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INVESTIGATING CAUSE-AND-EFFECT RELATIONSHIPS BETWEEN SUPPLY CHAIN 4.0 TECHNOLOGIES

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ABSTRACT
The developments of the fourth industrial revolution have caused changes in all areas of society, including production. The changes in production caused by the fourth industrial revolution have also resulted in fundamental changes in the supply chain and have converted it to supply chain 4.0. Organisations must be receptive to supply chain 4.0 to maintain their competitive advantage. Therefore, this study aimed to investigate the relationships among supply chain 4.0 technologies so that, by learning and understanding these connections, industries can pave the way for the implementation of these technologies in their supply chains and use them in problem-solving. The literature review was used to identify the supply chain 4.0 technologies, and the Delphi technique was applied to extract them, including the Internet of Things (IoT), cyber-physical systems, cloud computing, big data, blockchain, artificial intelligence, Radio-frequency Identification (RFID), augmented reality, virtual reality, and simulation. The relationships of supply chain 4.0 technologies were examined using the DEMATEL technique and based on interpretive structural modelling (ISM), their deployment map was drawn. The type of technologies was determined using the MICMAC method. The MICMAC analysis found that the artificial intelligence technology is independent and, based on the findings through the DEMATEL technique, this technology is related to simulation, which belongs to the first level of the interpretive structural modelling technique, and IoT, cloud computing, big data, and blockchain technologies, which are at the second level. Based on the ISM method, RFID, virtual reality, augmented reality and simulation technologies are located at the first level; IoT, cyber-physical systems, cloud computing, big data and blockchain technologies are situated in the second level; and artificial intelligence technology belongs to the third level. According to the related literature, few studies have been conducted on the issues of supply chain 4.0 and the technologies that affect it.

KEY WORDS
supply chain management (SCM), supply chain 4.0, Industry 4.0, DEMATEL, ISM, MICMAC

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INTRODUCTION

The supply chain is vital to the organisation as it must provide the facilities needed to meet critical processes and procurement requirements (Sobb, Turnbull & Moustafa, 2020). The supply chain is a type of pull production that processes in response to customer requests and consists of all stakeholders, including customers, suppliers, manufacturers, transportation, warehouse workers, etc. To keep its competitive advantage, the supply chain must adapt to

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changes in technology and customer needs and requirements (Ramirez-Peña et al., 2020).

With the advent of the Fourth Industrial Revolution, to achieve or maintain a competitive advantage, the supply chain must achieve advanced technological changes to meet the expectations of its stakeholders. The Fourth Industrial Revolution restructured all supply chain processes from the supply of raw materials to the production line and the last stage when the product reaches the end customer. Under these circumstances, the supply chain is digitised and renewed with more advanced technological equipment (Kaya, Paksoy & Garza-Reyes, 2020).

The Fourth Industrial Revolution, or Industry 4.0, was introduced in 2011 in Hannover, Germany. The strategy of Industry 4.0 has directly affected the competitive global market and is also a natural source of value creation (Frederico, 2021a). The biggest goal of Industry 4.0 is to develop an automated production system in which different machines in a factory can communicate with each other, detect environmental conditions (heat, humidity, energy, weather, etc.) and identify the needs of the system through analysing the collected data (Kaya, Paksoy & Garza-Reyes, 2020). Industry 4.0 changes in production have also affected the supply chain because it is inseparable from production.

With the advent of Industry 4.0 systems, the term "supply chain 4.0" was coined, which expressly signifies the Fourth Industrial Revolution and the integration of intelligent systems into supply chain systems. Supply chain 4.0 is known for the physical and technological integration of systems across the network, which enables increased productivity, organisation, and profitability. It is identified with actions independent from location, prevalent integration, various automated services, and its ability to respond to customer needs and requirements (Sobb, Turnbull & Moustafa, 2020). Supply chain 4.0 drivers are mainly big data and the IoT, under which complementary technologies such as Radio-frequency identification (RFID), sensors, Global Positioning System (GPS), Electronic Data Interchange (EDI), and data sensing equipment can be easily tracked throughout supply chain activities (Kaya, Paksoy & Garza-Reyes, 2020).

Based on the literature review, a limited number of studies have been conducted on supply chain 4.0 and the technologies that affect it. In research with a systematic literature review and content analysis on the issues of knowledge management and supply chain 4.0, Sartori et al. (2021) proposed a conceptual model for knowledge management in the area of supply chain 4.0. Liu & Chiu (2021) investigated the relationships between supply chain digitisation and firm performance using the PLS-SEM method. Kaya et al. (2020) investigated the impact of Industry 4.0 on the supply chain and the role of the IoT and big data in the supply chain industry. Sobb et al. (2020) studied military supply chains 4.0 and explored their unique differences from commercial supply chains. Ramirez-Peña et al. (2020) investigated the relationships among supply chain 4.0 sustainability in the aerospace, shipbuilding and automotive sectors. In their research results, it was found that the lack of identification of supply chain 4.0 technologies has caused the lack of understanding of supply chain 4.0 by industries. Therefore, to fill this gap, this study first identified these technologies and then investigated the relationships among them.

According to the studies described in the supply chain literature, supply chains are currently ineffective and lack transparency. Creating a supply chain and maintaining its effective management is complicated, which affects not only the profits of companies and manufacturers but also the final price of the product. Therefore, under these circumstances, most supply and distribution networks face problems with managing all these components together. Many of the problems of current supply chains can be solved by applying and implementing supply chain 4.0 technologies because supply chain 4.0, by relying on its ability, offers excellent and innovative ways to maintain competitive advantage and better supply chain management. Therefore, this study aimed to investigate the relationships among supply chain 4.0 technologies using DEMATEL and ISM methods so that by learning and understanding these relationships, the industries can implement the technologies in their supply chains and solve related problems.

This study focused on supply chain 4.0 technologies to increase the productivity of industries and reduce or eliminate the major problems of the traditional supply chain. The next sections of this paper discuss the theoretical foundations, the methodology, conclusions, discussion, and, finally, present conclusions.

1. Literature review

1.1. Supply chain 4.0

A supply chain is a network of systems, processes, and organisations that produce valuable goods and services and deliver them to the end user. Supply chains are the links between nations, physical distribution networks, and transportation systems, forming a global network. Supply chains include flows of materials, goods, and information that passes within and through the organisations. They are linked by a range of tangible and intangible facilitators, including relationships, processes, activities, and integrated information systems. Their essential technologies are transport systems, communication platforms and networks, and physical distribution networks (Sobb, Turnbull & Moustafa, 2020; Kozma, 2017).

The supply chain has undergone fundamental changes with the advent of the fourth industrial revolution or the so-called industry 4.0. Industry 4.0 combines advanced manufacturing techniques and Information Technologies (IT) to create intelligent systems. Industry 4.0 is building Intelligent Manufacturing Systems (IMS) by changing modes of operation, design, product service, and manufacturing systems. This is a new technological and forward-looking perspective aimed at increasing the effectiveness and efficiency of the whole industry chain. Industry 4.0 is based on the advent of new technologies, including Additive Manufacturing, cloud computing, the Internet of Things (IoT), Cyber-Physical Systems (CPS), and big data systems. These technologies can provide operations control and enable real-time adaptability and flexibility based on demands. They also allow the production of small and customised batches of production. The main advantages of these technologies are the creation of intelligent systems that provide better energy efficiency at the factory level and thus have positive environmental impacts (Nara et al., 2021). The changes that the Industry 4.0 technologies have made to the supply chain have led to fundamental changes in the supply chain and the advent of a new form of the supply chain, known as the fourth-generation supply chain or supply chain 4.0.

Supply Chain 4.0 is defined as a set of related activities linked to each other through the coordination, planning, and control of products and services to suppliers and consumers. It aims to find new ways to create added value for customers and suppliers and generate more revenue through the integration and coordination of forecasting, ownership, production, distribution, sales, and marketing processes (Martins, Simon & Campos, 2020). Supply chain 4.0 is the integration of communication and production technologies that enhance the production of traditional supply chain systems through location-independent actions, routine integration, various automated services, and its ability to respond to customer needs and requirements. Fig. 1 shows the dependence of a supply chain in the Industry 4.0 context, which indicates the integration of customers, suppliers, tools, factories, and engineering to get connected through the physical supply network (Sobb, Turnbull & Moustafa, 2020).

Having additive manufacturing technologies, automation, industrial robots, augmented reality, cyber security, blockchain, the Internet of Data — people and services —, semantic technologies, simu-

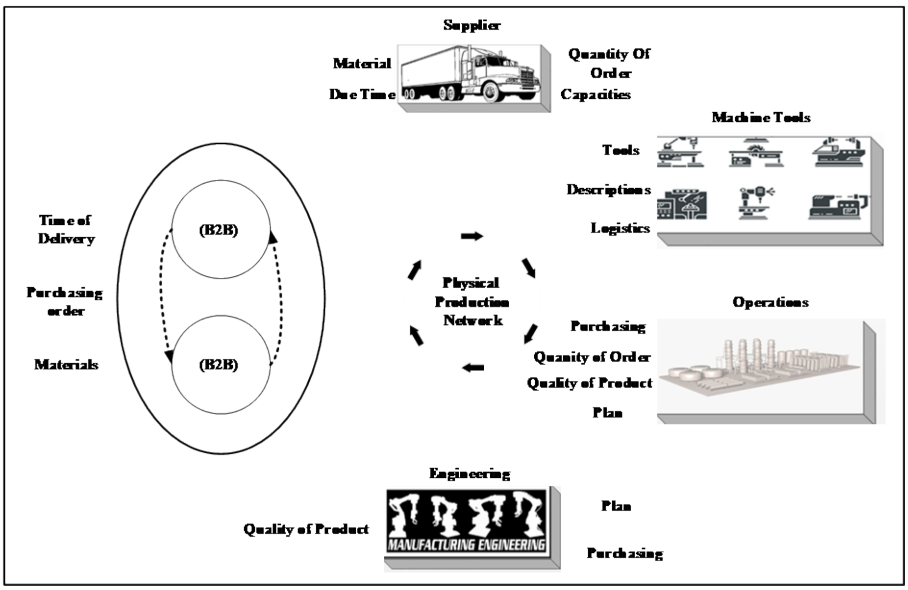

Fig. 1. Conceptual architecture of supply chain 4.0
Source: Sobb, Turnbull & Moustafa, 2020.

lation, and modelling in the context of Industry 4.0, the whole supply chain (not only customers and suppliers but also their assets, products, and operating environment) can be integrated. More data can be generated with excellent quality and higher speed. In addition, these technologies allow organisations to increase flexibility, productivity, reliability, and accountability in their operations. Also, by allowing real-time reorganisation of entire processes, organisations can reduce the effect of Bullwhip and the costs associated with supply chain operations (Martins, Simon & Campos, 2020).

