Deep Science Publishing
https://doi.org/10.70593/978-81-981271-8-1_3

Chapter 3

Artificial intelligence, machine learning, and deep learning for enhancing resilience in industry 4.0, 5.0, and society 5.0

Nitin Liladhar Rane [1], Ömer Kaya [2], Jayesh Rane [3]

[1] *Vivekanand Education Society's College of Architecture (VESCOA), Mumbai 400074, India*
[2] *Engineering and Architecture Faculty, Erzurum Technical University, Erzurum 25050, Turkey*
[3] *Pillai HOC College of Engineering and Technology, Rasayani, India*
[1] nitinrane33@gmail.com

Abstract: Industry 4.0, 5.0, as well as Society 5.0, is a period of the new era's revolutions when artificial intelligence (AI), machine learning (ML), and deep learning (DL) become the tools of improving and ensuring resilience in different spheres. The current research focuses on the operation, urban, psychological, cyber, supply chain, and social resilience. Resilience is a powerful tool in the modern context, and AI-based systems help to build capacities and reduce negative impacts. Operational and production resilience can be achieved with the help of ML systems designed for predictive maintenance and anomaly detection. These tools allow reducing downtime, estimating changes properly, and making timely decisions to optimize the production process and increase the level of productivity. At the same time, cybersecurity applications become more sophisticated with the introduction of advanced ML technologies. In the context of supply chain resilience, AI and ML become essential parts of predictive analytics which enables to anticipate possible disruptions, manage logistics, and optimize quantities and loci of needed items. Smart manufacturing systems with AI make production processes more adaptive and flexible, which is crucial in the situation of current challenges. Society 5.0 cannot exist without social resilience, and it is realized with the help of AI, for example, in managing strategies aimed at disaster management, healthcare, or designing cities. Real-time data analytics and innovative intelligent systems can be developed with the help of AI even in those spheres where human intervention has always been considered crucial. In addition, DL helps to design autonomous systems that are crucial for increasing resilience in transportation and logistics processes.

Keywords: Resilience, Artificial intelligence, Machine learning, Deep learning, Supply chain resilience, Psychological resilience, Urban resilience, Social resilience.

Citation: Rane, N. L., Kaya, O., & Rane, J. (2024). Artificial intelligence, machine learning, and deep learning for enhancing resilience in industry 4.0, 5.0, and society 5.0. In *Artificial Intelligence, Machine Learning, and Deep Learning for Sustainable Industry 5.0* (pp. 53-72). Deep Science Publishing. https://doi.org/10.70593/978-81-981271-8-1_3

3.1 Introduction

Industry 4.0, 5.0, and Society 5.0 paradigms have become more intensive and ambitious, through which resiliency appears to be one of the central points (Habibi Rad et al., 2021; Al-Banna et al., 2023; Marinagi et al., 2023). Industry 4.0 reflects the idea of integrating next-gen technologies to improve the work of any organization, bringing speed, quality, and value (Peres et al., 2020; Rane et al., 2024a). It is realized in the form of advanced manufacturing processes that are more flexible and dynamic and, thus, allow for predictive maintenance, real-time data analytics, and autonomous backlogs or error correction. Considering an Industry 5.0 approach, human beings come into the centre of the system, providing ways of collaboration with smart machines that act like managers' best assistants (Golovianko et al., 2023; Ivanov, 2023). The concept, developed by Japan and known as Society 5.0, is similar to Industry 5.0 but is oriented primarily at the integration of digital transformations and AI.

Artificial intelligence (AI), machine learning (ML), and deep learning (DL) are likely at the core of these transformative industrial and societal frameworks, but more significantly is the role they must play (Grabowska et al., 2022; Sindhwani et al., 2022; Paramesha et al., 2024a). The capabilities of AI technologies to create intelligent, responsive, and flexible systems could potentially lead the way out of a foreseeable disaster. ML algorithms have the ability to learn from large scale data to provide predictive insights which can help identify and even optimize processes across different domains. By deploying a more powerful technique called DL, which is a subset of ML itself, it is using neural networks to achieve more advanced tasks including image/speech recognition, natural language processing, and autonomous system control. Collectively, these technologies deliver the resiliency and flexibility necessary to navigate the complexities of Industry 4.0, Industry 5.0, and Society 5.0 (Leng et al., 2023; Ahmed et al., 2023; Raja Santhi, & Muthuswamy, 2023; Paramesha et al., 2024b). Therefore, it is important to ensure that they are robust, and they continue to perform over the long-term, especially under the wonderful uncertainties of future economic cycles, cyber threats, environmental changes etc. They are applied in a wide variety of use cases, including but not limited to improving supply chain management, energy efficiency, cybersecurity, and disaster response. With the advancement in industries and societies AI, ML, and DL can be combined to play an essential role in helping to improve resilience and in achieving sustainable development goals.

