widely recognized practice in supply chain literature to enhance operations and increase efficiencies. However, empirical studies focusing on the Industry 4.0 concept within supply networks are limited, with most existing studies falling under the conceptual framework. Consequently, there is a dearth of research on the practical application of Industry 4.0 throughout supply chains. To address this gap, this study proposes a progressive framework for implementing industry 4.0 across the entire supply chain, based on exploratory investigations of technology adoption within supply networks. The framework consists of four levels of interaction among supply chain participants and emphasizes the adoption of cutting-edge technologies while highlighting the organizational enablers required for successful implementation. It is worth noting that the first stage of the framework focuses on establishing foundational elements such as team building, cross-functional collaboration, and project visualization. Companies with a history of cross-functional continuous improvement programs are better positioned to advance quickly to the subsequent phases. The following stages involve the adoption of advanced tools like IoT and machine learning, leveraging the existing cooperation among supply chain partners. The adoption of Industry 4.0 concepts across supply chains should not be seen as the completion of a project but rather as the start of a new journey of discovery and continuous application of evolving technologies. This proposed framework provides insights for firms aiming to leverage Industry 4.0 throughout their supply chains. It emphasizes the importance of relationship components among supply chain participants in the effective implementation of intelligent initiatives across the entire supply chain. Additionally, the study highlights the value of integrating data specialists who can access external knowledge, expanding the team's expertise.

Further research can expand on this framework by examining the application of Industry 4.0 tools in different sectors and geographical areas. The study acknowledges that only a few Industry 4.0 tools were explored, and future research could investigate the broader utilization of technologies such as additive manufacturing, augmented reality, and autonomous robots at various supply chain levels. Industry 4.0 is a new phenomenon that requires coordination and connectivity across organizational boundaries, providing opportunities to investigate relationship dynamics within this larger phenomenon. It is also crucial to examine the technological capabilities and cooperation history of partnering companies. By considering these factors and conducting further research, a deeper understanding of Industry 4.0 and its implications for supply chains can be achieved, leading to more effective and innovative implementations in the future.

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