1.2. Technologies affecting the supply chain 4.0

1.2.1. Internet of Things (IoT)

IoT is a network of physical and virtual objects with embedded technology described as a means to communicate, identify, or interact with internal states or the external environment. The Internet of Things contains an ecosystem that includes objects, communications, applications, and data analytics in which each object is identifiable. The IoT is used in industrial processing, agriculture, logistics, product lifecycle management, medicine, healthcare, smart home/building, public safety, environmental monitoring, intelligent mobility, and intelligent tourism (Rueda-Rueda & Portocarrero, 2021). Fig. 2 shows the communications in the context of IoT.

With the digitalisation of supply chain processes, such technologies as IoT are becoming increasingly important for organisations interested in embracing and applying Industry 4.0 developments. IoT is closely related to energy management in factories, logistics, transportation, and the creation of smart business models. IoT is becoming increasingly important in terms of the need to realise real-time information as well as the need to improve after-sale services through sensors existing inside its products, which are based on big data technology; because its performance, defects and consumption patterns are provided for the customer (Ramirez-Peña et al., 2020).

IoT in the supply chain is defined as a network of physical objects that digitally shares the supply chain interactions among multiple organisations, enables agility, visibility, and information sharing, and facilitates planning, controlling, and coordinating supply chain processes (Rejeb et al., 2020). Abdel-basset, Manogaran and Mohamed (2018) used the IoT to create an intelligent and secure supply chain management system by providing a website for suppliers. On this website, managers and suppliers get complete information about the whole supply chain, which has made the supply chain transparent. Mostafa, Hamdy and Alawady (2019) presented a new approach to the Internet of Things in warehouse management. In this approach, by connecting to several objects through collecting real-time data, IoT enables sharing of real-time data. The resulting information can then be used to support automated decision-making. Sharma, Kaur and Singh (2020) proved that the IoT provides real-time storage conditions in warehousing and supply chain management of pharmaceutical products

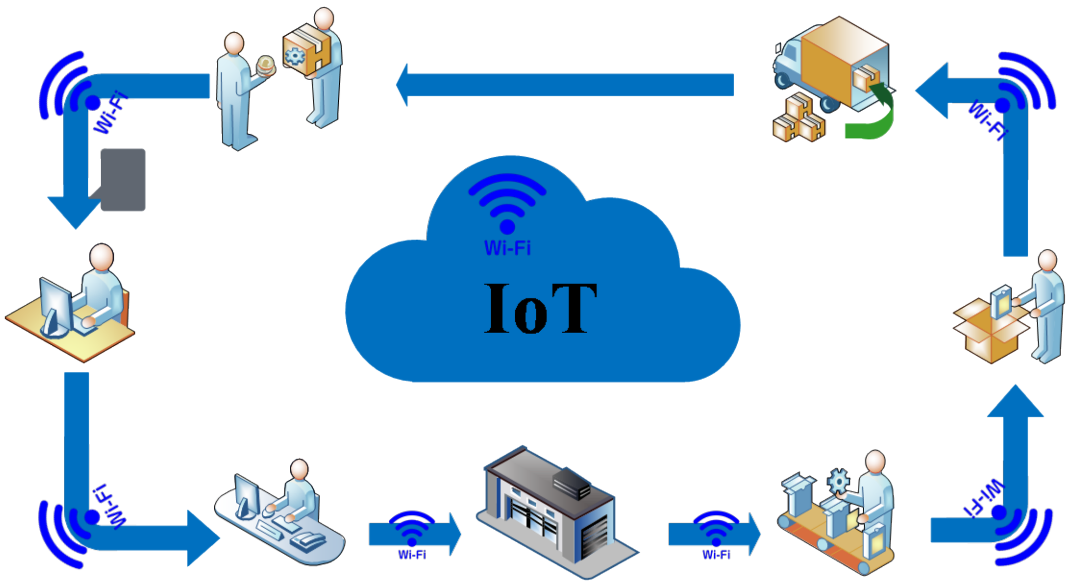

Fig. 2. Communications in the context of IoT

and improves visibility to increase operational efficiency. Al-Rakhami and Al-Mashari (2021) created a trust model in the supply chain with IoT elements. The trust model makes the supply chain more efficient, simplifies data sharing, and reduces computational storage and latency requirements while increasing the security of IoT-based supply chain management.

1.2.2. Cyber-physical systems (CPS)

Cyber-physical systems include machines, storage systems, and manufacturing facilities that are digitally developed and provide integration based on information and communication technologies (ICT). Cyber-physical systems are characterised by decentralisation, adaptation, and autonomous behaviour. Cyber-physical systems also offer supply chain opportunities for real-time monitoring of production conditions and logistics activities while enabling prognosis, diagnosis, and remote control (Martins, Simon & Campos, 2020). Cyber-physical systems are often combined with data collection and monitoring control systems. Moreover, cyber-physical systems can be used in several areas of the supply chain, especially in the production space. These systems can potentially change how people interact with supply chain products and processes and potentially improve service levels' performance and flexibility (Sobb, Turnbull & Moustafa, 2020). Chen, Dui and Zhang (2020) studied supply chain resilience using cyber-physical systems. Wang and Zhang (2020) investigated the use of cyber-physical systems to identify defects in supply chain management.

1.2.3. Cloud computing

The basis of cloud computing expanded in the 1980s with the advent of the Internet. Cloud computing is currently one of the best computing paradigms of information technology. This is due to the advances in existing computational models that include parallel computing, network computing, distributed computing, and other computational paradigms. This technological strategy allows consumers to introduce their communications to a system of computing resources where users can quickly increase or decrease their demands with minimal interaction from third parties (Alam, 2020). Elements of cloud computing include computing, analytics, networking, and storage; these elements are identified in service categories as software services, platforms, networks, and infrastructures. In general, the benefits of cloud computing include flexibility, location independence, scalability, and cost-effectiveness (Sobb, Turnbull & Moustafa, 2020). The cloud computing concept is shown in Fig. 3.

Singh et al. (2015) proposed an integrated system using cloud computing technology in which all stakeholders of the beef supply chain can minimise and measure carbon dioxide emissions with reasonable costs and infrastructure. Schniederjans, Ozpolat and

Fig. 3. A view of cloud computing

Chen (2016) proved that cloud computing technology has a positive and significant effect on cooperation between humanitarian organisations and their suppliers, which causes a substantial increase in the agility of humanitarian organisations. Suherman and Simatupang (2017), using cloud computing technology, proposed a business network model that integrates such systems as ERP in the supply chain and creates an overall perspective in the supply chain, which includes buying, distributing, and viewing inventory. Li, Sun and Wu (2019) used cloud computing technology to improve the logistics distribution planning of coastal ports. Lu et al. (2021) conducted a study in which they addressed reducing the risks of the financing supply chain using cloud computing.

1.2.4. Big data

Big data is the generic term for large, defined or undefined giant data. An unimaginable massive amount of data is generated daily in various sectors such as health, management, social networks, marketing, finance, etc. Since this collected data is nothing but a vast amount of data, it is essential to interpret it to be analysed quickly. Previously, businesses did not prefer to keep their data in archives for long periods and did not analyse their data set. However, with new technological advances, data can be examined, stored, and made available in a secure environment (Kaya, Paksoy & Garza-Reyes, 2020). The importance of big data has been acknowledged because of the significant challenge that factories face in processing large amounts of information. These intelligent systems can monitor and control supply chain processes and also provide information about the breakdowns for the entire planning system and production control, and ultimately offer helpful solutions to employees (Ramirez-Peña et al., 2020).

Lamba and Singh (2017) investigated big data in operations and supply chains and optimised them. Researchers also found that big data can facilitate setting up, procuring, and selecting suppliers. Hofmann (2017) studied the use of big data features to reduce the Bullwhip effect. Raman et al. (2018) developed a reference model of supply chain operations by combining big data and supply chain management. Kamble and Gunasekaran (2020) studied supply chain performance measures and metrics using big data.

Maheshwari, Gautam and Jaggi (2021) acknowledged that big data analysis in supply chain management, logistics management, and inventory management facilitates customer behaviour analysis, consequently optimising business operations.

1.2.5. Additive manufacturing

The basic premise of additive manufacturing technology is that a model initially generated by a computer through a 3D design system can be built directly without the need for process planning. Although this may not seem easy at first, additive manufacturing technology dramatically now simplifies the process of producing complex 3D objects from computer-aided design data. Other manufacturing strategies require careful analysis of the part geometry to determine such things as the construction order of various features, the tools and processes that must be used, and the additional equipment that might be needed to complete the part. Still, additive manufacturing only requires some basic dimensional details and little understanding of how the additive manufacturing machine works and the used materials (Gibson et al., 2021). Additive manufacturing, together with product design freedom, customisation ability, and product diversity, which are determinants of supply chain competition, play an essential role in the viability of a complex product and also help reduce wasted resources and emissions by setting up a collaborative program (Ramirez-Peña et al., 2020).

