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Marco Ardolino, Andrea Bacchetti, Alexandre Dolgui, Guglielmo Franchini,  
Dmitry Ivanov, Anand Nair

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## The impacts of digital technologies on coping with the COVID-19 pandemic in the manufacturing industry: A systematic literature review

Marco Ardolino – Rise laboratory, University of Brescia ([marco.ardolino@unibs.it](mailto:marco.ardolino@unibs.it))

Andrea Bacchetti – Rise laboratory, University of Brescia ([andrea.bacchetti@unibs.it](mailto:andrea.bacchetti@unibs.it))

Alexandre Dolgui – IMT Atlantique, LS2N – CNRS ([alexandre.dolgui@imt-atlantique.fr](mailto:alexandre.dolgui@imt-atlantique.fr))

Guglielmo Franchini – Rise laboratory, University of Brescia  
([g.franchini002@studenti@unibs.it](mailto:g.franchini002@studenti@unibs.it))

Dmitry Ivanov – Berlin School of Economics and Law ([divanov@hwr-berlin.de](mailto:divanov@hwr-berlin.de))

Anand Nair – Michigan State University ([nair@broad.msu.edu](mailto:nair@broad.msu.edu))

### Abstract

The COVID-19 pandemic's impacts have been devastating for the global economy, particularly for manufacturing companies that have been forced to face challenges that were almost unheard of before. Many companies were completely unprepared for an event of this magnitude and tried to limit the damage by adopting specific countermeasures. Some of these were possible thanks to digital technologies and the digitization of business processes, which sometimes made it possible to reduce or eliminate negative effects. In particular, digital technologies have helped companies adapt during the crisis and ensure business continuity. This article aims to investigate how digital and Industry 4.0-enabling technologies have helped manufacturing companies cope with the pandemic's effects. The study indicates that some technologies have contributed more than others, although the Industry 4.0 paradigm's potential has not been exploited fully. This calls for future research directions to extend the scope of analysis in these aspects, particularly five specific areas: data and information management; (re)organization of work; de-globalization and reshoring; supply chain resilience; and environmental and social sustainability.

**Keywords:** COVID-19; digital technologies; Industry 4.0; systematic literature review

# 1 Introduction

The external shock from the COVID-19 pandemic and the containment measures that various governments have taken revolutionized manufacturing companies' operations. Unexpectedly, manufacturers found themselves reorganizing how they work, adapting their technological infrastructures to support remote work, revising departmental layouts to support social distancing, and managing forced quarantine situations for their employees (Wang & Wang, 2021). The acceleration of digital transformation from the pandemic also has affected companies, public bodies, and individuals (Almeida et al., 2020). During the pandemic, employees in the manufacturing sector became familiar with digital tools that enabled remote work and distance learning, such as Zoom, Microsoft Teams, and Google Meet applications (Jiang, 2020). These tools have helped manufacturing companies introduce remote work in white-collar departments, while little or nothing has been achieved in blue-collar departments (Rapaccini et al., 2020). Despite this practice's strong social impact, its benefits, inefficiencies, and obstacles have been treated superficially in the literature (Rapaccini et al., 2020). Similarly, no scientific study has investigated how digital technologies (DTs) have overcome these problems and limited it to worker activity in production departments. For manufacturing operations, DTs potentially can be implemented to enable remote operations, automate processes, allow machines to work autonomously, and reduce on-site personnel (Kamal, 2020). DTs also can make manufacturing companies and the entire supply chain (SC) more resilient to deal with disruptive events such as a pandemic, as well as make processes more efficient, increase productivity, and make work more reliable and safer for workers (Kamarthi & Li, 2020). DTs' potential to mitigate the COVID-19 pandemic's effects has been studied in the literature, but these studies often remain on a very theoretical level without entering into the merits of applications with manufacturing companies' various business processes (Dubey et al., 2020; Ivanov & Dolgui, 2020). Wuest et al. (2020) emphasized that while COVID-19's sudden appearance shifted the focus to short-term solutions, academics, manufacturers, and policymakers should concentrate on long-term benefits from crisis-induced digitization. While many articles have proposed frameworks and strategies to implement DTs and Industry 4.0 (I4.0), Paul and Chowdhury (2020) mentioned the importance of in-depth case studies and large-scale surveys to validate theories. There are also a number of aspects that the literature has not yet explored regarding the impact of the Industry 4.0 paradigm on the evolution of the supply chain (Hofmann et al., 2019). Furthermore, the literature indicates a distinct lack of systematic studies aimed at identifying

potential applications of digital technologies in manufacturing to mitigate the COVID-19 pandemic and similar events' effects.

This study aims to fill the aforementioned literature gaps, as well as collect and systematize existing knowledge on applications of digital technologies in the manufacturing industry, focusing on effects from the COVID-19 pandemic and future research opportunities. In short, this research aims to analyze how adoption of DTs has helped mitigate effects from the pandemic in the manufacturing industry. Furthermore, an open research agenda was developed based on five areas of interest: data and information management; work organization; de-globalization and reshoring; manufacturing resilience; and environmental and social sustainability.

To achieve the objective, this research focuses on answering the following research question:

*RQ: What is DT applications' role in overcoming the COVID-19 pandemic at manufacturing companies?*

In this regard, this study's contribution concerns both theoretical and practical aspects. From a theoretical perspective, this work represents a systematization of the scientific research conducted on the application of DTs in the manufacturing industry to mitigate the effects from COVID-19's proliferation. Furthermore, open research questions were identified that could be addressed in the future. From a managerial perspective, this study can give practitioners an overview of various DTs' potential to improve factory production activities and innovate all business processes to address future disruptive events similar to the COVID-19 pandemic. The rest of this article is organized into the following sections. Section 2 discusses the present study's conceptual background. In Section 3, the chosen methodology is presented. In Section 4, the study's results are presented, including applications of digital technologies to mitigate COVID-19's effects in the manufacturing industry. In Section 5, the article discusses the study's research findings, while Section 6 offers future research avenues according to a structured research agenda. Finally, Section 7 draws conclusions and also discusses the study's main limitations.

## **2 Background**

### 2.1 Industry 4.0 and digital technologies

The concept of Industry 4.0 (I4.0) was introduced at Germany's Hannover Fair in 2011 and became the nation's strategic initiative to introduce integrated digital technologies within

manufacturing companies (Lu, 2017; Xie et al., 2020; L. Da Xu et al., 2018). The main enabler of I4.0 was the spread of digital manufacturing through smart networking between industrial units – such as assets, machines, systems, and devices – promoting effective integration with customers and suppliers (Kamble et al., 2018). The I4.0 paradigm, in a most inclusive definition, is a framework for implementation of information technology (IT) and cyber-physical systems (CPS) through modern technologies in manufacturing, logistics, and SCs (Ivanov & Dolgui, 2021a).

This concept also often is referred to as the fourth industrial revolution, characterized mainly by the digitalization of production processes through the introduction of technologies such as cyber-physical systems (CPS), Internet of Things (IoT), and cloud computing (Zhong et al., 2017). Thus, the fourth industrial revolution is a digital revolution, which, starting from production processes, has come to impact all processes within manufacturing companies and beyond (Kornysheva & Barrios, 2020).

The diffusion and adoption of I4.0 by many manufacturing companies caused a lot of excitement among scholars and practitioners, but Industry 4.0's definition is not yet definitive because many enabling technologies still are emerging and have not yet reached an appropriate maturity level (Majumdar et al., 2021; Nosalska et al., 2020). The scope and focus of I4.0 depend very much on the industrial context in which it takes place, mainly because of most DTs' innate flexibility, so applications vary according to individual companies' objectives and strategic choices (Ivanov et al., 2021).

Digitalization of manufacturing processes requires enterprises to innovate traditional business models, achieving much more customer intimacy (Bravi & Murmura, 2021; Rejikumar et al., 2019). Furthermore, the adoption of I4.0 helps realize important strategic benefits concerning improvement of economic and financial performance (Cassetta et al., 2020). To better cope with increasingly complex contexts, implementation of digital technologies also makes it possible to improve flexibility and agility to absorb any external shocks that may impact demand (Rejikumar et al., 2019).