The intent study is guided by the following main research question and contributions:

1) What is the existing research about AI, ML, and DL applications supporting the modern Industry 4.0, Industry 5.0, and Society 5.0 in term of enhancing the resilience?

2) This research leverages state-of-the-art bibliometrics to investigate key words, co-occurrence patterns and clusters to identify potential hot topics, emerging themes, and collaborative networks that underpin this literature.
3) The results from this review and analysis provide a set of research ideas for further research, pointing out the possible application and challenges to improve advancement in resilience by means of AI technology.

3.2 Methodology

This research reviews the existing literature on the subject, analyzing the role of AI, ML, and DL for the specific case of resilience in Industry 4.0, Industry 5.0, and Society 5.0. In literature review, systematic identification, evaluation and synthesis of the available research articles, papers and technical reports are done through academic databases of IEEE Xplore, Scopus, Web of Science. Software tools like VOSviewer used to conduct keyword analysis and identify key themes and trends. The identified literature includes keywords such resilience, AI, ML, DL, Industry 4.0, Industry 5.0, and the Society 5.0. These keywords enable a co-occurrence analysis to be performed that indicates the frequency and relationships between them, revealing the most important concepts and emergent topics in the field. Secondly, analogously to our document clustering, we conduct cluster analysis to view topically related studies as one (as to obtain research clusters). It uses algorithms such as k-means and hierarchical clustering to group the literature according to thematic similarities. The results from the cluster analysis contribute to identifying the key research areas and areas that require further attention related to the field of study.

3.3 Results and discussions

Co-occurrence and cluster analysis of the keywords

The network diagram (Fig. 3.1) shows intricate connections and the words related to AI, machine learning, deep learning, and resilience in Industry 4.0, Industry 5.0, and Society 5.0. The fact that "machine learning," "deep learning," "artificial intelligence," and "resilience" are rather centrally placed highlights their importance for the debate. Their size indicates that the use of these words is common and can be very relevant. The heavy many connections coming out of them, in turn, could suggest that these words can be used in different disciplines. Gazing at the term "machine learning," though, one would be able to note that this is a general idea uniting many applications and subfields. In this sense, the term "deep learning" looks very much alike, demonstrating the hierarchical relationship. In other words, "machine learning" is a subset of "deep learning" as it involves more and more sophisticated neural network topologies. This could generally establish the interdependent relationship between the two notions, with the development of deep learning techniques having a substantial effect on machine learning at large.