Ming-Chuan Chiu (2016) stated in his study that additive manufacturing improves lead time and total cost in supply chain performance. According to Handal (2017), additive manufacturing in the supply chain must be used when it can adopt supply chain strategies and when the product is unique and complex. Luomaranta and Martinsuo (2020) stated in their study that additive manufacturing efficiency requires innovation at the supply chain level, which includes innovations in business processes, technology, and structure. Arora et al. (2020) conducted a study to fill the gap in the supply chain localisation of a device in the medical industry through additive manufacturing. Afshari, Searcy and Jaber (2020) explored the applications of the drivers of additive manufacturing innovation in green supply chains.

1.2.6. Blockchain

Blockchain can be defined as a decentralised and distributed guide for smart contracts delivering opportunities for tracking, document management, supply chain automation, payment applications, and other business transactions. Among a network of trading partners, blockchain provides documents replicated in almost real-time among a network of trading partners and documents remain unchanged. Blockchain captures information from enterprise resource planning and distributes it available to a network of documents across different companies. The benefits of blockchain enable organisations to understand their customers better, especially their demands (Javaid et al., 2021).

Blockchain is widely used in such digital currencies as bitcoin, while blockchain technology can be applied to various systems and processes, including the supply chain. Implementing a blockchain in the supply chain increases chain security. Also, it increases the flexibility of the supply chain against cyber-attacks by identifying vulnerable or potentially exploited components in all stages of the chain (Sobb, Turnbull & Moustafa, 2020).

Francisco and Swanson (2018) studied the use of blockchain to improve transparency and traceability in the supply chain. Longo et al. (2019) used the design and development of a software interface to connect the blockchain to the organisation's systems and allow organisations to share information with their partners at different levels. They examined the accuracy, integrity, and non-manipulation of data over time through blockchain, which builds confidence in the non-manipulation of data. Moreover, the software interface presented in their study leads to the reconstruction of supply chain operations and the integration of the supply chain with the blockchain. Azzi, Chamoun and Sokhn (2019) investigated how to integrate the blockchain into supply chain architecture to create a reliable, transparent, and secure system. Rejeb and Rejeb (2020) studied supply chain sustainability through blockchain. Researchers have declared that the economic, social, and environmental aspects of the supply chain with blockchain lead to new business models without new intermediaries, higher operational efficiency, building loyal relationships between supply chain partners, and supporting humanitarian logistics. Wang, Chen and Zghari-Sales (2021) studied ways to design an active supply chain with a blockchain that leads to transparency and profitability of a blockchain-based supply chain.

1.2.7 Artificial intelligence

Artificial intelligence (AI) works to replicate some aspects of technology-based human intelligence. From a business perspective, artificial intelligence and data analytics systems allow individuals to systematise information that is usually already available in the marketplace in a segregated way and turn data into business decisions. Therefore, they consider only tools that are useful for facilitating an organisation's decision-making processes (Sestino & De Mauro, 2021). Artificial intelligence-based systems and capabilities enable them to have a high degree of self-control, and by these means, respond to situations that were not pre-planned or explicitly anticipated during their development and make independent decisions and choices of action, with little or no control of their users (Thiebes, Lins & Sunyaev, 2021).

Baryannis, Dani et al. (2019) used artificial intelligence in the field of supply chain risk management to analyse data and make decisions about potential risks. Baryannis, Validi et al. (2019) studied the use of artificial intelligence in solving problems in the risk supply chain. Modgil, Singh and Claire (2021) worked on using artificial intelligence in their study to develop the capabilities of vision, risk, sourcing, and distribution which in turn leads to the improvement of supply chain resilience. Belhadi, Mani et al. (2021) examined the maximisation of the benefits of artificial intelligence to create sustainable supply chain performance. Belhadi, Kamble et al. (2021) explored the applications of artificial intelligence, such as fuzzy logic programming and big data, in machine learning and operating systems and considered them the most promising techniques to improve resilience supply chain strategies.

1.2.8. Augmented reality

Augmented reality combines such digital components as graphics, sound, and other sensory enhancements which affect real-world video streams with real-time interaction between the user and digital elements. Although virtual reality replaces the natural world with the virtual world, augmented reality completes the user's perception of the real world in a comprehensive way without completely hiding the real world (Venkatesan et al., 2021). Augmented reality systems can play a role in logistics operations, construction, training and maintenance and help employees by combining computer-generated data and the physical world. It also helps to select logistics solutions, leading to a quick and efficient selection of products and, at the same time, reduces operating time (Demir & Paksoy, 2020). Demir, Yilmaz and Paksoy (2020) stated in their study that augmented reality in logistics allows quick access to predicted information. Bhatia (2021) showed how different stakeholders of a supply chain could use the potential of augmented reality to play their roles and perform their tasks efficiently.

1.2.9. Virtual reality

Virtual reality is an artificial environment experienced through sensory stimuli (such as sights and sounds) provided by a computer, in which one's actions partly determine what occurs in the environment. Virtual reality technology aims to immerse users in a completely artificial environment with different forms of technology to address one or more senses (Scavarelli, Arya & Teather, 2021). The virtual reality user is fully involved in an artificial environment and has no interaction with the surrounding real world. However, augmented reality allows the user to see and interact with the real world and virtual objects. Virtual reality replaces reality with an artificial environment, but augmented reality improves the real environment instead of replacing it (Demir, Yilmaz & Paksoy, 2020).

1.2.10. Simulation

Simulation is an imitation of the performance of a real-world design or process on a computer platform. Simulation makes it possible to generate the system's artificial history and view it to infer the operational characteristics of the natural system (Kaya, Paksoy & Garza-Reyes, 2020). Supply chain flexibility through simulation enables risks to be assessed before implementation, positively impacting supply chain risk management and saving many natural resources, making the supply chain more sustainable (Ramirez-Peña et al., 2020). Supply chain 4.0 technologies and their brief description can be seen in Table 1.

Tab. 1. Supply chain 4.0 technologies

Supply chain 4.0 technologies	Brief definition	Source
Internet of Things (IoT)	Connecting any physical object to the world wide web and identifying it in the virtual world	Abdel-basset et al., 2018; Al-Rakhami & Al-Mashari, 2021; Cañas et al., 2020; Kaya et al., 2020; Mostafa et al., 2019; Ramirez-Peña et al., 2020; Rejeb et al., 2020; Rueda-Rueda & Portocarrero, 2021; Sharma et al., 2020; Sobb et al., 2020; Frederico, 2021b
Cyber-Physical Systems (CPS)	Integrating all systems and subsystems and their monitoring and control	Cañas, Mula & Campuzano-Bolarín, 2020; Chen, Dui & Zhang, 2020; Kaya, Paksoy & Garza-Reyes, 2020; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Sobb, Turnbull & Moustafa, 2020; Wang & Zhang, 2020; Frederico, 2021a
Cloud Computing	Calculating data and analysing, connecting and storing it in the network	Singh et al., 2015; Schniederjans, Ozpolat & Chen, 2016; Suherman & Simatupang, 2017; Li, Sun & Wu, 2019; Alam, 2020; Kaya, Paksoy & Garza-Reyes, 2020; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Sobb, Turnbull & Moustafa, 2020; Lu et al., 2021
Big Data	Massive volumes of structured or unstructured data that are continuous, heterogeneous, and variable, from connecting people with mobile devices, objects, and machines to the world wide web	Hofmann, 2017; Lamba & Singh, 2017; Raman et al., 2018; Cañas, Mula & Campuzano-Bolarín, 2020; Kamble & Gunasekaran, 2020; Kaya, Paksoy & Garza-Reyes, 2020; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Frederico, 2021a; Maheshwari, Gautam & Jaggi, 2021
Additive Manufacturing	Rapid prototyping process and 3D printing	Afshari et al., 2020; Arora et al., 2020; Gibson et al., 2021; Handal, 2017; L iu & Chiu, 2021; Luomaranta & Martinsuo, 2020; F. de C. Martins et al., 2020b; Ming-Chuan Chiu, 2016; Ramirez-Peña et al., 2020
Blockchain	A decentralised and distributed guide for smart contracts	Francisco & Swanson, 2018; Azzi, Chamoun & Sokhn, 2019; Longo et al., 2019; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Rejeb & Rejeb, 2020; Sobb, Turnbull & Moustafa, 2020; Frederico, 2021a; Javaid et al., 2021; Wang, Chen & Zghari-Sales, 2021
Artificial intelligence	Replicating some aspects of technology-based human intelligence	Baryannis, Dani, et al., 2019; Baryannis, Validi, et al., 2019; Ramirez-Peña et al., 2020; Sobb, Turnbull & Moustafa, 2020; Belhadi, Mani, et al., 2021; Modgil, Singh & Claire, 2021; Sestino & De Mauro, 2021; Thiebes, Lins & Sunyaev, 2021

Radio-frequency identification (RFID)	A mechanism for obtaining pre-embedded information in the object label via radio frequency	Martins, Simon & Campos, 2020; Frederico, 2021a
Augmented Reality	Adding a new layer of information to the real human environment	Cañas, Mula & Campuzano-Bolarín, 2020; Demir & Paksoy, 2020; Martins, Simon & Campos, 2020; Bhatia, 2021; Liu & Chiu, 2021; Venkatesan et al., 2021
Virtual Reality	A three-dimensional environment generated to be able to produce real-world works and experiences with a high degree of precision	Demir, Yilmaz & Paksoy, 2020; Kaya, Paksoy & Garza-Reyes, 2020; Scavarelli, Arya & Teather, 2021
Simulation	An approximate imitation of an operation, process, or system that represents its performance over time	Kaya, Paksoy & Garza-Reyes, 2020; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Frederico, 2021a

1.3. Related studies on supply chain 4.0

The literature review found that few studies have been done on implementing supply chain 4.0 in industries, and most of these studies only addressed the supply chain 4.0 literature. None of these studies addressed the relationships and rankings of supply chain 4.0 technologies and mostly referred to the application of Industry 4.0 technologies in the supply chain. Some of the research efforts on supply chain 4.0 are discussed next.