However, manufacturers also may face managerial barriers in trying to adopt I4.0 principles (Schneider, 2018). Using digital technologies requires a new skilled workforce that goes beyond traditional job profiles (Nimawat & Gidwani, 2021). Last, but not least, implementation costs can be an insurmountable barrier, particularly for manufacturing companies that do not have sufficient financial capacity to support the investment (Raj et al., 2020).

For this work's scope, all relevant DTs in the field of manufacturing were considered: Internet of Things (IoT); big data analytics (BDA); cloud computing; artificial intelligence (AI); blockchain (BC); augmented reality (AR); virtual reality (VR); industrial and collaborative robots; additive manufacturing (AM); autonomous vehicles; and drones. While some of these technologies are not strictly digital, they are included more widely in our definition of DTs, as they are related to digitized operations or parts of the I4.0 transition. These technologies are defined in Table 1.

Technology	Definition	References
Internet of Things (IoT)	Connections between devices and smart objects. A network of physical and digital assets that enables many types of operations, from remote monitoring and real-time data collection to direct control of production systems.	(Končar et al., 2020; Mohammed & Isa, 2021; Yadav et al., 2021)
Big Data Analytics (BDA)	The process of extraction (mining) and organization of large sets of digital information to make them useful for decision-making.	(Almeida et al., 2020; Ivanov et al., 2021; Zhong et al., 2017)
Cloud Computing	Digital services accessible directly on the Internet. The primary goal is to make these services accessible through different devices, without the need for specific storage or computational capabilities, regardless of geographical location.	(Nandi et al., 2021; Rananga & Venter, 2020)
Artificial Intelligence (AI)	A machine or digital application's ability to understand inputs and distinguish them from several variables in a given environment.	(Di Vaio et al., 2020; Longo et al., 2019; Peres et al., 2020; Ruhela & Riaz, 2019; Yun et al., 2021)
Blockchain	A distributed system comprising different and remote records (blocks) that are linked cryptographically (chained). Each block subsequently verifies transactions or data, building a decentralized consensus ecosystem.	(Hopkins, 2021; Lin et al., 2020; Wu et al., 2020; Yadav et al., 2021)
Augmented Reality and Virtual Reality (AR and VR)	Digital applications that can simulate and visually represent interactive objects or entire environments. The substantial difference between the two is that while VR does not necessarily have any connection with the real world, AR is a virtual extension of reality.	(Hanson et al., 2017; Hopkins, 2021; Scurati et al., 2018)
Industrial and Collaborative Robots	Advanced physical systems and machines designed and programmed to perform specific tasks or assist human operators' activities automatically.	(Poor et al., 2019; Shen et al., 2021; Wan et al., 2016)
Additive Manufacturing (AM)	The process of part manufacturing, replicating a three-dimensional digital model through layer-on-layer material deposition.	(Hopkins, 2021; Jemghili et al., 2020; Rainnie, 2020)
Autonomous Vehicles (AVs)	Vehicles capable of autonomous movement and routing without a driver or remote operator. They can avoid obstacles and operate safely on a factory floor.	(Hopkins, 2021; Ivanov et al., 2021; Sjoberg, 2020)
Drones	Also called unmanned aerial vehicles, they are flying devices piloted remotely either by a human or computer.	(Beke et al., 2018; EUCHI, 2020; Luque Vega et al., 2020)

Table 1: Definitions of digital technologies considered

## 2.2 COVID-19's impacts on manufacturing

The COVID-19 pandemic has elicited devastating effects on many aspects of daily life worldwide, particularly its disruptive effects on the global economy (Dwivedi et al., 2020). The spread of pandemics and epidemics, in addition to causing the loss of many lives, very often leads to major repercussions in economic and industrial activities (Ivanov & Dolgui, 2021b).

Manufacturing companies have faced multiple effects from the pandemic, which disrupted several aspects of daily life, as industrial organizations tried to maintain operations during the pandemic (Dwivedi et al., 2020). Government directives, as well as supply shortages and pressures, forced manufacturing companies to adjust their operational processes and adapt their working environments (Jones et al., 2021). Another important effect was workforce reduction due to employee infections, particularly in cases in which, due to COVID-19 containment regulations, confirmation of a case within a company led to preventive quarantines of whole teams of workers (T. Chen & Lin, 2020). Thus, the new and unexpected pandemic scenario has led both companies and academics to consider the challenges and opportunities of reorganizing work (Almeida et al., 2020).

The rapid adoption of safety measures and change in daily routines for most people induced an increased unpredictability in demand for various products on the world market, while production disruptions led to erratic supply levels (Li et al., 2020a). Discontinuities in the production of raw materials and components, as well as logistics setbacks, have led to shortages in many industries (Taqi et al., 2020). Electronics, machinery, and automobiles in particular have been affected significantly in this regard, as cheap supplies, globalization of the market, and minimal stock management have helped make the SC more susceptible to disruptive events (Cai & Luo, 2020). Furthermore, the production stoppages' consequences spread downstream along the SC through the knock-on effect, inflating prices, reducing production performance, and ultimately affecting the level of service that enterprises provided (Dolgui & Ivanov, 2021b). Based on these facets, much emphasis has been placed on the literature on issues of SC sustainability, resilience, transparency, and risk management (Aldrighetti et al., 2021; El Baz & Ruel, 2021). Manufacturing companies have implemented new procedures or even changed entire processes to comply with newly imposed security measures, and changes in assessed production systems have impacted quality negatively (Zimmerling & Chen, 2021).

All these effects have led to major system shocks, particularly a recession in the manufacturing ecosystem (Harris et al., 2020). This unpredictable and unexpected crisis has made a huge impact on businesses and society (Tang et al., 2021). From iconic brands to SMEs, the pandemic spared no one in its devastation of the global economy, particularly in the manufacturing industry (Mirza et al., 2020).

### **3 Methodology**

Academic publications were reviewed using the systematic literature review (SLR) method. In particular, an SLR was conducted on scientific articles related to DTs and COVID-19 in the manufacturing industry. This methodological approach was used to answer the research question. SLRs summarize existing knowledge and evaluate available research papers on a particular phenomenon to fill research gaps and strengthen the field of study (Petticrew & Roberts, 2008). Although this methodological approach originated in the field of medicine, it has been used in studies concerning COVID-19's impact on the manufacturing sector (Ardolino et al., 2021).

As part of this systematic literature review we follow the three phases suggested by Tranfield et al. (2003). First stage involved planning the review, through the identification of specific literature gaps to be filled and the planning of a structured process for conducting the review. The second phase involved the actual conduct of the review, with the identification and selection of research studies to be investigated, data extraction process and analysis.

To ensure generalizability and rigor, a structured selection process was implemented, and structured criteria were adopted to include related articles and exclude unrelated cases (Figure 1).



