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Enhancing supply chain resilience: The impact of 4.0 technologies

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Background: Every company has a supply chain (SC) and must deal with its uncertainty, which can provoke a bullwhip effect; resilience of SCs is a main characteristic to be achieved. However, studies on the creation of digital SCs adopting Industry 4.0 (I4.0) are very scarce and require more attention.

Objectives: Industry 4.0 is very little studied in *the* field of resilience of SCs, despite the huge benefits it can provide. This study aims to evaluate I4.0 to improve both strategic and operational performance.

Method: Initially, a deep literature has been carried out to find out the requirements to improve the resilience of a SC and how I4.0 can contribute. Then, a framework has been developed using Internet of Things (IoT), artificial intelligence (AI), augmented reality (AR) and virtual reality (VR).

Results: The resilience of SC is a very new topic, and I4.0 can provide great benefits. The designed framework can improve resilience by integrating new technologies.

Conclusion: Adopting I4.0 into the SC can be challenging, but it is mandatory to integrate it to keep competitiveness high and improve the resilience of the company. Internet of Things can collect data, analysed by AI and made available with AR and VR to operators.

Contribution: This study helps in closing the gap between the need of resilience in SC and technological solutions based on I4.0. This improves warehousing, inventory management and demand forecasting with distribution communications and information technology.

Keywords: supply chain, IoT, artificial intelligence, AI, virtual reality, augmented reality, digital supply chain, resilience.

Introduction

Recent developments in the business environment, including the coronavirus disease 2019 (COVID-19) pandemic, the war in Ukraine (Bygballe, Dubois & Jahre 2023), urban floods and typhoons (Wang et al. 2024), have caused significant disruptions in global supply chains (SCs), revealing their vulnerability (Bygballe et al. 2023). These disruptive events have prompted researchers to expand their focus beyond sustainability to include risk management in the SC, leading to the development of an integrated sustainable-resilience paradigm (Habib & Hwang 2024). The concept of resilience goes hand in hand with the sustainability of SCs: among the main aspects of a SC's resilience are its ability to withstand disruptions and ripple effects and to recover. In fact, it develops its sustainability through the ability to maintain itself and survive in an ever-changing environment (Zaoui et al. 2023). As a result, supply chain management (SCM) is one of the most critical operational processes, significantly impacting the economy, environment and society (Tirkolaee et al. 2023). Moreover, because of the globalisation process (which increases exposure to risk), a growing number of experts have dedicated efforts to understanding, managing and developing resilient strategies to cope with sudden disruptions (Safari et al. 2023). Given the importance of this issue and the scarcity of studies related to the application of Industry 4.0 (I4.0) in SCs (Joseph Jerome et al. 2022), this study proposes an innovative Supply Chain Resilience 4.0 framework to highlight the advantages of applying technologies such as Global Positioning System (GPS), Internet of things (IoT), artificial intelligence (AI), augmented reality (AR) and virtual reality (VR) in enhancing supply chain resilience. Specifically, the project focusses on the adoption of IoT sensors and real-time GPS tracking to improve operational visibility, the use of AI algorithms to optimise decision-making and predict early signs of potential crises, the implementation of AR to facilitate training and emergency management during disruptions and the use of VR to simulate complex environments in the event of unexpected interruptions.

The aim of this article is to link the above-mentioned I4.0 technologies with resilience. The authors developed their own framework to improve this characteristic and analysed the expected impact. To successfully reach this goal, the article is divided as follows: problem statement and research questions (RQs), stating the gap to be closed; methodology, how the literature has been searched and how the framework has been developed; the literature review, resuming and clustering the existing papers on this topic; the framework, describing how the technologies have been integrated and what is the impact over resilience; result and discussion, resuming and generalising what was obtained by this work and conclusions, where the RQs are answered.

Problem statement and research questions

Every company must deal with the SC problems and issues. The bullwhip effect turns a single adverse event into disruption all across the SC. The resilience thus becomes a fundamental feature that every company must achieve to improve their ability to face disruption (Briatore & Braggio 2024). However, despite this great need, very few studies try to link resilience with I4.0 technologies. In fact, most of them focus on methodologies, rather than innovation. This leads companies to have limited knowledge about how to exploit digital transformation in this direction.