Frederico (2021a) conducted a study that aimed to present the concept of the supply chain in the Industry 5.0 phenomenon. His study, "From Supply Chain 4.0 to Supply Chain 5.0: Findings from a Systematic Literature Review and Research Directions", used a systematic literature review method. The findings indicate a substantial gap related to Industry 5.0 approaches in the supply chain area. The researcher also acknowledged that industry strategy, innovation and technology, society and sustainability, and transition issues are the foundations of Industry 5.0 and noted that the leadership of organisations, policymakers and other stakeholders that are involved in the supply chain, and mainly users that currently work with Industry 4.0 plans, can benefit from this research with clear guidance on the dimensions required for structural design and implementation of the Industry 5.0 strategy.

Sartori, Frederico and de Fátima Nunes Silva (2021) conducted a study, "Organizational knowledge management in the context of supply chain 4.0: A systematic literature review and conceptual model proposal", aimed at a systematic literature review and content analysis of knowledge management and supply chain 4.0. The researchers proposed a conceptual model for knowledge management in the field of supply chain 4.0. Also, the researchers found that Industry 4.0 made significant changes in supply chain management and knowledge management.

Liu and Chiu (2021) investigated the relationships between supply chain digitisation, supply chain integration and a firm's performance. In their study, "Supply Chain 4.0: the impact of supply chain digitalisation and integration on firm performance", the researchers used an online survey of Chinese employees in the supply chain industry and found that both digitisation and supply chain integration have a positive effect on the firm's performance. The researchers also acknowledged that supply chain digitisation positively moderates the relationship between supply chain integration and the firm's performance.

Kaya, Paksoy and Garza-Reyes (2020) conducted a study to explore how Industry 4.0 affects the supply chain and investigate the role of the Internet of Things and big data in the supply chain industry. Researchers in their study found that the Internet of Things (IoT) is used in the entire process from supplier to material handling, material transportation, and production to product delivery to customers. Moreover, IoT can also optimise the processes of the transportation management system, and the potential use of IoT technology is enormous across the supply chain. The researchers acknowledged that the IoT-enabled supply chain could be visualised as an intelligent, interconnected network that physically connects the levels of many suppliers, manufacturers, service providers, distributors, and customers in different parts of the world.

Cañas, Mula and Campuzano-Bolarín (2020) explored the current knowledge of supply chain 4.0 with a sustainability approach. Reviewing the literature, the researchers considered the three main dimensions of sustainability, namely economic, social and environmental. They found that more attention has been paid to the environmental dimension in Industry 4.0, while less attention has been given to the social dimension. The researchers also acknowledged that reference frameworks were identified along with Industry 4.0 models, algorithms, heuris-

Tab. 2. Summary of related research on supply chain 4.0

Authors	Title	Aims	Type/Approach
Frederico, 2021a	From Supply Chain 4.0 to Supply Chain 5.0: Findings from a Systematic Literature Review and Research Directions	Proposing a conceptual model for knowledge management in the field of supply chain 4.0	literature review
Sartori et al., 2021	Organisational knowledge management in the context of supply chain 4.0: A systematic literature review and conceptual model proposal	Investigating the relationships between supply chain digitisation, supply chain integration and firm performance	PLS-SEM
Liu & Chiu, 2021	Supply Chain 4.0: the impact of supply chain digitalisation and integration on firm performance	Providing a conceptual framework for project management in Supply Chains 4.0	literature review
Kaya et al., 2020	The Impact of the Internet of Things on Supply Chain 4.0	Investigating the way Industry 4.0 affects the supply chain and the role of the Internet of Things and big data in the supply chain industry	literature review
Cañas et al., 2020	A General Outline of a Sustainable Supply Chain 4.0	Investigating the current knowledge of the supply chain 4.0 with a sustainability approach	literature review
Sobb et al., 2020	Supply Chain 4.0: A Survey of Cyber Security Challenges, Solutions and Future Directions	Investigating the military supply chains 4.0 and their unique differences from commercial supply chain	literature review
Ramirez-Peña et al., 2020	Sustainability in the Aerospace, Naval, and Automotive Supply Chain 4.0: Descriptive Review	Investigating the relationship between supply chain 4.0 sustainability in the aerospace, shipbuilding and automotive sectors	literature review

tics, metaheuristics, and technologies, which enable sustainability in supply chains.

Sobb, Turnbull and Moustafa (2020) investigated the military supply chains 4.0 and their unique differences from the commercial supply chains. They also explored their strengths, weaknesses, dependencies, and the fundamental technologies on which they are built. According to the findings of their study, the technologies that underpin supply chain 4.0 include blockchain, smart contracts, artificial intelligence applications, cyber-physical systems, and the industrial Internet of Things. The researchers acknowledged that each of these technologies, individually and in combination, creates cyber security issues that must be addressed.

Ramirez-Peña et al. (2020) investigated the relationship between supply chain 4.0 sustainability in the aerospace, shipbuilding, and automotive sectors. They found that lean methods are common in three areas and different technologies focus on sustainability. The researchers acknowledged that the automotive industry is one of the industries that can be very useful to the other two sectors through collaborative programmes and help them the most. As a result, the automotive sector benefits from the consequent applicable advantages. The researchers also declared that the aerospace and shipbuilding sectors do not do much work to promote a sustainable culture in supply chain management or to include training programmes for their personnel on issues related to Industry 4.0.

Table 2. shows the summary of the literature review on related research.

2. Research methods

Improving supply chain performance is one of the Multi-Criteria Decision-Making (MCDM) issues. To improve supply chain performance, various evaluation criteria must be considered. Therefore, it is appropriate to use existing methods in multi-criteria issues to improve supply chain performance. In the present study, two methods of literature review and field study have been used. The literature review was collected by reviewing the studies that were accessible via the Internet. The methodology of the study is shown in Fig. 4.

The literature review found that the fourth-generation supply chain has been considered in universities and science centres and has not been thoughtfully implemented in the industry, and this has led to a lack of industry awareness in this area. Therefore, experts of the present study were selected from university professors who had mastered supply chain 4.0.

This study aims to investigate supply chain 4.0 technologies and analyse the cause-and-effect relationships between them. To achieve this goal, supply chain 4.0 technologies were first identified in the research literature. In the next step, to select the critical factors in the study area, questionnaires based on the Delphi method were distributed among the experts and the factors with the mean higher than seven were selected. According to previous studies, the threshold limit of seven was considered because it leads to a better correlation among the data (Lewis, 1993). After selecting the final most influential elements, various techniques were used to determine the relationships. According to the studies that were conducted, Decision Making Trial and Evaluation (DEMATEL) technique is one of the best techniques in this regard in terms of analysing relationships and also determining the importance of factors. For this reason, this technique was used in the present study. DEMATEL is a valuable method for the analysis of cause-and-effect relationships, where it can provide quantitative measures and consider the relevant structural model. Also, this method can effectively structure a relationship map for each criterion with clear interrelationships between sub-criteria. It can also be used to create causal diagrams that can visualise the cause-and-effect relationships of subsystems. The Interpretive Structural Modelling (ISM) technique was also used to rank the supply chain 4.0 technologies. The ISM is also a pioneer in terms of being understandable to a wide range of users, as well as being a tool for integrating the different perceptions of experts compared to other methods, and it is also applicable in studying complex and diverse systems.

2.1. DEMATEL technique

The DEMATEL technique was first introduced by Gabus and Fontela (1972) to solve real-world problems. The DEMATEL technique is an effective way to analyse direct and indirect relationships between system components according to their type and intensity (Wu & Chang, 2015). Analysing the general relationship between the components in the DEMATEL technique allows for obtaining a better understanding of structural relationships, as well as an ideal way to solve complex system problems. Next, the steps of the DEMATEL technique are discussed (Dwijendra et al., 2021).

Step 1: A four-level comparative scale for measuring the relationship between criteria with the help of expert opinions is required after collecting the desired criteria. These four scales that are used to

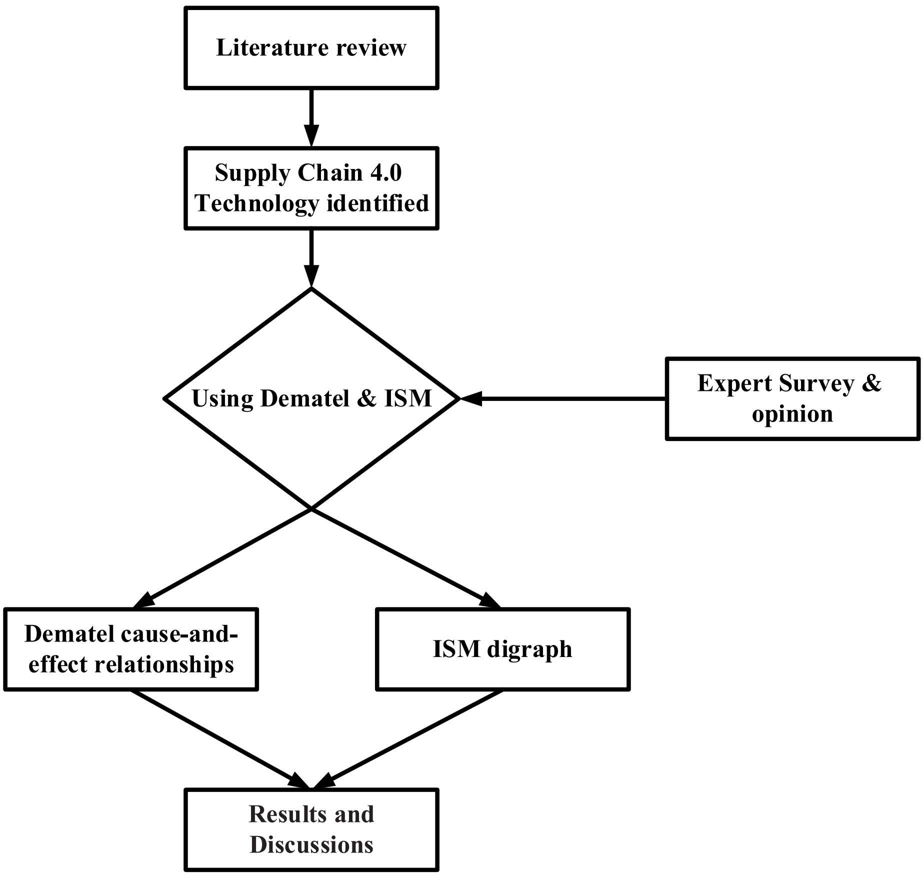

Fig. 4. Methodology of the study

describe the relationship between the criteria are, respectively, 0 (No impact), 1 (Low impact), 2 (Equal impact), 3 (High impact), and 4 (Very high impact). The next step is to get expert opinions regarding pairwise comparisons. The result of this step is displayed using the D Matrix and its components with aij. Each member represents the degree of influence that criteria i has on criteria j.