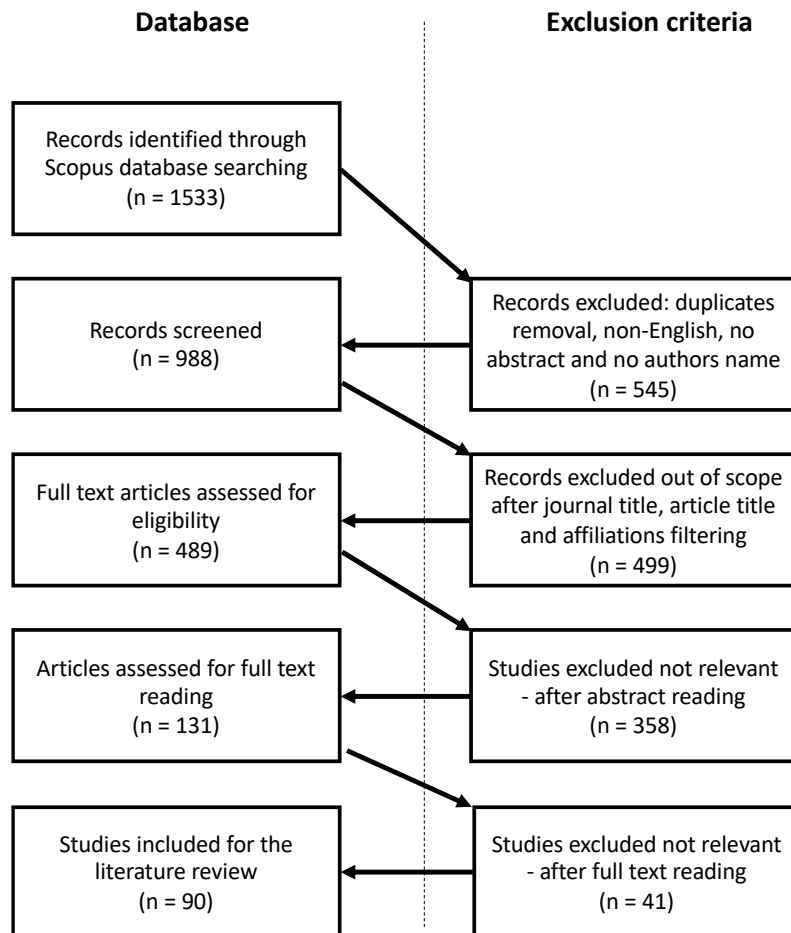


Figure 1: SLR selection process

The first step was to extract articles from the Scopus database, which was facilitated through a search string using the keywords *manufacturing* (and its derivatives), *COVID-19* (and its derivatives), and the names of the various technologies considered in this study. The articles were extracted at the beginning of March 2021. This yielded an initial database of 1,533 articles. Duplicates and articles without abstracts or author names were removed, as well as any that were not available in English. This reduced the total to 988. At this point, the database was filtered using keywords to exclude articles that did not relate to the search field. Several articles were related to health issues and topics because of the presence of the word *COVID-19* in the Scopus extraction. It was decided to filter by journal title, article title, and affiliation. The keywords and word roots *medic*, *health*, *pharma*, *clinic*, *bio*, *virus*, *immun*, *surger*, *disease*, *vacc*, *drug*, and *hosp* were used to exclude journal titles, affiliations, and article titles. The abstracts from each of the 489 remaining articles were read to assess their relevance to the review. Altogether, 358 were excluded after reading the abstracts because they were outside this review's scope, and 41 were excluded after reading the full text.

Therefore, this SLR comprised a final total of 90 articles on the topic of DTs' applications in the manufacturing industry during the pandemic.

We assume that one or more technologies can be implemented for a specific application. All these applications have been mapped by considering the benefits brought by each of them. Once this analysis was carried out, all applications and benefits were then reviewed to group them into individual categories if there were strong similarities between them. This allowed for a categorization that would allow for a more effective synthesis of the intended outcomes.

The selected articles were read and analyzed with the support of Mendeley© and Microsoft Excel©. The articles were catalogued in Mendeley, and after an initial reading, each one was assigned a tag related to the technologies investigated, highlighting the main application in manufacturing companies to mitigate the pandemic's effects. In a second step, all highlighted parts were entered into a Microsoft Excel© spreadsheet, identifying each item that the technologies involved, the main applications, and the business processes involved in the applications. Then, for each technology, the applications were grouped through standardized coding.

After the completion of stages 1 and 2, the study proceeded with stage 3 that involved "reporting and dissemination" by means of descriptive and thematic analyses. The results of descriptive analysis are presented below while those of the thematical analysis are presented in the next section.

Table 2 lists the journals in which the articles selected for this literature review were published. Both journal papers and conference proceedings have been considered. The *Journal of Manufacturing Systems*, *Smart and Sustainable Manufacturing Systems*, *Sustainability*, *IEEE Engineering Management Review*, and *IEEE Access* were the top five listed journals. The list features production-oriented journals and others more focused on information and operations technology. Furthermore, there was no shortage of contributions from journals that focus on sustainability issues.

Journal	N° papers	%
Journal of Manufacturing Systems	6	6,7%
Smart and Sustainable Manufacturing Systems	6	6,7%
Sustainability (Switzerland)	5	5,6%
IEEE Engineering Management Review	5	5,6%
IEEE Access	3	3,3%
Procedia CIRP	2	2,2%
Sustainable Production and Consumption	2	2,2%
International Journal of Production Research	2	2,2%

11th IEEE International Conference on Cognitive Infocommunications, CogInfoCom 2020 - Proceedings	2	2,2%
IEEE International Conference on Industrial Engineering and Engineering Management	2	2,2%
Procedia Computer Science	2	2,2%
International Journal of Information Management	2	2,2%
Others	51	56,7%
<b>Total</b>	<b>90</b>	<b>100%</b>

Table 2: Journal contributions on the topic of digital technologies and COVID-19 in manufacturing

The distribution of articles in 2020 and 2021 is presented in Table 3.

Year	N° papers	%
2020	63	70%
2021	27	30%
<b>Total</b>	<b>90</b>	<b>100%</b>

Table 3: Year-wise publication

## 4 Results

### 4.1 Internet of Things

The IoT is the foundation on which industrial networks are built and is essential to enabling the automatic collection and transfer of data. Digital factories need to manage large amounts of data efficiently (Baurina, 2020), and IoT improves accessibility by enhancing workflow optimization (Terry et al., 2020). Generally, IoT is applied in tandem with other DTs, such as blockchain (Lin et al., 2020), AI (Terry et al., 2020), and BDA (Yadav et al., 2021). The adoption of sensory devices increased dramatically during the COVID-19 pandemic to predict infection cases by analyzing symptoms using wearable sensors (Sharma & Ahmed, 2021). Furthermore, to improve contact tracing's effectiveness, countries most affected by the pandemic have leveraged IoT to support traditional manual contact tracing to track individuals who have come into close contact with identified COVID-19 patients (Shahroz et al., 2021). Therefore, many IoT-based contact tracking apps have been implemented (Ahmed et al., 2020).

However, in addition to applications in the field of infection monitoring, IoT adoption also has its uses on the factory floor. Adoption of IoT as a lower-contact system could be very effective for cases in which manufacturing and marketing processes have reduced contact with people (Firmansah et al., 2021). Moreover, as a tool for real-time data acquisition, use of IoT ranges from process monitoring to planning (Mantravadi et al., 2020; Wu et al., 2020). Applications with smart devices and machines equipped with sensors allow for remote monitoring of conditions, improving reliability and drastically reducing the need for risky contact between people (T. Chen & Lin, 2020).

This type of application, together with AI machine learning techniques, enables predictive maintenance on near-failure components, thereby reducing costly unscheduled production stops and unscheduled external service on the shop floor (Akpan et al., 2020; X. Li et al., 2020b; Terry et al., 2020). IoT also can be applied to inventory management and even automate purchasing processes (Wu et al., 2020) or track product flow via RFID (Končar et al., 2020; Lin et al., 2020; Wu et al., 2020), thereby reducing human involvement in monitoring operations and improving transparency and resilience (Siriwardhana et al., 2020). As an added benefit, use of IoT sensors reduces manual data entry errors, thereby improving efficiency in data management (Lin et al., 2020). In particular, the entire SC can benefit from improved traceability and transparency, particularly with a pandemic scenario in which logistical failures of medical equipment can be fatal (Ibn-Mohammed et al., 2021b).

Studies also have highlighted how IoT can strengthen collaboration between SC actors. By sharing inventory and production plan information, different factories can share production resources to balance capacity and demand (X. Li et al., 2020b; Chen & Lin, 2020) to adjust to market fluctuations typical of situations like pandemics or natural disasters (Li et al., 2020a). Improving connectivity between industrial assets not only offers a great opportunity to improve performance (Baurina, 2020), but also has the potential to deepen understanding of processes within the company, change management's view of operations, and ultimately create a competitive advantage (Almeida et al., 2020).

## 4.2 Big Data Analytics

In an increasingly connected business environment, the amount of data available to companies is increasing (Almeida et al., 2020). Big data is a resource for tackling production management's growing complexity (Monostori & Váncza, 2020), and BDA plays a role in making these data useful by extracting valuable information for decision-makers (Akpan et al., 2020). Big data have multiple sources; they can be mined on the Internet or come from online social networks, smart devices, or IoT sensors (Akpan et al., 2020). BDA techniques can work on both structured and unstructured data sets (Li et al., 2020a).

In the context of the COVID-19 pandemic, data collection and analysis in the process of developing a new product could be extraordinarily difficult, considering that the exchange of ideas, working arrangements, and corporate communication are changing constantly. Tsang et al. (2021) presented a framework for adoption of big data found online in the fuzzy front end of new product development, highlighting the best insight into market evolution, as well as the benefits of more

focused product design. Furthermore, big data collected from smart products can be used for product development and innovation, acting as a feedback tool to gauge user behavior and preferences (Akpan et al., 2020; Almeida et al., 2020). Consumer behavior data collected by different technologies can be analyzed through BDA to increase designers' ability to translate users' voices into product characteristics and quality requirements (Qi et al., 2021).