To try to solve this problem, this study addressed three research questions (Research question [RQ]1): *How IoT, GPS, AI, AR and VR can improve the resilience of a SC?*

The aim is to understand how these technologies, both individually and when integrated, can be applied to improve supply chain resilience, highlighting their respective advantages and disadvantages (RQ2): *How can the previous technologies be integrated to create a Supply Chain Resilience 4.0 framework?*

The aim is to develop a framework integrating the aforementioned technologies. This is a crucial aspect of the project, as it is designed to be implemented as a pilot project, thereby facilitating the adoption of advanced technologies (RQ3): *What is the impact of such a framework on the supply chain resilience?*

The final RQ analyses the impact of the proposed framework on resilience. This is a fundamental feature of any system and a key issue investigated in this work, with the goal of understanding whether I4.0 technologies can ensure a rapid response and effective management of disruptions.

Research methods and design

To maximise the quality of the work, a search was conducted on Scopus using the following strings:

- 'GPS' OR 'IoT' OR 'augmented reality' OR 'virtual reality' OR 'artificial intelligence'

  AND

- 'supply chain*'

  AND

- 'resilien*'

The search resulted in 473 records. The research was then carried out for only keywords, reducing this amount to 121. To focus on the most recent works, only those from 2020 have been included (109). Furthermore, the authors chose to address the subject area 'Engineering', 'Business, Management and Accounting' and 'Decision Sciences' (80). Of these 80 articles, 47 were in journals and only the 46 written in English have been considered. Of them, the available ones were 41, resulting in 30 of interest. Finally, to bring further value to research, other 30 articles were added using a snowballing approach. As a result, a total of 60 articles were used for the literature review.

Subsequently, with the information gathered, the Supply Chain Resilience 4.0 framework was developed, analysing both the individual technologies and their combined impact. Finally, the framework's impact on supply chain resilience was evaluated. Through a working methodology that includes literature review, scientific analysis and architectural design, the study aims to provide a solid foundation for the creation of an advanced system to enhance the resilience of SCs, capable of anticipating and efficiently managing disruptions.

Literature review

In an increasingly uncertain and volatile business climate, the digitalisation of the SC represents the only recourse for enhancing its resilience and ensuring positive long-term performance (Abourokbah, Mashat & Salam 2023). Resilience is defined as the ability of an organisation or SC to respond to disruptions and return to its original state with minimal delay (Samadhiya et al. 2023). In recent years, SCs have undergone technological transformations that demand highly flexible and adaptable networks, featuring structural diversity and multifunctional processes (Ivanov 2024). Through the adoption of I4.0 technologies such as AI, IoT, AR, VR (along with Cloud Computing and Blockchain) and Industry 3.0 technologies like GPS, numerous benefits are expected in terms of improving supply chain resilience, also because digitalisation and resilience are closely interconnected (Ivanov 2024). Specifically, these technologies enable real-time data analysis and sharing upstream and downstream, enhance traceability (Alkhatib & Momani 2023), optimise processes across the chain and ensure transparency among various stakeholders (Nagy et al. 2022), thereby supporting decision-making (Harju et al. 2023). Therefore, it is important to have intelligent and flexible information systems that can facilitate the discovery, recovery and redesign of SC operations when a disruptive event occurs (Gupta et al. 2024). However, few empirical studies explore how the

practical application of I4.0 technologies influence supply chain resilience. The available case studies primarily focus on the impact of blockchain. Although current research has analysed the theoretical benefits that these technologies can offer for supply chain resilience, there is a lack of case studies that delve into how such innovations actually affect resilience capabilities in SCs (Brookbanks & Parry 2024).

Global Positioning System is a global satellite navigation system in which a group of Earth-orbiting satellites communicates with a GPS device anywhere on Earth, providing information on location, speed and time. GPS technology is highly effective for outdoor use as satellite signals are significantly stronger outside buildings than inside (Alzoubi 2018). It is primarily used in the transport sector to monitor goods (including vehicles) and other expensive equipment. For example, it can be used in the event of a truck breakdown, as it allows for the location of the vehicle and quick resumption of shipment (He et al. 2009).