Step 2: Equations 1 and 2 can be used to convert the matrix of direct relations (D) into the normalised matrix of direct relations.

Step 3: Once the normalised matrix (X) is formed, the total relation matrix (T) is received from Equation 3, in which I is the identity matrix.

Step 4: The causal diagram is drawn based on the total relation matrix. To do so, the sum of the elements in the rows and columns of the matrix T are named r and c and are calculated using Equations 4 and 5. Then, the horizontal axis of the diagram is calculated by adding r and c (r + c), which is called the significance axis. The vertical axis of the diagram, which is called the dependency axis, is obtained by subtracting r and c (r-c). In general, if (r-c) is positive, the criterion belongs to the cause group; otherwise, it belongs to the effect group. Therefore, a causal diagram is obtained through points with coordinates r + c and r-c.

2.2. Interpretative Structural Modelling Technique

Interpretative Structural Modelling Technique was first proposed by Warfield (1973) to analyse complex socioeconomic systems. This technique helps people to show the complexity of knowledge in the field of study as a model of interaction to increase their understanding. The steps of the interpretative structural modelling technique are as follows (Chauhan et al., 2018):

Step 1: List the desired criteria or elements.

Step 2: Use the criteria that were identified in the first step and define a content relationship between them according to each pair of criteria.

Step 3: Form the Structural Self-Interaction Matrix (SSIM): experts perform pairwise comparisons between the two criteria i and j based on four symbols:

V: If criterion i only affects criterion j.

A: If criterion j only affects criterion i.

X: If criterion i affects criterion j, criterion j also affects criterion i.

O: If there is no relationship between criterion i and criterion j.

Step 4: Form the initial reachability matrix: the SSIM is formed using pairwise comparisons based on the four symbols of V, A, X and O. This structural matrix is then converted to a zero-one matrix called the initial reachability matrix. In this matrix, only the numbers 0 and 1 exist, and the rule is to place the numbers 0 and 1 instead of the four symbols to show the kind of relationship between the two criteria i and j as follows:

- If the intersection of the criteria (i, j) in the structural self-interaction matrix is V, in the initial reachability matrix, the element (i, j) is 1, and the element (j, i) is 0.
- If the intersection of the criteria (i, j) in the structural self-interaction matrix is A, in the initial reachability matrix, the element (i, j) is 0, and the element (j, i) is 1.
- If the intersection of the criteria (i, j) in the structural self-interaction matrix is X, in the initial reachability matrix, the element (i, j) and the element (j, i) are 1.
- If the intersection of the criteria (i, j) in the structural self-interaction matrix is O, in the initial reachability matrix, the element (i, j) and the element (j, i) are 0.

Step 5: Form the final reachability matrix: After the formation of the initial reachability matrix, the

$$X=D.S \tag{1}$$

$$s = max(max_{1\le i\le n} \sum_{j=1}^{n} a_{ij}\ ,\ max_{1\le j\le n} \sum_{i=1}^{n} a_{ij})\ ,\ i.j = 1,2,\dots,n \tag{2}$$

$$T = X(I - X)^{-1} \qquad When\ \lim_{m\to\infty} X^m = [0]_{n\times n} \tag{3}$$

$$r = (r_i)_{n\times 1} = (\sum_{j=1}^{n} t_{ij})_{n\times 1} \tag{4}$$

$$c = (c_j)_{1\times n} = (\sum_{i=1}^{n} t_{ij})_{1\times n} \tag{5}$$

final reachability matrix is formed using the criteria that are obtained by considering the transgression relationship. Transgression means that if criterion "a" is related to criterion "b" and criterion "b" is related to criterion "c", then criterion "a" is also related to criterion "c". It should be noted that in the final reachability matrix, the entries obtained through the transgression relations are shown as 1. After the formation of the final reachability matrix, this matrix is added to the unit matrix and called the final reachability matrix.

Step 6: Level the final reachability matrix: After forming the final reachability matrix, the criteria are levelled by determining the reachability set and antecedent set for each of the criteria and determining the common set. The reachability set of each variable contains the criteria that lead to or affect that variable. In other words, for the criteria that number 1 is placed in their variable column, the reachability set comes in a column. Conversely, it shows the antecedent set of criteria that are affected by a variable or a system component. The commonality of the two sets of reachability and antecedent, a common set, is an intersection. Criteria with the common set the same as the antecedent set have the first priority level. By eliminating these criteria and repeating this process for other criteria, the levels of other criteria are also determined. After levelling the final reachability matrix, draw the ISM diagram.

Step 7: Analyse the classification of criteria, using diving power and dependence: to classify criteria in the final reachability matrix, influence and dependency must be calculated for each element. The penetrating power of a component or criterion is the number of criteria affected by the relevant criterion, including the criterion itself. The dependency power is the number of criteria that affect the relevant criterion and lead to its achievement. These penetrating and dependency powers are used in the cross-impact matrix multiplication applied to classification (MICMAC), in which the criteria are divided into four groups: autonomous, dependent, linkage, and independent criteria. Autonomous criteria have weak influence and dependence. These criteria are relatively separate from the system and, in fact, have little link or connection to other elements of the system, although their relationship might be substantial. Dependent criteria have low penetrating power but high dependency power. Linking criteria have strong linkage, strong influence, and strong dependency. These criteria are unstable because any action on these criteria will affect other criteria or feedback to them. Independent criteria have high penetrating power with low dependency power.

3. Research results

As mentioned before, the expert population of the present study included five academic-industrial experts who are fully acquainted with the subject under study. First, the experts were interviewed to determine the importance of each of the fourth-generation technologies. They were analysed using the Delphi technique, and as a result, the final technologies of the supply chain 4.0 were shown in (Table 3) with their equivalent names:

After identifying the essential technologies of supply chain 4.0, the DEMATEL technique was used to determine the cause-and-effect relationships between the technologies. Therefore, the questionnaire was administered to experts, and they made pairwise comparisons based on the following scale: No impact (0), Low impact (1), Equal impact (2), High impact (3), Very high impact (4). After collecting expert responses and aggregating their opinions using the arithmetic mean, the initial reachable matrix was formed, as shown in (Table 4).

The initial relation matrix was normalised based on Equation 1 and named N. In Equation 1, (D) is the initial relation matrix and (S) is the largest number in the row and column, as shown in (Table 5). After the formation of the normalised matrix (X), we get the total relation matrix (T) from Equation 3, in which I is the identity matrix (Table 6).

Based on the total relation matrix, we draw the causal diagram. To do so, the sum of the elements in the rows and columns of the matrix T is named r and c and calculated using Equations 4 and 5. Then, the horizontal axis of the diagram is calculated by adding r and c (r + c), which is called the significance axis. The vertical axis of the diagram, which is called the dependency axis, is obtained by subtracting r and c (r-c). In general, if (r-c) is positive, the criterion belongs to the cause group; otherwise, it belongs to the effect group. Therefore, the causal diagram is obtained through points with coordinates r + c and r-c. Table 7 shows the values of r and c, and Fig. 5 shows the cause and effect of supply chain 4.0 technology.

As shown in Fig. 5, C2 (cyber-physical systems), C8 (augmented reality), and C9 (virtual reality) technologies belong to the cause group, and C1 (the Internet of Things), C3 (cloud computing), C4 (big

Tab. 3. Supply chain 4.0 technologies and their equivalent names

Supply chain 4.0 technologies	Equivalent names
Internet of Things (IoT)	C_1
Cyber-Physical Systems (CPS)	C_2
Cloud Computing	C_3
Big Data	C_4
Blockchain	C_5
Artificial intelligence	C_6
Radio-frequency identification (RFID)	C_7
Augmented Reality	C_8
Virtual Reality	C_9
Simulation	C_{10}

Tab. 4. Initial reachability matrix

D	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Σ
C1	0/0	3/8	4/0	3/7	4/0	3/6	3/8	2/4	3/4	2/3	31
C2	3/6	0	2/4	2/9	3/2	4	1/3	2/3	2/4	2/7	24/8
C3	2/4	1/3	0	3/4	3/8	2/8	1/3	1/8	2/9	3/2	22/9
C4	3/6	2/4	3/8	0	3/9	2/8	1/7	1/2	2/3	2/7	24/4
C5	4	2/3	1/7	2/4	0	4	3/9	1/3	1/4	2/3	23/3
C6	3/7	1/4	3/7	3/4	2/6	0	0/8	2/2	1/3	3/6	22/7
C7	4	2/3	1/8	1/4	2/9	1/3	0	0/8	1/4	1/2	17/1
C8	3/8	1/8	2/3	1/8	2/4	1/3	2/8	0	3/8	4	24
C9	3/7	2/4	1/7	3/6	3/7	2/3	1/4	3/7	0	3/8	26/3
C10	2/9	0/4	1/3	2/3	1/4	3/8	0/4	3/8	4	0	20/3
Σ	31/7	18/1	22/7	24/9	27/9	25/9	17/4	19/5	22/9	25/8	