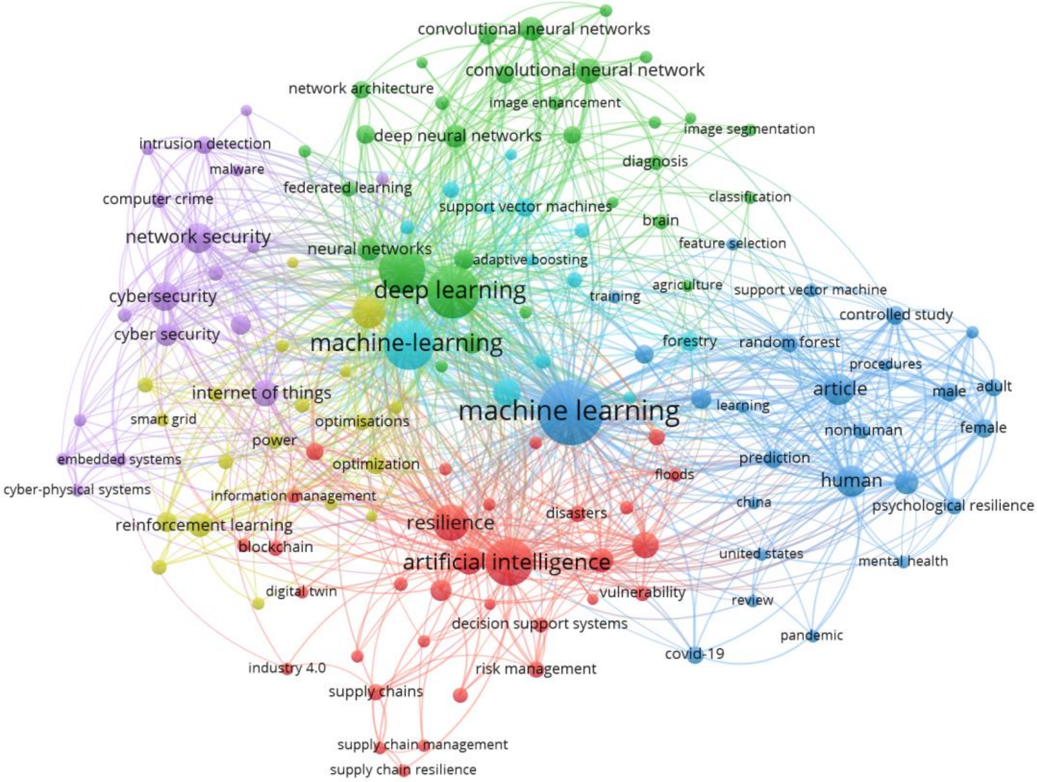

Fig. 3.1 Co-occurrence analysis of the keywords in literature

"Deep learning," "neural networks," "convolutional neural networks," and "convolutional neural network" belong to a cluster of words next to each other. As a matter of fact, the words represent some of the deep learning methods that are essential for the task of processing images and pattern recognition. Meanwhile, in the cluster with "deep learning," we see that there are such words next to it as "diagnosis," "image segmentation," and "network architecture." This indicates that our field of study, in which the word "deep learning" is central, is medicine and the diagnosis of diseases through medical images. Meanwhile, the fact that "support vector machines" and "random forest" are almost in the same cluster as "secure learning" and others shows that there is a set of machine learning methods used in conjunction with deep learning to solve a range of problems. Another cluster, which is approaching the "deep learning" one, is the "artificial intelligence" cluster that includes "machine learning" and "resilience." In the cluster, we can see words such as "risk management," "decision support systems," "supply chains," among others. This indicates that industrial and supply chain uses made AI apt, and this was purposeful to enhance judgment and cut down on risk. These words appear alongside "digital twin" and "blockchain," which shows that cutting-edge technology and artificial intelligence are combined to create systems that are more reliable and effective than ever before.

This cluster of resilience includes the ideas concerning both supply chain management and supply chain resilience, vulnerability, and disasters. These concepts are conveyed in a single chain connecting all the notions to how predictive analytics and AI-optimized operations can enhance the functioning of supplying networks increasing their ability to recover from a disruption. In other words, resilience is to construct rich industrial systems that will have the strength and robustness to be alive in the face of either exogenous or endogenous disruptions of any kind. This idea is shared with Industry 4.0 and Industry 5.0 clusters, trying to bundle them into the "resilience" context. On the other hand, the internet of things is usually employed in defining not only cybersecurity but also machine learning and network security. Moreover, the advent of the Internet of Things and machine learning is thought to facilitate the proper handling of massive data flows. It is careless that the very terms related directly to the internet of things, namely "cybersecurity" and "network security," imply that the systems should be protected against cyber-attacks. This, in its turn, is considered a necessary part of resilience in today's world.

The IoT and cybersecurity clusters usually contain words such embedded systems, cyber-physical systems, and smart grid. They pertain to the use of artificial intelligence or machine learning for the management and protection of complex infrastructures that are crucial for the advancement of modern industrial processes such as embedded systems or energy grids. Yet there is also trained a human-centric cluster which includes words like "human," "psychological resilience," "mental health," and "pandemic." It rather means that people nowadays begin to pay ever more common attention to the connections of technology and humans. Especially in the context of such present-day global challenges as the COVID-19 pandemic. Words "mental health" and "psychological resilience" are linked to the efforts to use AI or machine learning towards enhanced human welfare and psychological resilience, especially in such challenging times as big emergencies.