Furthermore, use of BDA is spreading rapidly in sales forecasting (Almeida et al., 2020). Market fluctuation data can be used to estimate demand and adapt to disruptive events, such as the COVID-19 pandemic (Akpan et al., 2020; Z. Xu et al., 2020). Ivanov et al. (2021) discussed a BDA-enabled SC digital twin that simulates dynamic SC behavior during disruptive events. Thus, SC simulation has the potential to improve companies' strategic choices and recovery plans within disruptive scenarios by using historical data to predict responses to specific inputs (Ivanov & Dolgui, 2021b; Queiroz et al., 2020). Simulation and optimization techniques can be applied to allocate resources during an emergency, prepare for demand ramping, and avoid shortages (Queiroz et al., 2020). Furthermore, forecasting the performance of production resource layouts makes it possible to assess specific investments' impact on equipment and new technologies (Malik et al., 2020).

Digitally simulating the course of the crisis allows the manufacturer to predict supplier bottlenecks, modify production volumes, and adapt short-term strategies to manage resources (Belhadi et al., 2020; Li et al., 2020a; Monostori & Váncza, 2020). Thus, SC risk management is an important topic in the literature on industries experiencing COVID-19 disruptions, and risk analysis is expected to receive more and more attention in the near future (Free & Hecimovic, 2021). The implementation of AI further extends the possibilities of predictive analysis and simulation within BDA through development of advanced algorithms (Ivanov et al., 2021; Terry et al., 2020). BDA also can be applied to procurement process optimization (Wu et al., 2020), aiding supplier selection (Belhadi et al., 2020; Ibn-Mohammed et al., 2021b), reducing production lead time, and optimizing logistics (Karmaker et al., 2021).

### 4.3 Cloud Computing

By providing ubiquitous data storage and computing power, cloud services played a strong role in enabling remote work, a practice that proved vital during the pandemic lockdowns (Akpan et al., 2020; R. P. Singh et al., 2021). By facilitating data sharing among staff members, the cloud also facilitates document collaboration and task management, thereby improving teamwork (Telukdarie et al., 2020b). Connecting an IoT facility infrastructure to the cloud allows operators to access the network and any resources within it remotely, thereby ensuring long-term operations (Li et al.,

2020a). By moving data to the Internet, cloud services improve information dissemination and accessibility (Acioli et al., 2021; Baurina, 2020). Therefore, the cloud enables real-time information sharing that facilitates supplier relations (Ibn-Mohammed et al., 2021b), thereby making the SC more sustainable and resilient amid disruptions (Acioli et al., 2021; Cai & Luo, 2020). In fact, reactive and resilient production systems are more likely to survive in the face of unforeseen variables, such as the pandemic (Guo et al., 2021).

In the cloud, IT resources become services and allow companies to scale costs based on short-term needs, rather than making an upfront investment based on a long-term forecast (Akpan et al., 2020; Terry et al., 2020). Cloud-based management software also is cheaper and faster than local network solutions (Baurina, 2020), as maintenance costs are reduced, workforce mobility is improved, and high-performance solutions become available even to small companies with limited budgets (Lukman, 2020; Rananga & Venter, 2020; R. P. Singh et al., 2021). Ultimately, cloud platforms' properties offer the possibility of leveraging their flexibility to improve efficiency, agility, security, sustainability, and performance (Akpan et al., 2020; Baurina, 2020; Hoosain et al., 2020; Terry et al., 2020).

#### 4.4 Artificial Intelligence

AI can perform a range of tasks in the digital space of production management, such as capacity planning, production schedule optimization, and management of personnel and inventory levels (Li et al., 2020a). Using images of parts, AI can monitor product quality and even identify the source of defects within the production process, minimizing the need for human supervision and, thus, reducing the risk of contagion, as in the case of a pandemic scenario (Di Vaio et al., 2020; Li et al., 2020a). Furthermore, AI can help complex robots work safely in close contact with human workers on certain tasks, reducing the number of people needed for a specific task (Gupta et al., 2021; Terry et al., 2020). In logistics, AI can be used to improve automation by assigning tasks to robots and driving autonomous vehicles (Gupta et al., 2021). Within the design processes, AI is also applied in the configuration of production resource layouts (Li et al., 2020a). Connected to smart devices or cameras on the shop floor, AI can assist workers by monitoring compliance with safety measures (Di Vaio et al., 2020), such as anti-COVID social distancing and mask wearing, as well as, e.g., alerting a worker via a smart device if a violation is detected (Kamarthi & Li, 2020; Wuest et al., 2020). W. Liu et al. (2020) designed a low-cost, AI-based, open-source device for mass fever screening, demonstrating this type of technology's accessibility for small businesses.

AI also has great potential to assist managers with decision-making – proving to be very effective in many contexts, particularly within very turbulent and highly variable scenarios (Di Vaio et al., 2020; Dwivedi et al., 2020; Monostori & Váncza, 2020). Furthermore, AI can identify data anomalies in SC processes to manage risk and maintain quality standards (Free & Hecimovic, 2021), as well as improve the selection process with suppliers and potential employees (Terry et al., 2020). AI is also a powerful tool for simulation and predictive analysis (Hoosain et al., 2020; Terry et al., 2020). When applied to market data, AI makes it possible to respond quickly to unexpected changes in demand (Akpan et al., 2020; Baurina, 2020; Li et al., 2020a). Another field of application is predictive maintenance, in which AI can monitor the state of machinery components and estimate the time until failure, allowing management to optimize repair work through production planning and avoid unplanned downtime (Li et al., 2020a; Monostori & Váncza, 2020). Thus, optimizing resources through AI improves the social and environmental efficiency and sustainability of SC, making it less susceptible to disruption (Di Vaio et al., 2020). Ultimately, AI can be utilized to automate the SC (Dwivedi et al., 2020) and analyze production processes (Baurina, 2020), reducing the need for human supervision. Furthermore, AI makes it possible to maintain critical operations throughout disruptive periods, such as the COVID-19 pandemic; mitigate effects from crises; and improve resilience (Ibn-Mohammed et al., 2021b).

## 4.5 Blockchain

Providing a secure, tamper-proof system for exchanging data is the core of blockchain technology (Kho & Jeong, 2020). Organizations can use it to build an automated SC, simplifying the transaction validation process that usually requires human supervision (Dwivedi et al., 2020). In this regard, Kho and Jeong (2020) discussed the possibility of building a blockchain-based network for smart factories to collect, store, and transfer data along the SC. A trusted data network also strengthens circular economy practices to build a more socioeconomically sustainable and resilient SC (Nandi et al., 2020; Pandey & Litoriya, 2020). Together with IoT, blockchain can secure SC tracking systems and prove the authenticity of any type of data, including capital, inventory levels, machine status, work-batch progress, logistics information, and payments, all of which can aid decision-making, increase traceability and transparency, incentivize collaboration, and automate trust between businesses (Cai & Luo, 2020; Hoosain et al., 2020; Ibn-Mohammed et al., 2021a; Kamarthi & Li, 2020; Karmaker et al., 2021; Lin et al., 2020; Nandi et al., 2020, 2021; Wu et al., 2020).

However, vulnerabilities along the SC challenge companies to manage prevention and respond to disruptions. With its consensus network mechanism, blockchain is the foundation on which

cryptocurrencies are built. As an alternative means of money transfer, it reduces costs by eliminating the need for intermediaries (Lin et al., 2020) and also can help firms detect and prevent contract fraud in contexts of high uncertainty (Wu et al., 2020). Blockchain-based smart contracts have the potential to reduce information asymmetry between entities in the economic network, again reducing costs associated with intermediaries while discouraging fraudulent behavior that would be visible to network participants (Kasten, 2020).

Automation of data collection through IoT and blockchain reduces manual entry errors, improving efficiency (Lin et al., 2020). Simultaneously, with a large and reliable database, blockchain allows for the application of BDA (Karmaker et al., 2021). Nandi et al. (2020) stated that firms' localization, agility, and digitization capabilities are correlated with adoption of circular economy blockchain systems. This is particularly important in light of the SC's fragility in the event of disruptions, such as the pandemic.