Tab. 5. Normalised matrix

X	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	0/00	0/12	0/13	0/12	0/13	0/11	0/12	0/08	0/11	0/07
C2	0/11	0/00	0/08	0/09	0/10	0/13	0/04	0/07	0/08	0/09
C3	0/08	0/04	0/00	0/11	0/12	0/09	0/04	0/06	0/09	0/10
C4	0/11	0/08	0/12	0/00	0/12	0/09	0/05	0/04	0/07	0/09
C5	0/13	0/07	0/05	0/08	0/00	0/13	0/12	0/04	0/04	0/07
C6	0/12	0/04	0/12	0/11	0/08	0/00	0/03	0/07	0/04	0/11
C7	0/13	0/07	0/06	0/04	0/09	0/04	0/00	0/03	0/04	0/04
C8	0/12	0/06	0/07	0/06	0/08	0/04	0/09	0/00	0/12	0/13
C9	0/12	0/08	0/05	0/11	0/12	0/07	0/04	0/12	0/00	0/12
C10	0/09	0/01	0/04	0/07	0/04	0/12	0/01	0/12	0/13	0/00

Tab. 6. Total relation matrix

T	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	0/39	0/34	0/41	0/42	0/46	0/43	0/34	0/32	0/38	0/39
C_2	0/42	0/20	0/32	0/35	0/38	0/39	0/23	0/28	0/31	0/35
C_3	0/37	0/22	0/22	0/34	0/37	0/34	0/21	0/25	0/30	0/34
C_4	0/42	0/26	0/35	0/26	0/39	0/35	0/24	0/24	0/30	0/34
C_5	0/41	0/25	0/28	0/31	0/27	0/37	0/29	0/23	0/26	0/31
C_6	0/40	0/22	0/33	0/34	0/34	0/26	0/20	0/26	0/26	0/35
C_7	0/34	0/21	0/23	0/23	0/29	0/24	0/14	0/17	0/21	0/22
C_8	0/42	0/24	0/30	0/31	0/35	0/30	0/27	0/20	0/34	0/37
C_9	0/44	0/28	0/31	0/38	0/41	0/36	0/25	0/33	0/26	0/39
C_{10}	0/35	0/18	0/25	0/29	0/28	0/34	0/17	0/29	0/32	0/23

data), C5 (blockchain), C6 (artificial intelligence), C7 (radio-frequency identification (RFID)), and C10 (simulation) technologies belong to the effect group.

To describe the structural relationships between supply chain 4.0 technologies, a threshold value of p must be obtained from the T matrix. In the present study, the threshold is obtained through the mean of the T matrix, and its value is equal to 0.3065. (Table 8) shows the entries maintained if a variable in the T matrix is larger than the threshold, and they are considered zero if the variable is smaller than the threshold.

According to Table 8, C1 (the Internet of Things) technology has a relationship with itself, and C2 (cyber-physical systems), C3 (cloud computing), C4 (big data), C5 (blockchain), C6 (artificial intelligence), C7 (radio-frequency identification (RFID)), C8 (augmented reality), C9 (virtual reality) and C10 (simulation) technologies;

Tab. 7. Values of importance and dependent axis

	R	C	R+C	R-C
C_1	3/89	3/96	7/85	-0/07
C_2	3/22	2/4	5/62	0/82
C_3	2/96	2/98	5/94	-0/02
C_4	3/16	3/24	6/4	-0/09
C_5	2/99	3/55	6/54	-0/57
C_6	2/96	3/38	6/34	-0/42
C_7	2/3	2/34	4/63	-0/04
C_8	3/1	2/56	5/66	0/54
C_9	3/39	2/96	6/35	0/44
C_{10}	2/7	3/29	5/99	-0/59

C2 (cyber-physical systems) technology has a relationship with C1 (the Internet of Things), C3 (cloud computing), C4 (big data), C5 (blockchain), C6 (artificial intelligence), C9 (virtual reality), and C10 (simulation) technologies;

C3 (cloud computing) technology has a relationship with C1 (the Internet of Things), C4 (big data), C5 (blockchain), C6 (artificial intelligence), and C10 (simulation) technologies;

C4 (big data) technology has a relationship with C1 (the Internet of Things), C3 (cloud computing), C5 (blockchain), C6 (artificial intelligence), and C10 (simulation) technologies;

C5 (blockchain) technology has relationship with C1 (the Internet of Things), C4 (big data), C6 (artificial intelligence) and C10 (simulation) technologies;

C6 (artificial intelligence) technology has a relationship with C1 (the Internet of Things), C3 (cloud computing), C4 (big data), C5 (blockchain), and C10 (simulation) technologies;

C7 (radio-frequency identification (RFID)) technology has only a relationship with C1 (the Internet of Things) technology;

C8 (augmented reality) technology has a relationship with C1 (the Internet of Things), C4 (big data), C5 (blockchain), C9 (virtual reality), and C10 (simulation) technologies;

C9 (virtual reality) technology has a relationship with C1 (the Internet of Things), C3 (cloud computing), C4 (big data), C5 (blockchain), C6 (artificial intelligence), C8 (augmented reality), and C10 (simulation) technologies;

C10 (simulation) technology has a relationship with C1 (the Internet of Things), C6 (artificial intelligence), and C9 (virtual reality) technologies.

To draw the deployment map of supply chain 4.0 technologies, the interpretative structural modelling

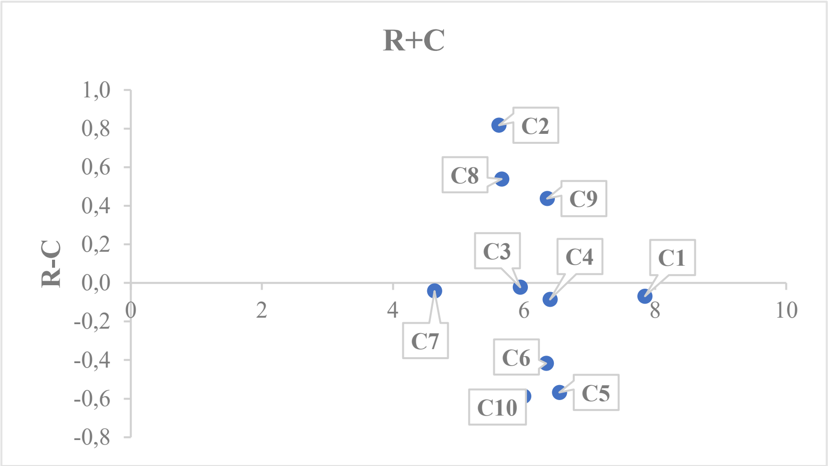

Fig. 5. Causal diagram

Tab. 8. Matrix of relationships between supply chain 4.0 technologies

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	0/39	0/34	0/41	0/42	0/46	0/43	0/34	0/32	0/38	0/39
C_2	0/42	0/00	0/32	0/35	0/38	0/39	0/00	0/00	0/31	0/35
C_3	0/37	0/00	0/00	0/34	0/37	0/34	0/00	0/00	0/00	0/34
C_4	0/42	0/00	0/35	0/00	0/39	0/35	0/00	0/00	0/00	0/34
C_5	0/41	0/00	0/00	0/31	0/00	0/37	0/00	0/00	0/00	0/31
C_6	0/40	0/00	0/33	0/34	0/34	0/00	0/00	0/00	0/00	0/35
C_7	0/34	0/00	0/00	0/00	0/00	0/00	0/00	0/00	0/00	0/00
C_8	0/42	0/00	0/00	0/31	0/35	0/00	0/00	0/00	0/34	0/37
C_9	0/44	0/00	0/31	0/38	0/41	0/36	0/00	0/33	0/00	0/39
C_{10}	0/35	0/00	0/00	0/00	0/00	0/34	0/00	0/00	0/32	0/00

Tab. 9. Structural Self-Interaction Matrix (SSIM)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	-	X	O	O	O	O	V	O	O	O
C_2		-	O	V	X	O	O	O	V	O
C_3			-	X	A	A	O	O	O	O
C_4				-	V	O	O	V	V	O
C_5					-	O	O	O	O	O
C_6						-	O	O	O	O
C_7							-	O	O	O
C_8								-	X	X
C_9									-	X
C_{10}										-

technique has been used. To show how the relationship between the two criteria i and j was, the experts performed pairwise comparisons based on VAXO symbols. The Structural Self-Interaction Matrix and Initial reachability matrix are shown in Tables 9 and 10.

After the formation of the initial reachability matrix, the final reachability matrix is formed through the criteria that are obtained by considering transgression relation. In the final reachability matrix, the criteria obtained through the transgression relation 1 are shown as 1. Table 11 shows the final reachability matrix

After the final reachability matrix is formed, the criteria are levelled by determining the reachability set and antecedent set for each of the criteria and determining the common set. After determining the level Table 12–14, the deployment map of the supply chain 4.0 technologies is drawn in Fig. 6.