Internet of Things is a digital technology consisting of a vast network of interconnected devices that collect and share information about the surrounding environment with the help of sensors and a common platform (Joseph Jerome et al. 2022; Mosca et al. 2023b, 2023c). For example, the availability of data on the food SC could alleviate uncertainties associated with SC disruptions, and the need for data, along with the ability to process and synthesise it, can minimise risks related to uncertainty in the SC (Njomane & Telukdarie 2022). In logistics, the real advantage of this technology lies in its ability to collect real-time data on the location and tracking of goods in warehouses, thereby increasing data sharing (Küffner et al. 2022). In addition, IoT is considered one of the crucial technologies for promoting a cyber-physical SC that uses integrated sensor systems (Sultana et al. 2022). The benefits of this technology are achieved through tools like radio frequency identification (RFID), wireless sensors and tracking systems. In summary, the adoption of IoT offers numerous advantages, including the ability to improve operational efficiency, reduce waste and enhance preventive maintenance through data analysis (Al-Banna, Yaqot & Menezes 2024). However, like all I4.0 technologies, IoT has some challenges. As it is an integrated system, companies must develop cybersecurity measures to ensure the privacy of data and exchanged information (Iftikhar et al. 2022). At the same time, the adoption of IoT and digital twin technologies is estimated to generate an economic value between USD 5.5 trillion and USD 12.6 trillion globally by 2030 (Biller & Biller 2023). In recent years, the integration of the IoT and Big Data Analysis (BDA), known as IoT-BDA, has made SCs more transparent, enhancing consumer trust. This synergy can improve traceability, speed up deliveries and synchronise partners, maximising the value of data generated along SCs and fostering innovation and efficiency in sectors such as manufacturing, healthcare, agriculture, transportation and smart cities. The BDA market for SCM, valued at $3.55 billion in 2020, is expected to reach $9.28 billion by 2026, with an annual growth rate of 17.31%. However, recent studies show mixed results regarding the improvement of business performance through IoT-BDA adoption, as effectiveness varies based on investments and technological capabilities (Agrawal et al. 2023). Ultimately, Ivanov (2023) introduces the concept of the 'Intelligent Digital Twin' (iDT), a human-AI system that digitises SCs, collects and analyses data for modelling through analytical methods, imitates human decision-making and generates new knowledge and decision-making algorithms (Ivanov 2023).

Augmented reality consists of technologies that combine the real world and the virtual world (Rejeb et al. 2021), meaning it is a perfect mix of information, text, images and audio-visual enhancements that enable a better understanding of the environment, localisation and real-time task execution (Joseph Jerome et al. 2022). Augmented reality can simplify logistics processes, help reduce the time needed to identify packages, optimise truck sequencing and loading, and improve routing strategies (Rejeb et al. 2021) while also training a semi-skilled workforce more quickly (Joseph Jerome et al. 2022). Moreover, by combining AR and RFID, it is possible to visualise information on containers and other types of packed objects, improving traceability and transparency across the entire SC (Rejeb et al. 2021).

Virtual reality creates a computer-generated artificial environment where an advanced human-computer interface connects simulations and real-time interactions through multisensory channels such as sight, hearing, touch, smell and taste. In the VR context, users can create a simulation or a self-contained world disconnected from reality (Rejeb et al. 2021). For example, Domino's Pizza has implemented an AI-powered chatbot for customer service and has incorporated AR for virtual pizza building and customisation (Pal, Ganguly & Chaudhuri 2024). In the manufacturing industry, for example, a methodology has been proposed for the commissioning of multi-robot manufacturing cells using digital twin and VR, which can improve the efficiency of the commissioning process and identify potential vulnerabilities and threats before they occur (Al-Banna et al. 2023). In addition, the application of AI in SCM enhances the automation of SCs through the deployment of virtual assistants, both within a particular organisation and among members of the SC (Kazancoglu et al. 2023).