#### 4.6 Augmented Reality and Virtual Reality

The use of 3D digital visual simulation has an interesting application in helping human workers in different fields. The training of operators derives enormous benefits from augmented and virtual reality (Napoleone & Prativiera, 2020). Immersive interfaces and virtual simulation provide a safe environment for practice and have been found to enhance the learning process, as opposed to purely theoretical teaching (Diaz-Elsayed et al., 2020; Kamarthi & Li, 2020; Luimula et al., 2020; Siriwardhana et al., 2020). Smith et al. (2021) confirmed that mixed reality tools for training are beneficial if implemented with an adequate degree of accessibility and are particularly useful in contexts such as lockdowns in which face-to-face training is not an option.

VR facilitates remote control of IoT-connected cyber-physical systems on the shop floor, providing a dynamic real-time digital representation of the environment (Kamarthi & Li, 2020). Production and maintenance are also fields in which operators' activities can be facilitated by AR, improving how information is given to staff (Siriwardhana et al., 2020). Through common smart devices and cameras, the operator, aided by 3D signals and animation, receives clear instructions on how to perform tasks, such as maintenance and assembly. This also enables remote assistance, providing a way to communicate with service department and receive real-time instructions from trained technicians (Siriwardhana et al., 2020). Naumov et al. (2021) developed a smartphone-based AR headset device specifically designed for industrial tasks, such as maintenance assistance.



## 4.7 Industrial and Collaborative Robots

During the COVID-19 pandemic, researchers focused on studying the application of robots to prevent contamination and maintain production (Cao et al., 2020). Collaborative robots (i.e., *cobots*) can be deployed in close contact with humans, which can increase productivity by helping human staff with specific tasks, allowing them to practice social distancing. Malik et al. (2020) presented a model for the rapid integration of cobots to increase production of mechanical fans during the pandemic, as cobots tend to be more flexible and easier to install than traditional robots. Furthermore, replacing manual production tasks with robots reduces the need for on-site workers, ensuring safety and long-term operations during a pandemic. Using robots to load and unload parts on machine tools provides a good example of this type of application (Ech-Chhibat et al., 2020). In fact, robots not only can be programmed for typical repetitive automated tasks, but also can be operated through voice, gestures, or digital applications, allowing for remote control of the machine (T. Chen & Lin, 2020; Kamarthi & Li, 2020; Telukdarie et al., 2020b). The logistics sector has been under pressure due to the increase in online shopping. Robots are particularly well-suited to meet the need for speed and efficiency, and are used as palletizers and to move items through automated shelves (Gupta et al., 2021). Telepresence robots are remotely piloted devices that allow individuals to interact with people and navigate a remote location. Gupta et al. (2021) studied their use in clinical and educational settings, reporting engagement benefits for students and easier interactions with infectious patients for doctors during the pandemic. Similar devices can be used on the shop floor to allow visitors, staff, and service technicians to navigate an industrial facility remotely in a safe manner.

## 4.8 Additive Manufacturing

The main attraction of 3D printing technology is its high degree of flexibility (Kunovjanek & Wankmüller, 2020). As such, AM is suitable for prototyping, in which its benefits and practicality have been proven (Omidvarkarjan et al., 2020; Rainnie, 2020). AM can replace traditional machining to produce certain components. The benefits that justify the choice are reduced time to market, rapid response to changes in demand, better customization, and reduced waste in tools and raw materials (Karmaker et al., 2021; Fredrick Madaraka Mwema & Akinlabi, 2020; Napoleone & Prativiera, 2020; Wu et al., 2020). In this case, AM also may help in redesigning SC procurement strategies (Wu et al., 2020). For example, the production of spare parts is a particularly interesting field and makes it possible to build a distributed network of suppliers, reducing logistics time and costs (Acioli et al., 2021; Hoosain et al., 2020). During the first months of the COVID-19 pandemic,

PPE and medical equipment demand increased rapidly. Manufacturing companies' capacity became saturated, and companies that could provide AM services, in many cases, were able to mitigate the pandemic's effects by converting production facilities and supplying 3D-printed medical equipment parts and PPE rapidly (Ibn-Mohammed et al., 2021b; Fredrick Madaraka Mwema & Akinlabi, 2020). Furthermore, manufacturing data sharing and collaboration were facilitated, which are particularly effective for AM compared with traditional machining because there are fewer technical obstacles to using the same process data on different machines (Patel & Gohil, 2020). Likewise, the idea of clusters of AM producers sharing their ability to meet demand and optimize resources has received interest from scholars, although the practicality of this type of business remains debatable (Free & Hecimovic, 2021; Kunovjanek & Wankmüller, 2020). Frankly, the AM process remains slow and unsuitable for mass production in its current state (Kunovjanek & Wankmüller, 2020). However, it positively impacts SC resilience, as evidenced during the pandemic (Ibn-Mohammed et al., 2021b; Monostori & Váncza, 2020).

#### 4.9 Autonomous Vehicles and Drones

Applications of autonomous vehicles (AVs), revolve around internal logistics and production automation and are used to transport materials, tools, and batches between workstations or machines, with benefits in terms of reliability, efficiency, and operator safety (Hopkins, 2021). Adoption of an autonomous logistics vehicle to achieve contactless freight transport also could alleviate the risk of viral transmission between the driver and customers. This need to minimize contact between people led to the development and testing of contactless freight transport during the COVID-19 pandemic under various traffic conditions (T. Liu et al., 2021). Moreover, during the pandemic, workplace sanitization became a relevant issue. Bačík et al. (2020) designed a flexible AV that can be equipped to perform various logistical tasks, as well as sanitize surfaces through a UV light attack.

The development and use of drones also has received a new impetus after the pandemic surfaced. Logistics companies recently have started to use drones for deliveries. Being remotely piloted and not restricted by ground transportation networks, such as roads, makes them very flexible and reliable (Shen et al., 2021; Siriwardhana et al., 2020). In warehouses, drones have been introduced for rapid inventory counting, reducing the presence of operators in the aisles and improving safety (Kamarthi & Li, 2020; Shen et al., 2021). Studies have reported on drones being used within city administrations during the COVID-19 pandemic to perform tasks such as disinfecting public spaces and monitoring compliance with movement-restriction policies (Patel & Gohil, 2020;

Shen et al., 2021). Drones also can be used for this type of operation in an industrial environment and could be particularly effective with large structures, in which their agility and range can prove useful.

## **5 Discussion**

The COVID-19 pandemic made a devastating impact on the global manufacturing industry, but it also provided an opportunity for companies to turn disruption into innovation and move toward a more digitized and resilient supply chain organization.

Considering the plethora of applications of digital technologies to mitigate the pandemic's impact, every business process in the manufacturing industry has been affected by DTs to some extent. The SLR's results indicated varying degrees of impact, depending on several factors, such as each technology's maturity level and potential application in counteracting viral spread. Different digital technologies have been investigated in the literature with varying levels of intensity, with some business processes receiving more attention than others (Figure 2).

This study in particular considered six main business processes according to Zheng et al.'s (2020) study, namely product development, supply chain management, internal logistics, production management, maintenance management, and after-sale services.

Supply chain and production management processes have received much more attention than the others. Production management is the core of the manufacturing industry's value chain and includes many factory activities, so scientific interest generally is greater (Meindl et al., 2021).

However, the focus on SC management is related more to pandemic-related contingencies. Supply chain disruption was one of the most devastating effects during the pandemic, affecting all sectors of the manufacturing industry across the board. Furthermore, safety regulations and mandates negatively impacted international trade and material supply, with many studies focusing on problems and solutions. The least-investigated processes in the literature have been those related to maintenance management and after-sale service. Maintenance management has received few contributions in the literature, as many plants' production was suspended due to the pandemic, and non-essential commodity sectors were forced to suspend operations for some time. The main contributions in this area have focused on the analysis of predictive maintenance (Ibn-Mohammed et al., 2021b; Terry et al., 2020) and optimization applications (Aldrighetti et al., 2021; Brundage & Weiss, 2020). Regarding after-sales processes, the literature has focused mainly on using digital technologies to enable and support recycling and reuse policies for finished products

(Ibn-Mohammed et al., 2021b; Kamarthi & Li, 2020), as well as the opportunity to adopt innovative business models oriented toward the use of products, not just ownership (Rapaccini et al., 2020).