To classify supply chain 4.0 technologies in the final reachability matrix, influence and dependency must be calculated for each element. Dependence and power values are shown in Table 15. The penetrating power of a component or criterion is the number of criteria that are affected by the relevant criterion, including the criterion itself. The dependency power is the number of criteria that affect the relevant criterion and lead to its achievement. These penetrating and dependency powers are used in the cross-impact matrix multiplication applied to classification (MICMAC), in which the criteria are divided into four groups: autonomous, dependent, linkage, and independent (stimulus criterion) criteria. According to Fig. 7, C1 (the Internet of Things), C2 (cyber-physical

Tab. 10. Initial reachability matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	-	1	0	0	0	0	1	0	0	0
C_2	1	-	0	1	1	0	0	0	1	0
C_3	0	0	-	1	0	0	0	0	0	0
C_4	0	0	1	-	1	0	0	1	1	0
C_5	0	1	1	0	-	0	0	0	0	0
C_6	0	0	1	0	0	-	0	0	0	0
C_7	0	0	0	0	0	0	-	0	0	0
C_8	0	0	0	0	0	0	0	-	1	1
C_9	0	0	0	0	0	0	0	1	-	1
C_{10}	0	0	0	0	0	0	0	1	1	-

Tab. 11. Final reachability matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	1	1	*1*	*1*	*1*	0	1	*1*	*1*	*1*
C_2	1	1	*1*	1	1	0	*1*	*1*	1	*1*
C_3	*1*	*1*	1	1	*1*	0	*1*	*1*	*1*	*1*
C_4	*1*	*1*	1	1	*1*	0	*1*	*1*	1	*1*
C_5	*1*	1	1	*1*	1	0	*1*	*1*	*1*	*1*
C_6	*1*	*1*	1	*1*	*1*	1	*1*	*1*	*1*	*1*
C_7	0	0	0	0	0	0	1	0	0	0
C_8	0	0	0	0	0	0	0	1	1	1
C_9	0	0	0	0	0	0	0	1	1	1
C_{10}	0	0	0	0	0	0	0	1	1	1

systems), C3 (cloud computing), C4 (big data), and C5 (blockchain) are interconnected technologies, while C6 (artificial intelligence) technology is independent, and C7 (radio frequency identification (RFID)), C8 (augmented reality), C9 (virtual reality), and C10 (simulation) technologies are dependent. MICMAC analysis is shown in Fig. 7.

According to the relationships obtained from the DEMATEL technique and the levelling of the ISM, the relationships among the technologies of the supply chain 4.0 based on the levels obtained from the ISM are shown in Fig. 8. As it can be seen, the critical technology of artificial intelligence is related to the simulation technologies that are at the first level and the technologies of IoT, cloud computing, big data, and blockchain that are at the second level. Other relationships are as follows:

4. Discussion of the results

Reviewing the literature revealed the increasing number of research works in supply chain 4.0. Based on the bibliometric analysis, the term "supply chain 4.0" is used more frequently in engineering, computer science, business, and management compared to

Tab. 11. Final reachability matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	1	1	1	1	1	0	1	1	1	1
C_2	1	1	1	1	1	0	1	1	1	1
C_3	1	1	1	1	1	0	1	1	1	1
C_4	1	1	1	1	1	0	1	1	1	1
C_5	1	1	1	1	1	0	1	1	1	1
C_6	1	1	1	1	1	1	1	1	1	1
C_7	0	0	0	0	0	0	1	0	0	0
C_8	0	0	0	0	0	0	0	1	1	1
C_9	0	0	0	0	0	0	0	1	1	1
C_{10}	0	0	0	0	0	0	0	1	1	1

Tab. 12. Level partition matrix

Criterion	Reachability set	Antecedent set	Intersection set	Level 1
C_1	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_2	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_3	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_4	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_5	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_6	C_6	$C_1,C_2,C_3,C_5, C_6,C_7,C_8,C_9, C_{10}$	C_6	-
C_7	C_1,C_2,C_3,C_5,C_6,C_7	C_7	C_7	✓
C_8	$C_1,C_2,C_3,C_5,C_6, C_8,C_9, C_{10}$	C_8,C_9, C_{10}	C_8,C_9, C_{10}	✓
C_9	$C_1,C_2,C_3,C_5,C_6, C_8,C_9, C_{10}$	C_8,C_9, C_{10}	C_8,C_9, C_{10}	✓
C_{10}	$C_1,C_2,C_3,C_5,C_6, C_8,C_9, C_{10}$	C_8,C_9, C_{10}	C_8,C_9, C_{10}	✓

Tab. 13. Continuation Level partition Level 2

Criterion	Reachability set	Antecedent set	Intersection set	Level 2
C_1	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_2	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_3	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_4	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_5	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_6	C_6	C_1,C_2,C_3,C_5, C_6	C_6	-

Tab. 14. Continuation Level partition Level 3

Criterion	Reachability set	Antecedent set	Intersection set	Level 3
C_6	C_6	C_1,C_2,C_3,C_5, C_6	C_6	✓

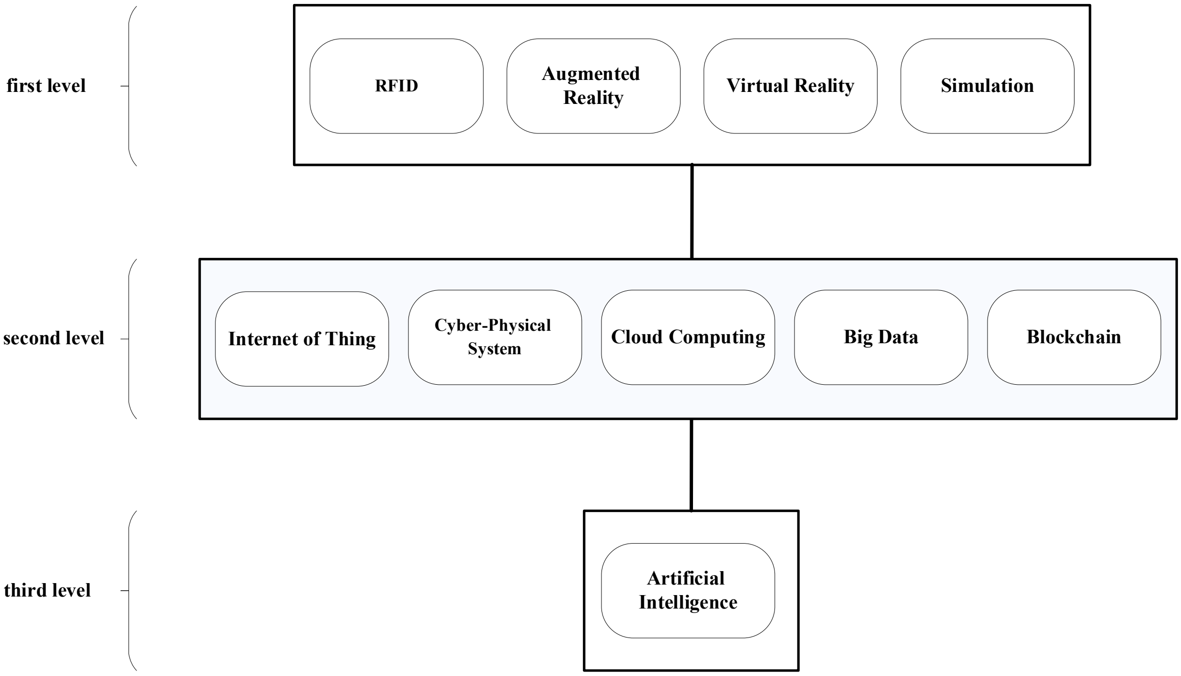

Fig. 6. Deployment map of supply chain 4.0 technologies

Tab. 15. Dependence and power values

	Power	Dependence
C_1	6	9
C_2	6	9
C_3	6	9
C_4	6	9
C_5	6	9
C_6	1	10
C_7	7	1
C_8	9	3
C_9	9	3
C_{10}	9	3

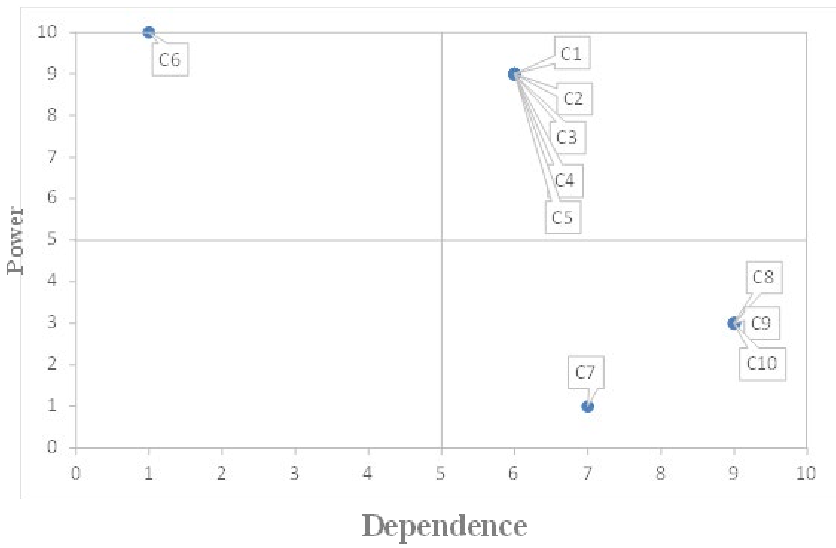

Fig. 7. Analysis of MICMAC

other fields. Generally, the studies conducted in this area have been in the form of review articles, and few of them have addressed the multi-criteria decision-making methods in supply chain 4.0. According to the supply chain 4.0 literature, the lack of identification of supply chain 4.0 technologies has made industries unable to understand supply chain 4.0. Govindan et al. (2022), in review research, investigated the enabling technologies of Industry 4.0 in supply chain 4.0, which include the IoT, cyber-physical systems, augmented reality, cloud computing, big data, and artificial intelligence. Zekhnini et al. (2022) identified the risk factors of supply chain 4.0 in their study and analysed them using the ISM method. Terra et al. (2021) investigated the barriers to world-class production in Industry 4.0. According to their