Artificial intelligence can find patterns in data, particularly suitable for forecasting (Briatore & Revetria 2022), fundamental in any field (Cassettari et al. 2017). In the SC context, AI is defined as the ability of a system to acquire and obtain knowledge through the analysis of data from the surrounding environment and to apply that knowledge to promote new strategies against potential disruptions, thus supporting decision-making processes (Belhadi et al. 2021, Briatore, Revetria & Rozhok 2023). Specifically, AI serves as a tool for companies to identify weaknesses in their SC and provides support for subsequent investment in corrective actions (Modgil et al. 2022). Artificial intelligence, therefore, facilitates the design thinking of business systems without

human interference and learns from information to build insights (Modgil et al. 2022). Utilising AI helps managers throughout the SC improve efficiency, quality and consequently, customer satisfaction (Jauhar et al. 2023). At the same time, AI integrated with BDA can analyse and convert data collected throughout SCs, helping organisations gain valuable insights for decision-making and enhancing resilience (Singh et al. 2024). Moreover, as SCs are continuously expanding their geographical reach, particularly in regions where they previously did not operate because of the pandemic, AI can assist companies in navigating market segments remotely, thereby facilitating more informed and precise business decisions (Mukherjee et al. 2024). Finally, in the case of a subset of AI, specifically machine learning (ML), it enhances SC resilience by learning from collected data and, for example, automating production and transportation processes (Küffner et al. 2022). In recent years, there has been a significant rise in investments, research projects, training programmes and academic publications focussed on AI and ML (Samadhiya et al. 2023). This is because AI plays a significant role in generating value by providing organisations with intelligent insights from large data sets (Dubey et al. 2022).

Finally, the innovative Industry 5.0 is also mentioned in the literature. It represents an evolution from I4.0 by integrating human values with disruptive technologies while not neglecting the environment. Its aim is to develop a resilient, human-centric SC capable of analysing risks and optimising operations to minimise demand fluctuations, showcasing significant potential for strategic optimisation and resilience (Ahmed et al. 2023). At the same time, the literature refers to the use of 6G, which is expected to improve society by making communications and intelligence more pervasive, drastically reducing energy consumption and introducing innovative applications across various fields, thereby enhancing resilience in the SC (Karam et al. 2022).

Supply chain resilience 4.0 framework

Data collection via Internet of Things (IoT) and predictive analysis with artificial intelligence

The framework proposes the strategic installation of IoT sensors at various upstream and downstream nodes of the SC, as well as in vehicles, to monitor critical parameters such as temperature, humidity and inventory levels. The specific sensors employed for real-time data collection include:

- Radio frequency identification -based sensors for object monitoring. These sensors enable precise tracking of the location and status of items throughout the SC, reducing the risk of losses, theft and inventory errors. Consequently, they can be used along the entire chain to provide visibility and improve processes (He et al. 2009);
- Temperature and humidity sensors, such as DHT11 or DHT22, which monitor environmental conditions. These are among the most commonly used and readily available sensors on the market, with the advantage of having two

functions integrated into a single sensor - measuring both air temperature and humidity (Yulizar et al. 2023). This is crucial for sensitive products, such as food and pharmaceuticals, ensuring that they are kept in optimal conditions during transportation and storage.

All these sensors continuously transmit data to a cloud platform, where it is stored, processed and analysed, centralising the information and making it accessible in real time to all SC stakeholders. Indeed, the adoption of lean coordination mechanisms along the SC can ensure business sustainability and resilience (Trabucco & De Giovanni 2021).

In addition, it is important to highlight the improvements in operational efficiency, the reduction of time and resource waste and the acceleration of decision-making processes based on stored data —all positive outcomes that can be achieved through IoT (Qader et al. 2022). By adopting AI algorithms, particularly ML models (a subset of AI that ensures the execution of assigned tasks without human intervention [Kassa et al. 2023]), deep neural networks and regression algorithms (as well as clustering techniques), the data collected from IoT sensors and inventory management systems are analysed. These algorithms enable accurate forecasting of future demand, optimising orders and inventory management, reducing operational costs and improving product availability. Specifically, integrating BDA (which is considered crucial for leveraging disruptive technologies of I4.0, allowing for the analysis and processing of information to make suitable strategic decisions [Chatterjee et al. 2023]) with AI allows the identification of potential disruption signals, such as delivery delays or production issues, enabling timely corrective actions. As a result, real-time data management and predictive analysis allow the SC to quickly adapt to changes in market conditions or customer needs. The integration of IoT sensors and AI not only improves the ability to detect critical conditions that could affect product quality, preventing damage and waste but also facilitates a more dynamic, responsive and resilient SC by identifying early warning signs of sudden disruptions. Furthermore, the integration of AI with BDA has the potential to significantly enhance the resilience of SCs and facilitate more effective management of SC resources (Zamani et al. 2023).