Enhancing resilience through artificial intelligence, machine learning, and deep learning

Resilience in Industry is the capability of an industry to anticipate, prepare for, respond and adapt to incremental change and sudden disruptions and opportunities to maintain and improve industry capacity for continuous operation and adaptive evolution (Al-Banna et al., 2023; Marinagi et al., 2023; Paramesha et al., 2024c). Technologies like AI, ML, and

DL have brought a colossal revolution in the industrial sector, providing much more resilience to the industries (Grabowska et al., 2022; Sindhwani et al., 2022). With solutions for risk prediction, risk mitigation, operations, and business continuity, these technologies are paving the way for the future in the industry.

Predictive maintenance and asset management

One of the important factors with respect to industrial resilience is asset maintenance. AI and ML-based predictive maintenance help industries predict future equipment failures before they happen (Biard, & Nour, 2021; Compare et al., 2019; Rane et al., 2024b). AI algorithms, for example, can sort through massive volumes of data from sensors and machine logs and predict with great accuracy when a piece of equipment is likely to fail, and then schedule maintenance accordingly. This preventative strategy can decrease downtime, increase equipment useful life, and in general will lower cost due to unscheduled repairs. In manufacturing, companies are deploying AI-based predictive maintenance systems - Siemens and General Electric have both rolled out similar solutions - that have not only boosted operational efficiency but also system resilience.

Supply chain resilience

The arrival of the COVID-19 pandemic has further reinforced the need for resilient supply chains in the face of a crisis. With demand forecasting improvement, optimization of inventory levels and disruption identification, AI and ML participate in the reinforcement of supply chain resilience (Sobb et al., 2020; Bedi et al., 2021). AI algorithms can analyse historical data, market trends, and external factors to give accurate demand predictions to businesses and help them to keep their inventory level right so they won't fall short of having the stock or face an overstock situation (Bedi et al., 2021; Qader et al., 2022; Rane et al., 2024c). Furthermore, AI based supply chain management system would be able to detect impending disruptions (natural calamities and geo-political events) and recommend backup sourcing options. This enables industries to function smoothly, despite adversities.

Cybersecurity resilience

Cybersecurity enables industrial resilience in the age of the digital transformation (Ferrag et al., 2021; Paramesha et al., 2024d). These cyber threats are being detected and prevented using AI/ML/DL (Bécue et al., 2021; Moustafa et al., 2023). These technologies give the capability to analyse network traffic, spot anomalies and alert to a potential security breach as it is happening. In particular, deep learning models are superb at identifying intricate patterns and able to discern sophisticated cyber-attacks that traditional security systems may overlook; therefore, an AI-powered cybersecurity system can respond to threats in a much timelier and efficient manner, allowing the protection of vital industrial infrastructure and data thorough constant data gathering and analysis. Table 3.1 shows resilience through AI, ML, and DL.

Operational optimization

Operational efficiency is the foundation of operational resilience in industry. From production processes to energy management, AI and ML can streamline operations across a spectrum of industrial operations (Lee et al., 2020; Mallioris et al., 2024). Manufacturing AI-powered systems in production, AI can analyse through production data to find bottlenecks, smooth workflows and boost productivity. For instance, AI can help to plan the scheduling of tasks and resources inside a factory so that production lines move quickly and smoothly. Artificial intelligent powered algorithms when implemented in energy management to analysing energy using patterns and energy usage optimization reducing the losses and making it more sustainable.

Table 3.1 Enhancing resilience through artificial intelligence, machine learning, and deep learning

References	Resilience	AI	ML	DL
Lee et al., (2020) Mallioris et al., (2024)	Operational Resilience	Predictive maintenance for machinery	Anomaly detection in production lines	Predictive analytics for equipment failures
Bécue et al., (2021); Moustafa et al., (2023); Ferrag et al., (2021)	Cyber Resilience	Intrusion detection systems (IDS)	Pattern recognition in network traffic for identifying potential threats	Deep packet inspection using neural networks
Burrell, (2024); Ali et al., (2024)	Financial Resilience	Fraud detection systems using AI algorithms	Credit scoring and loan approval processes using ML models	Analyzing vast financial datasets for hidden patterns
Romão, & Pereira, (2021); Bongomin et al., (2020)	Community Resilience	Disaster response planning and simulation	Predictive modeling for disaster impact assessment	Image and video analysis for damage assessment
Mumtaz et al., (2022); Chen, et al., (2023)	Environmental Resilience	Climate modeling and prediction	Predictive analytics for environmental changes	Analyzing satellite imagery for deforestation detection