Furthermore, the literature mainly has focused on technologies that can collect data (IoT), store and share it (cloud), and analyze it for decision-making information (BDA). In particular, the application of BDA to analyze market fluctuations and aid decision makers has attracted many scholars (Akpan et al., 2020; Dolgui & Ivanov, 2021b; Ivanov et al., 2021). IoT also has been studied thoroughly with applications for all business processes; however, AVs, drones, AR, and VR are the least-studied technologies, probably because their impact is mostly practical, and their applications are related to a few specific activities, such as material transportation, inventory management, machinery maintenance, and workforce training.

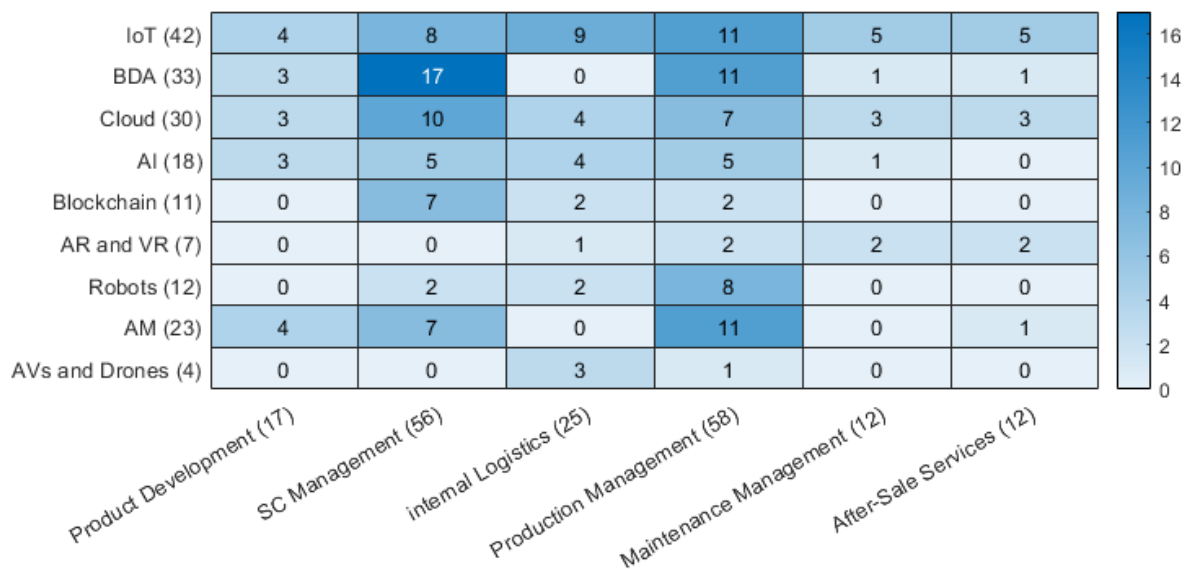


Figure 2. Research focus heatmap

The adoption of an I4.0 strategy implies the application of several integrated technologies for the transition to the digital factory, and several potential applications need to be considered to digitize business processes (Sanchez et al., 2020). In fact, DTs could be implemented synergistically to increase the results' effectiveness. For example, BDA is enhanced by AI to provide analytical insights into a database, or it can be used to extract data from sources outside the company to build a database that's useful in a data-mining process, thereby providing important market insights in times of turbulence and high uncertainty (Hopkins, 2021). Furthermore, AI technology has the potential to perform labor-intensive tasks, such as searching for data that relate to a specific topic,

excluding noise data that may not relate to the research, to improve decision-making. On a larger scale, blockchain also can be used in data mining to ensure that only reliable data are used. IoT is a key enabler of BDA, considering that in many cases, it makes data available. During the pandemic, many national governments incentivized the use of smartphone tracking apps to monitor COVID-19 virus carriers' contacts on a large scale. This type of IoT data source is perfect for BDA to predict viral spread. The IoT also synergizes with robots, AGVs, and drones, enabling the implementation of CPS to reduce human contact on the factory floor. Furthermore, the increased system control enabled by IoT benefits automation in general. Many industrial machinery companies already have learned this lesson, further incentivized by national policies, and provide I4.0-ready solutions to customers. These types of applications are mostly cloud-based, leveraging cloud computing and storage power, and providing ubiquitous accessibility to data, further incentivizing staff mobility and remote work, including working from home.

Based on this study's results, Table 4 summarizes the main applications of the digital technologies examined to support supply chain resilience in disruptive contexts, such as the COVID-19 pandemic. The technologies are grouped into six categories – infrastructure, communication, automation, identification and alerting, data processing, and collaboration – following the classifications offered in Dolgui and Ivanov (2021), Ivanov (2021), and Ivanov and Dolgui (2021b). The applications are listed using the plan-source-make-deliver-return (SCOR) model. On one hand, some applications are repeated in the same way in different groups of technologies, demonstrating that results very often are obtained through joint application of different technologies. On the other hand, the presence of some empty cells highlights clear gaps and research opportunities to focus on in the future. Furthermore, Table 3 clearly indicates existing research gaps (i.e., empty cells) that we will elaborate on in Section 6, along with other gaps and open issues identified earlier in our SLR.

	<b>Plan</b>	<b>Source</b>	<b>Make</b>	<b>Deliver</b>	<b>Return</b>
<b>Infrastructure technology (Internet-of-Things, 5G, cyber-physical systems)</b>	Increased stock visibility in all the nodes of the supply chain Real-time data collection	Procurement strategy optimization	Machine remote control Predictive maintenance	Increased traceability in the supply chain	
<b>Communication technology (trace and tracking systems; blockchain; real-time process monitoring; sensors; AR/VR)</b>	Data integrity and transparency Supply chain finance Real time data collection	Smart contracts Greater security in supply chain traceability		Goods tracking	
<b>Automation technology (Additive manufacturing; collaborative robots; drones; mobile robots; AGVs)</b>	Supply chain autonomy	Lead time reduction	Machine remote control Optimization of internal handling processes Increased efficiency in re-purposing Shared manufacturing	Lead time reduction	Spare parts management decentralization
<b>Identification and alert technology (Early-warning system; RFID)</b>		Increased traceability in the supply chain			
<b>Data processing technology (big data analytics; ERP)</b>	Supplier selection optimization Balancing demand and supply Bullwhip effect minimization Decision-making support Supply chain visibility	Lead time reduction Raw materials and component shortage reduction		Lead time reduction Improved sales forecasting analysis Servitization strategy	Servitization strategy
<b>Collaboration technology (Collaborative supplier portals; machine-to-machine (M2M); cloud)</b>	Optimization of resource utilization Improved flexibility	Improved relationships with suppliers	Machine remote control Cloud manufacturing Increased scalability		

Table 4: Applications of digital technologies to support supply chain resilience



## 6 Future research agenda

This section aims to shed light on the main theoretical and managerial implications of this research, with the main objective of developing a research agenda aimed at identifying potential research topics related to the adoption of digital technologies to mitigate and counteract events such as the COVID-19 pandemic in the future.

The pandemic shed light on how fragile the global economic system is in its current state. The literature surveyed has demonstrated that investing in long-term resilience and business sustainability over short-term optimization and margin improvements must be a priority for manufacturers and managers to be prepared for similar circumstances in the future. In this regard, most of the articles reviewed took a theoretical approach, and more empirical studies would be useful to provide a better understanding of the application of DTs and I4.0 practices to navigate the pandemic's uncertainties and adapt to the new normal (Ivanov & Dolgui, 2021b). This is particularly true for SMEs that may not have a structured R&D process to translate theory into practice, and instead rely mainly on pragmatic and unstructured innovation (Juergensen et al., 2020).

The pandemic also demonstrated technology adoption's potential to help manufacturers be more responsive and mitigate negative business impacts from disruptive events resulting from shocks in the external environment (Seetharaman, 2020). Furthermore, digital technologies could pave the way for increased flexibility to create a competitive advantage for long-term growth (Niewiadomski, 2020). However, the literature regarding digital technologies' role in mitigating the COVID-19 pandemic's impacts has focused mostly on the global SC, rather than considering individual factories (Ardolino et al., 2021). The reason for this may lie in the fact that while factories worldwide have faced different obstacles and closures, with differing needs in terms of short-term adaptation, the global SC has been compromised all along, from shortages of raw materials to intermittent restrictions in international transport of products and raw materials (Queiroz et al., 2020; Remko, 2020). The semiconductor SC is a perfect example, in that with a particularly centralized manufacturing industry, long lead times, and a rigid production process, microchip companies have been unable to keep up with global demand, affecting several consumer sectors, such as electronics, automotive, and aviation (Belhadi et al., 2020; Nayak et al., 2021; Rahman et al., 2020).