Resilience

The real-time monitoring of important variables is fundamental to take evidence-based decisions, both on operational and strategic point of view. Knowing the current environmental condition of products, it is possible to intervene timely, avoiding spreading problems and generating higher disruption. Moreover, real-time tracking of objects is very useful in case of loss. This can make a big difference when it comes to valuable resources and people. All these data generate Big Data, which are analysed by AI to extract in-depth knowledge.

Global positioning system tracking route optimisation through artificial intelligence

The framework also proposes the adoption of GPS devices, appropriately installed on transport vehicles, which are capable of tracking their real-time location (as outlined in the 'Literature review' section of this article). The data generated are continuously transmitted to the company's central system, allowing for the constant monitoring of shipments. This enhances SC visibility and control, enabling companies to respond quickly to delays or deviations, thereby improving delivery reliability and overall SC resilience. In addition, by utilising ML algorithms to analyse traffic forecasts and weather conditions, along with clustering techniques for data analysis, AI can optimise transport routes. It continuously analyses traffic data, road conditions and weather forecasts to select the most efficient routes, reducing delivery times and promoting resilience in cases such as sudden road closures or disruptions. At the same time, the adoption of explainable artificial intelligence (XAI) is essential in inventory design and management: this ensures real-time market trends, historical data and predictive analytics (Sadeghi et al. 2024). The integration of GPS data with enterprise resource planning (ERP) and warehouse management system (WMS) allows for a more comprehensive view of operations, improving stock management in warehouses and shipping efficiency. Therefore, it is essential to implement collaborative platforms that enable the sharing of information among all upstream and downstream SC actors to facilitate communication and coordination, thus reducing the risk of disruptions.

Resilience

Real-time tracking of vehicles enables to change routes and take advantage of quick optimisation. This capability is very useful in case of problems during the path and when internal problems lead to quick need of something. Drivers can therefore change their route and fix the shortage while avoiding risks on the path.

Response to disruptions (augmented reality) and simulative scenarios (virtual reality)

The proposed framework also includes the adoption of AR and VR technologies. In the event of critical deviations detected by IoT sensors, operators receive immediate notifications via AR devices. These devices provide real-time instructions directly overlaid on the relevant equipment, enabling quick and precise interventions. For example, if a sensor detects a temperature outside the allowed range, operators are instantly alerted and can view the necessary instructions to resolve the issue on their AR device, such as adjusting climate control systems or relocating products to a safer area. This minimises downtime and reduces the risk of equipment damage. Similarly, if a vehicle equipped with IoT sensors and GPS detects a critical variation (e.g., excessive temperature increase in refrigerated cargo), operators can receive immediate notifications through AR devices, guiding them on how to adjust the vehicle's refrigeration system. This timely intervention protects the integrity of the cargo, ensuring the product reaches its destination without spoilage, thus improving the resilience of the entire SC.

Virtual reality, on the other hand, is used to create immersive simulations of the SC, allowing managers to test various disruption scenarios and develop optimal response strategies without interrupting actual operations. Based on real-time data received from IoT sensors and subsequently analysed by AI algorithms, operators can conduct simulations of scenarios without directly intervening in the real system, reducing the risk of introducing errors throughout the SC. This enhances emergency preparedness and allows for effective response planning, increasing resilience across the entire SC. This simulation must take into account the stochasticity of the system (Allahi et al. 2017; Bendato et al. 2017).

Resilience

Augmented reality and VR enable employees to better view the situation as they add important information. Augmented reality can be used in warehouses, helping people to quickly find items and saving time. This can improve resilience as, in case of critical need, it is possible to collect what is required in a shorter time. Moreover, through AR, it is possible to send the notification of adverse events and problems, improving the speed of intervention. Finally, VR can be used to train workers to face different scenarios, improving the system ability to recover from adverse events and disruption.