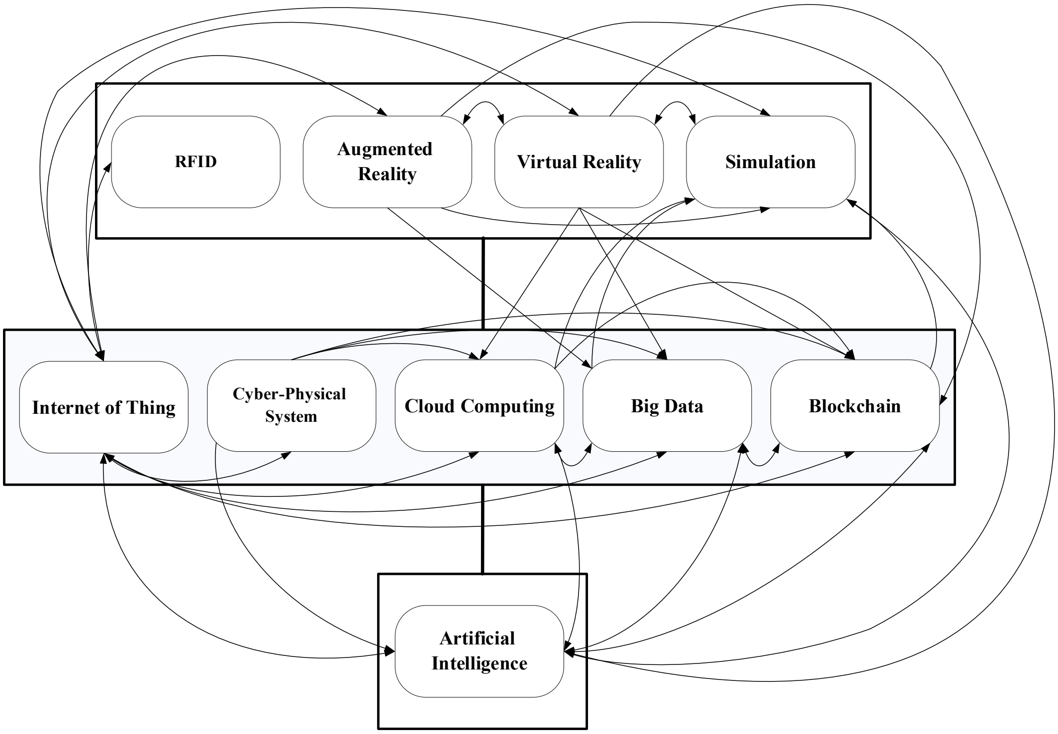

Fig. 8. Relationships within the levels of supply chain 4.0 technologies

findings, the lack of internal processing knowledge, lack of using the correct technologies, and trained manpower are the biggest obstacles in this regard. The sustainable use of resources, including manpower, enables the use of technologies in improvement projects through the reorganisation of work methods and the use of the correct techniques and tools. In practical terms, the direct efforts towards continuous monitoring of processes and use of data for project improvement, mutual training of human resources, and technology applications have been determined according to the strategic plan of Industry 4.0 trends. Szum (2021) studied digital tracking development through IoT sensors and image processing technologies. Łabędzka (2021) stated in his study that small and medium-sized enterprises (SMEs) speed up the dissemination of Industry 4.0 technologies, which consequently leads to innovation in the supply chain area. Intalar et al. (2021) indicated in their study that QR codes, IoT tools, and video cameras are used in performing image processing and tracking production status. Ali and Aboelmaged (2021) conducted a study in which they identified the drivers and obstacles of supply chain 4.0 in the food industry. According to their findings, the drivers of the supply chain include rapid changes in consumer needs, cost optimisation, threats of legal penalties, and reduction in supply-demand misalignment. Cañas, Mula and Campuzano-Bolarín (2020) investigated the supply chain 4.0 sustainability by reviewing the literature. In their study, considering the three main dimensions of sustainability, namely, economic, social, and environmental aspects, the researchers of this study identified and classified the articles in this field and found that in the literature on supply chain 4.0 sustainability, more attention has been paid to the environmental dimension and less attention has been paid to the social dimension. Sobb et al. (2020) studied the nature of supply chain 4.0 in the military industry. They acknowledged that the general infrastructure of supply chain 4.0 consists of blockchain, artificial intelligence, cyber-physical systems, and IoT technologies. Ramirez-Peña et al. (2020) categorised the critical technologies of Industry 4.0 in the supply chain 4.0 sustainability of the shipbuilding industry by reviewing the literature. According to their findings, some enabling technologies in supply chain 4.0 include big data analysis, cloud computing, augmented reality, artificial intelligence, blockchain, IoT, and simulation. They also investigated the sustainability of supply chain 4.0 in the aerospace, navy, and automotive industries. According to their findings, all three sectors have a strong interest in absorbing the IoT in supply chain 4.0. Moreover, they found that blockchain and big data technologies contribute to supply chain 4.0 sustainability more than other technologies in all three sectors.

Princes (2020) declared that digital tools such as big data analysis, artificial intelligence, IoT, and blockchain are suitable for facing the destructive challenges in supply chain 4.0. Frederico et al. (2019) proposed a framework for supply chain 4.0 in their study. This framework comprises four parts, including process and performance requirements, strategic outcomes, managerial and capabilities supporters, processes performance requirements, and technology levers. Some of the technologies used in the technology levels of this framework include IoT, cyber-physical systems, blockchain, automation, cloud technologies, augmented reality, RFID, and robots.

Scavarda et al. (2019) studied the supply chain 4.0 sustainability in the healthcare sector. According to the results of their study, social responsibility plays an essential role in the healthcare supply chain 4.0 sustainability through the IoT. Makris et al. (2019) acknowledged that big data, cloud computing, and 3D printer technologies are critical technologies in supply chain 4.0. Perussi, Gressler and Seleme (2019) investigated the equipment used in supply chain 4.0. According to their findings, for the operations inside industries and warehouses, the best equipment is the self-guided vehicle, and for delivering the product to the customer, the best equipment identified is the drone.

According to the results of the literature review, the enabling technologies in supply chain 4.0 are the same as the technologies identified in the present study. Moreover, some studies referred to the high importance of IoT in supply chain 4.0, which is in line with the finding of this study, in that using the DEMATEL technique in the current study, IoT is found to be of great importance. Of course, the results of this study can be a prelude to further research in the industries. Considering the study's limitations, we can refer to the lack of full implementation of supply chain 4.0 and the lack of experts familiar with supply chain 4.0 in industries.

Conclusions

With the transformation in manufacturing due to the Fourth Industrial Revolution, customer expectations have increased, and products have moved towards customisation and specialisation. Therefore, to maintain a competitive advantage, stakeholders must be willing to accept the Fourth Industrial Revolution and invest in it. On the other hand, it is undeniable that the supply chain is an essential part of the production, and it needs to be given priority in development and investments. Therefore, it is necessary to focus on supply chain 4.0 and adapt it to today's world and optimise it. Supply chain 4.0, with its core technologies, reduces costs and improves efficiency and effectiveness and requires organisations to identify new customer needs and solve problems related to meeting these needs and customer expectations in improving productivity. Supply chain 4.0 is characterised by high flexibility, greater agility, careful examination of details, and high efficiency.

According to the results of the conducted studies in this area, it was found that the lack of identification of the supply chain 4.0 technologies has caused the lack of understanding of supply chain 4.0 by industries. Therefore, to fill this gap, this study first identified these technologies and then investigated the relationships among them. This study aimed to investigate the relationships among supply chain 4.0 technologies using DEMATEL and ISM methods so that, by learning and understanding these relationships, the industries could implement supply chain 4.0 technologies in their supply chains and solve their related problems. To achieve this, supply chain 4.0 technologies were first identified in the research literature. Then, they were extracted using the Delphi method and experts were interviewed. Finally, supply chain 4.0 technologies were examined using the DEMATEL and interpretative structural modelling techniques. The DEMATEL technique identified the relationships between cause-and-effect technologies and found that IoT technology was more critical compared to others. The interpretative structural modelling technique found that radio-frequency identification (RFID), virtual reality, augmented reality, and simulation technologies should be deployed in the organisation first, while IoT technologies, cyber-physical systems (CPS), cloud computing, big data, blockchain, and AI should be deployed later. The MICMAC analysis found that artificial intelligence technology is independent. According to the DEMATEL technique results, this technology has a relationship with simulation technology, which is in the first level of the interpretative structural modelling technique, and IoT technologies, cloud computing, big data, and blockchain that are in the second level of the interpretative structural modelling technique.

According to the previous studies, little research has been done in the field of supply chain 4.0 technologies to be categorised and reviewed. The present study is a pioneer in this regard. According to the findings of the present study, researchers and industrial managers are recommended to pay special attention to the Industry 4.0 technologies examined in this study as the drivers of supply chain 4.0. These drivers can be implemented in future research in the industry, and their results can be discussed. These technologies can also be investigated and studied using other decision-making techniques. It seems that future research will go towards prioritising obstacles to the supply chain 4.0 implementation because to accept supply chain 4.0, it is essential to identify its barriers. Investigations of the relationships between supply chain 4.0, digital products, and Industry 4.0 can also be the possible subjects of future studies. Information security solutions in supply chain 4.0 can also be studied in the future. Supply chain 4.0 allows organisations to move from the traditional static and slow situation to dynamic, fast, and flexible frameworks. In this way, organisations can operate with simple and abundant access and without time or place restrictions. Furthermore, they cannot move without considering business processes and computer systems.

Traditional business approaches create substantial costs due to the inability to provide complex and diverse products, but new approaches seek to provide the needed services and products to the changing global markets. This issue is possible based on the combination of traditional business networks and communications and work interactions with the help of information and communication technologies.

There is a limited number of studies in the literature on supply chain 4.0, and many research gaps have remained unanswered. Due to the industries' lack of knowledge about the concepts and applications of supply chain 4.0, there are few operational experiences in this regard, and having access to experts who have complete mastery of the subject is also one of the limitations of this study.

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