Table 5 summarizes the open research questions related to the main literature gaps that emerged from this SLR, providing important suggestions to both scholars and practitioners. The



open research questions are organized into five specific areas of interest, namely data and information management, work (re-)organization, de-globalization and reshoring, supply chain resilience, and environmental and social sustainability.

Focus area	Open research questions
Data and information management	How can digital technologies help build an integrated data management system to reduce supply chain vulnerabilities to external shocks?
	What are the main risks in terms of data protection during disruptive events such as the COVID-19 pandemic, and how can digital technologies help mitigate these risks?
	What are the characteristics of effective integrated data system management to support decision making in highly variable environments?
Work (re-)organization	How can digital technologies support remote control of blue-collar employees' work processes?
	What were the main cost-benefit implications of adopting remote work during the COVID-19 pandemic?
	Which skills and capabilities will it be necessary to focus on to make remote work a long-term structural measure in the future?
De-globalization and reshoring	How can large-scale 3D printing technology be used to decentralize and shorten the supply chain?
	What is digitalization's potential role in facilitating re-shoring policies and localization of manufacturing processes?
	How can digitalization support collaborative distributed supply chains?
Supply chain resilience	How can digitalization help companies improve resilience?
	What trade-offs in terms of optimization and effectiveness should be expected when improving supply chain resilience, and how can digital technologies help achieve both benefits?
	How can companies integrate resilience as a KPI?
Environmental and social sustainability	What impact has the pandemic had on progress toward implementation of circular economy policies in manufacturing, and how can digitalization support it?
	What policies should be adopted to manage the final stages of a product's life cycle and safeguard supply chain resilience effectively?
	How can digital technologies such as blockchain help improve transparency and fair trade in developing countries in the future?

Table 5: Open research questions

The five areas are not isolated but are related to each other as shown in Figure 3. Accurate and integrated management of data and information between the nodes of the supply chain increases visibility. This improves the ability to adapt and react to disruptive events caused by the external environment. Hence, as shown in the relationship '(A)', data information and management is positively associated with supply chain resilience. Moreover, the reorganization of work through the effective introduction of smart working, as well as the introduction of remote communication tools, requires that all data and information are consistent and accessible by all members of the organization and at all levels of the supply chain. This relationship of work re-organization with data

information and management is shown in the relationship '(B)'. De-globalization and re-shoring strategies result in the shortening of supply chain. This improves the ability to react, thereby improving resilience performance as shown in the relationship '(C)'. The shortened distances resulting from de-globalization and re-shoring policies reduce long-haul transportation in the supply chain, which helps in reducing environmental emissions as shown in the relationship '(D)'. Reorganization of work encourages working from home, reducing the amount of travel, and energy consumption at workplaces. This helps in lowering the environmental impact. Work re-organization also increases the flexibility for families to manage work and family related obligations, which positively impacts social outcome. Hence, as shown in relationship '(E)' work re-organization is positively associated with environmental and social sustainability. Finally, localizing production and shortening supply chain result in closely connected collaborative networks where supply chain partners would rely on effective and continuous exchange of information. This is facilitated by data information and management, as shown by the moderating effect '(F)'.

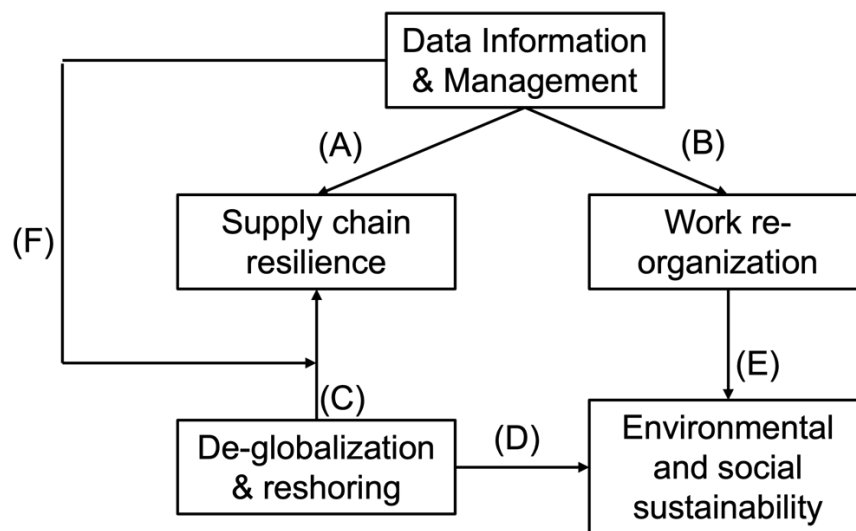


Figure 3: Integrated framework with relationships among research areas

## 6.1 Data and information management

The focus area of data and information management refers to all information management and sharing practices, both within the single company, and above all, among the actors involved in the supply chain. This topic is certainly much discussed in the literature related to COVID-19 viral spread and its impacts on production. This evidence is reinforced further by the numerous articles on two fundamental technologies for collecting, storing, and sharing data and information: IoT and the cloud. The benefits from having a structured data system are numerous. Unlocking access to data

helps companies develop a clearer and unbiased understanding of their business processes, thereby enabling them to respond quickly to changes and implement appropriate policies to deal with disruptions. Data management is also necessary to find vulnerabilities within the value chain and manage risk. In fact, effective data and information management can help increase the visibility of demand within the supply chain by sharing information among stakeholders (Diaz-Elsayed et al., 2020). Moreover, disruptions can be prevented from the outset if enough visibility exists between the multi-layered processes that characterize complex, global procurement systems (Farooq et al., 2021; Taqi et al., 2020). Other benefits include increased transparency and trust (Barrane et al., 2021). In this respect, the case of commodity shortages in the global SC during the pandemic is emblematic, with dramatic effects related to the exacerbation of the bullwhip effect and shocks in both demand and supply (Shen et al., 2021; Zhu et al., 2020). Similarly, effective integrated management of data systems can help managers make quick decisions even in very volatile environments. Although the benefits have been discussed, the literature lacks empirical studies that demonstrate how different technologies can work together in an integrated way to build a robust data system, implement it, and make it useful. In fact, the impact from companies' digitization level on their response to the pandemic is an under-researched topic in the literature. Furthermore, little consideration has been given to the issue of data security, a hot topic in a normal context and even more crucial during a disruptive event characterized by uncertainty and confusion. In this case, blockchain may represent an effective technology, but the literature is mostly vague regarding its applications in manufacturing, with the only dedicated studies concerning the agri-food and medical SCs, which are normally more interested in traceability (Lin et al., 2020).

## 6.2 Work (re-)organization

With the introduction of social distancing requirements, manufacturers already knew that they needed to make major changes in both work and workplace organization to be able to continue operating. During the first months of the pandemic, most production activities already had been halted, and smart working had been implemented to reduce the risk of infection (Rapaccini et al., 2020). Using technology such as email, video meetings, and cloud-based file management, employees from different sectors could get their work done while working remotely. During this period, there was a real explosion in the emergence and development of online platforms for collaboration and video conferencing (Telukdarie et al., 2020a). Furthermore, cloud computing's storage and sharing potential had proven to be a crucial resource for enabling remote work (R. P. Singh et al., 2021). While this change was forced by circumstances, the assessment of risks and

opportunities from digitally driven work reorganization has not received adequate attention in the literature. Costs and savings, staff productivity, and potential social effects on workers are all open topics for research.

Moreover, mobility, flexibility, and visibility are three key concepts associated with DTs that potentially could influence how production activities could be conducted in the future. The pandemic is expected to leave behind a new normal, so it is important to understand what DTs' role will be for work organization in the post-COVID era. Given this, it also would be interesting to better understand how workers feel about the topic and what their expectations are for the future. Simultaneously, it is important to understand which competencies are relevant for workers to be prepared to engage with these new digitized work procedures. It should be noted that since the advent of I4.0, the literature has focused mainly on manufacturing and smart products, mostly neglecting smart work and smart supply chains (Meindl et al., 2021). If the gap in SC seems to be at least partially filled, the same cannot be said for smart work, despite it being a trending topic since the beginning of the pandemic.