Proposed architecture

As discussed earlier on in the article, the integration of GPS, IoT, AI, AR and VR can significantly enhance the resilience of a SC. Figure 1 depicts the Supply Chain Resilience 4.0 framework, which constitutes the objective of this study. This framework represents a major step forward in predicting SC disruptions by combining advanced technologies to address the significant effects of adverse events that may impact all stakeholders involved in the SC and potentially cause global damage.

The proposed solution is able to interact within the entire SC, thus enabling warehouses to be integrated by using IoT and Big Data sharing.

Resilience

Real-time data are the basis to improve the knowledge of the system. Sensors collect data, and through IoT, it is possible to send Big Data to Cloud, where AI can extract critical information, pivotal to face disruption timely and effectively. Augmented reality and VR are then the instruments to improve employees' knowledge and training. Therefore, the time from a problem occurrence and its solution is shortened, while the effectiveness of actions is improved. The result is cost reduction, shorter

times of production stops and higher performance, also a learning curve from adverse events.

Results and discussion

Firstly, the study found that the majority of articles (53%) were written in 2023, showing an increase compared to 2021 and 2022, which is a clear sign of the novelty and current interest in this topic. Resilience, indeed, is a highly relevant issue today, and every organisation must incorporate it at all levels (Naz et al. 2022). It is no coincidence; therefore, that Alvarenga, Oliveira and Oliveira (2023) confirm that the topic of supply chain resilience is increasingly being addressed by academics, researchers and managers, who are investigating cutting-edge methods to best deal with sudden disruptions. At the same time, Dubey et al. (2023) state that despite the popularity of digitalisation, the role of digital technologies in enhancing supply chain resilience remains poorly understood and addressed, not only in literature but also in practice, underscoring the need for further studies.

Secondly, it is evident that while I4.0 technologies offer significant advantages individually, greater benefits are achieved when they are integrated. For this reason, the Supply Chain Resilience 4.0 framework was created, combining GPS, IoT, AI, AR and VR to provide an integrated solution aimed at enhancing the resilience of the SC. In particular, it has been highlighted how the adoption of digital technologies in SCs enables real-time information acquisition and processing, which accelerates decision-making, enhances SC visibility and fosters cooperation to strengthen supply chain resilience (Pal et al. 2024).

Thirdly, it has been demonstrated that the integration of IoT sensors and AI algorithms can optimise the operational efficiency of a SC and facilitate predictive analysis, while AR and VR improve the ability to respond to sudden events and simulate disruption scenarios within a SC. Consequently, it has been shown that adopting these technologies can enhance both the resilience and the response capacity of a SC.

Conclusion

In today's context, characterised by increasing complexity in global SCs, any disruption in the chain can cause it to stall, creating bottlenecks at various nodes (Huma & Siddiqui 2019). Indeed, disruptions in SCs can lead to costly economic, environmental and social consequences, making it essential for managers to adopt serious measures across all industrial sectors and their SCs (Tirkolaee et al. 2023). The study, therefore, presents itself as a crucial solution for enhancing the resilience of the SC through the integration of advanced technologies such as IoT, AI, GPS and AR and/or VR. Internet of Things sensors and GPS tracking improve operational visibility and control, AI algorithms enable accurate predictions of potential disruptions, and the adoption of AR and VR supports effective management of sudden changes and the simulation of possible disruption scenarios. Despite the open challenges related to complexity and managing the vast amount of data generated, these technologies significantly strengthen the adaptability and responsiveness of the SC, achieving the objectives as outlined earlier. The study has demonstrated that the integrated use of I4.0 technologies can provide a substantial contribution to disruption
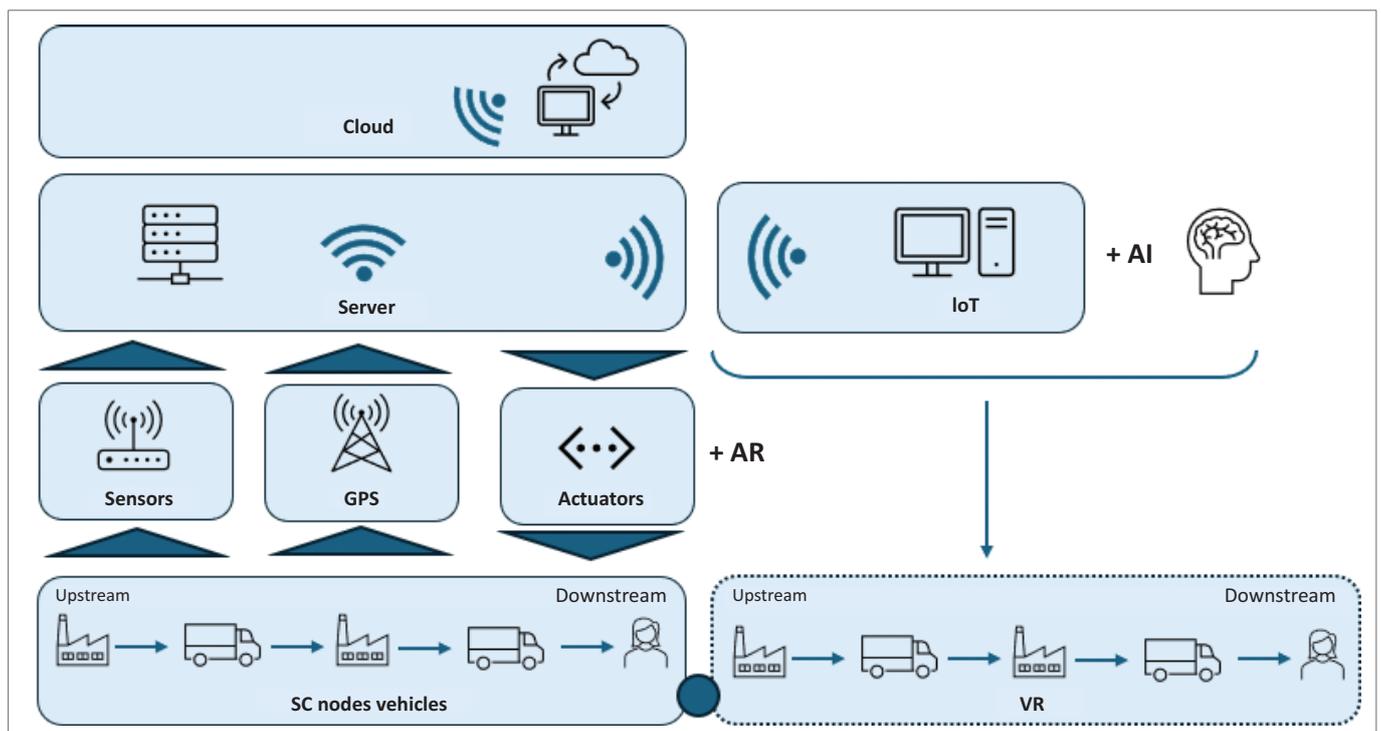
AR, augmented reality; VR, virtual reality; AI, artificial intelligence; IoT, Internet of Things; GPS, global positioning system.
FIGURE 1: Supply chain resilience 4.0 framework.

forecasting and enhancing supply chain resilience, confirming the importance of continuing to develop and adopt innovative solutions in this field.

In conclusion, it is important to emphasise that, beyond its technological advancements, I4.0 requires SC partners to adopt essential design principles such as interoperability, real-time capability, modularity, decentralisation and integrability, which enable the creation of a hyperconnected value system (Ghobakhloo et al. 2023).

Future research should carry out case studies to better understand the requirements for the successful implementation of I4.0 technologies and the barriers that must be faced. Also, more advanced simulations should be included (Cassettari et al. 2013, 2016). Moreover, depending on the type of product, the SC could have very different needs. For example, healthcare has specific requirements (Borelli et al. 2015, 2013; Mosca et al. 2022; R. Mosca et al. 2023a). The same happens for hydrogen because of the risks associated with it (Sgarbossa et al. 2022).

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