### 6.3 De-globalization and reshoring

The pandemic has exposed all the limits of global value chains and has led many scholars to question their fate (Palley, 2019). High dependence on remote sources and highly complex logistics networks were the main causes of the shock in several manufacturing supply chains (Cai & Luo, 2020).

The manufacturing slowdown in China, one of the world's leading export economies, rapidly affected downstream producers globally. With several supply chain networks' high dependence on Chinese suppliers in mind, scholars most often discuss the localization of certain portions of the supply chain through an appropriate re-shoring policy (Zhu et al., 2020). Therefore, more manufacturing companies are considering localizing the production of their goods, given the push toward reshoring strategies (Barbieri et al., 2020). The pandemic undoubtedly accentuated, and at times exacerbated, these trends, thereby reducing the global SC's vulnerability to disruptive events, such as the COVID-19 pandemic. This means localizing production and finding suppliers closer together to target bottlenecks and shortage risks, as well as building a broadly connected and collaborative production network while shortening the SC. On paper, digital technologies certainly can provide valuable support to achieve these goals. The case of the network of 3D printing companies demonstrates that local production is very effective at overcoming difficulties from international COVID-19 pandemic regulations (Napoleone & Pratavia, 2020), but systemic

adoption on a large scale certainly would come at an enormous cost. Localization's potential impact on the global SC and digitization's role within this issue remain under-researched topics, while many scientific contributions have reported that economic globalization is about to be transformed by this disruptive event (Free & Hecimovic, 2021). Therefore, a research gap remains in the literature to understand the need to revise the economic exchange model on a global level.

## 6.4 Supply chain resilience

*Resilience*, in a more inclusive definition, is understood as the ability to mitigate disruptive events' effects and navigate critical economic scenarios. Resilience themes are by far the most recurrent concepts in the reviewed literature, and the COVID-19 pandemic exposed the global SC's fragility, with many scholars focusing on digitization's theoretically positive effects on SC resilience (Ralston & Blackhurst, 2020). Manufacturing is evolving toward data- and technology-driven networks, and digital ecosystems. Data analytics, additive manufacturing, and Industry 4.0 enable end-to-end supply chain visibility based on dynamically reconfigurable material flows and digital information flows (Qin et al. 2021, Shi et al. 2021). Robotics, artificial intelligence, cloud computing, and big data analytics could be crucial capabilities for improving SC resilience. Some technologies – such as robots, digital twins, blockchain, and additive manufacturing – have received much attention (Z. Chen & Cao, 2020; Ivanov & Dolgui, 2021b; Shen et al., 2021; S. Singh et al., 2020), while others mostly have been neglected (e.g., machine learning, artificial intelligence, and big data analytics).

Furthermore, manufacturing resilience includes not only the relationships between actors in the supply chain, but also other aspects concerning production and management, such as workforce agility, adherence to delivery times, production flexibility, and asset liquidity. These aspects have received much less attention in the literature. While most contributions have focused on the overall SC, use of DTs to support factory processes' continuity has yet to be investigated. Although reorganization strategies have been a lifeline for many factories during periods of forced closure, DTs' enabling role has not been discussed adequately in the literature (Burgos & Ivanov, 2021; Ivanov & Dolgui, 2021b).

The practice of resilience means building a more agile and flexible production workflow, which reasonably comes at the expense of optimization and short-term revenues (Free & Hecimovic, 2021). Digital technologies' role in addressing these opposing forces is an open field of research that certainly deserves attention in future studies.

## 6.5 Environmental and social sustainability

Due to worrisome trends in climate change, environmental sustainability has become an important topic in recent years. Representing a large proportion of carbon emission sources, the manufacturing industry has been scrutinized and is constantly being pushed to find ways to improve energy efficiency, as well as reduce resource use and waste (Diaz-Elsayed et al., 2020).

Despite the emphasis on the negative economic effects from the pandemic, the actions that governments took resulted in unintended positive externalities on the environment and natural ecosystem (Ibn-Mohammed et al., 2021a). The imposition of remote work has helped reduce fossil fuel consumption, with a significant reduction in emissions recorded during the first half of 2020 (Kanda & Kivimaa, 2020). In fact, transportation infrastructure has been used more sparingly, leading to a drastic overall reduction in oil consumption (Hosseini, 2020). Obviously, these effects, driven by viral spread, are only temporary, as this is a contingent situation, and positive environmental impacts could be overlooked in the fight for economic revival (Borsellino et al., 2020).

Moreover, Rapaccini et al. (2020) have demonstrated the competitive advantage of adopting service-oriented business models, such as pay-for-performance and renting/leasing, enabled by the adoption of digital technologies, which can help extend product life cycles. Furthermore, the literature affirms the importance of taking into account the goal of not burdening the environment to increase the resilience and flexibility of supply chains (Golan et al., 2020; Kumar & Kumar Singh, 2021). In this regard, the pandemic's effects on production sustainability and the process of factory digitization should receive further attention in the literature. Similarly, a concrete and structured plan should be developed for the adoption and development of alternative and renewable energies (Hosseini, 2020). Similarly, little emphasis has been placed on return logistics and reverse logistics processes. In a context strongly characterized by increasingly demanding consumers, it becomes essential to manage the product life cycle's final stages effectively, as well as management of spare parts that may be subject to rapid obsolescence.

Furthermore, the issue of social sustainability is a topic that has been little investigated amid the pandemic, which negatively impacted employment, but the impact from forced digitization in the workforce should not be ignored either. Innovation always elicits change in terms of required skills and job roles. Understanding what kind of training and skills manufacturing companies should focus on is key to being technically prepared for an effective introduction to DTs, both in the factory and in working remotely from home. The pandemic also has impacted factory workers' safety due to the risk of contagion from activities that require proximity to people. This is particularly the case in

developing countries, where national and regional authorities' containment policies have been more difficult to enforce, and the availability of protective equipment has been poor (F. M. Mwema & Nyika, 2020). In this context, digital technologies may represent more than just an opportunity to improve workplace safety. By improving SCs' transparency and helping managers monitor suppliers, DTs such as blockchain and IoT can facilitate sustainable development in countries where the workforce is at risk of exploitation, and the consequences of a pandemic or similar disruptive events can be particularly detrimental to workers' living conditions.

## **7 Conclusions and limitations**

The COVID-19 pandemic has made a major, disruptive impact on the global economy, particularly on manufacturing companies across all industries. This research sought to shed light on the relationship between the pandemic and the digitization of the manufacturing industry. Furthermore, the pandemic prompted scholars to study digitization's potential in building a more resilient global industrial SC. However, DTs helped overcome short-term problems induced by the disruptive change in environment that led to restrictions and security issues. Thus, the pandemic and DTs exerted a mutual influence.

Although the spread of COVID-19 is a relatively recent phenomenon, the literature on the subject is abundant. However, most articles have taken a theoretical approach, and empirical studies on the application of DTs are limited in number, although particularly useful for practice. The open research questions presented in this article reflect the need for a more in-depth study of some topics.

As a systematic literature review, this paper provides a solid synthesis of current knowledge on digital technologies' applications and potential in the manufacturing industry and their relationship to the pandemic context, as well as the implications for industrial processes. It also has enabled the identification of five focus areas that represent topics of scientific interest for future research.

However, this study has some limitations. The article database was highly dependent on the keywords chosen for the extraction of the first sample, which included only English-language articles and, therefore, may have overlooked some local contributions. Furthermore, the highlighted results, open research questions, and areas of interest have been influenced by researchers' experiences and biases. Moreover, SLRs usually are conducted on topics that have reached a certain level of maturity, whereas in this case, the COVID-19 pandemic remains an evolving phenomenon, preventing a level of global stability that would allow for definitive conclusions to be drawn. Therefore, the scope of this study is to review the topics that got immediate attention due to COVID-

19. Understandably, new themes are expected to emerge in the next few years, but the fact that the themes we identified were at the forefront of researchers' minds is important to document so that this can be compared with how research evolves in the future.



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