Mata et al., (2021); Futai et al., (2022); Paramesha et al., (2024e)	Infrastructure Resilience	Smart grid management and optimization	Predictive maintenance for infrastructure (e.g., bridges, roads)	Monitoring and analyzing structural health
Sobb et al., (2020); Bedi et al., (2021)	Supply Chain Resilience	Optimization of logistics and inventory management	Anomaly detection in supply chain operations	Real-time tracking of goods and shipments
Saha et al., (2022); Tortorella et al., (2022)	Healthcare Resilience	Predictive modeling for disease outbreaks	Early detection of diseases through pattern recognition	Analyzing patient data for predictive health monitoring
Nessari et al., (2024); Behl et al., (2023)	Economic Resilience	Economic impact analysis and prediction	Market trend prediction and economic forecasting	Real-time analysis of economic indicators
Pandey et al., (2023); Morelli et al., (2022);Khalid, (2024)	Energy Resilience	Smart energy management systems	Optimization of renewable energy sources	Real-time monitoring and analysis of energy consumption
Grybauskas et al., (2022); Abdillah et al., (2024); Qiu et al., (2022)	Social Resilience	Enhancing social services delivery	Predicting social unrest and public sentiment	Analyzing social networks for information dissemination
Bradu et al., (2023); Ramírez-Márquez et al., (2024)	Ecological Resilience	Monitoring biodiversity and ecosystem health	Analyzing patterns in species distribution and abundance	Predicting ecological changes and impacts from environmental stressors
Marinagi et al., (2023); Marcucci et al., (2022)	Technological Resilience	Ensuring robustness and adaptability of technological systems	Predicting and mitigating technology failures	Enhancing the resilience of critical technological infrastructures
Marcucci et al., (2022); Bianco et al., (2023)	Business Resilience	Strategic planning and	Customer behaviour	Enhancing the resilience of business

		risk management	prediction and personalization	operations through real-time data analysis
Habibi Rad et al., (2021); Chen et al., (2021)	Transportation Resilience	Traffic management and optimization	Predictive maintenance for transportation infrastructure	Route optimization and autonomous driving systems
Rane, (2023)	Educational Resilience	Personalized learning and adaptive educational systems	Analyzing educational outcomes and predicting student performance	Enhancing the resilience of educational institutions through real-time data analysis
Saefudin et al., (2022); Ricciardelli et al., (2023)	Cultural Resilience	Preserving cultural heritage through digitization and AI-driven restoration	Analyzing and predicting cultural trends and shifts	Enhancing cultural understanding through DL models of language and art

Quality control and assurance

Reliability is a critical part of customer trust as well as continued operation of the platform. AI and ML have completely changed the scenario of quality control of different industries (Ralston, & Blackhurst, 2020; Hsu et al., 2022). Using computer vision and DL, AI systems can scan parts immediately after production to detect and classify defects with unprecedented accuracy (Williams, & Tang, 2020; Hsu et al., 2022). Such systems are capable of analyzing images and data from the product line and revealing anomalies that a human inspector might not be able to catch. This improves the quality of work, reducing their cycle time and contributing to their overall productivity at the expense of reducing waste (reducing work that is produced and done again). In the automotive industry, BMW and Toyota, for example, deploy AI-quality control systems to ensure conformance to very high-quality standards of their vehicles.

Crisis management and disaster recovery

The companies should be able to face the crisis and manage to rebound from the disaster. If leveraged correctly, AI and ML can be useful instruments to aid in crisis management and disaster recovery (Romão, & Pereira, 2021; Bongomin et al., 2020). Predictive analytics powered by AI can actually simulate a critical situation and help organizations carve out the most suitable responder plan for such situations (Habibi Rad et al., 2021;

Raja Santhi, & Muthuswamy, 2022). In crisis, AI allows the analysis of real-time data to give invaluable insights that can support or influence decisions. AI could be used to analyze weather forecast and social media and compare to similar events stored in a database to help predict the impact of a natural disaster and determine the response strategy, in the event of that happening. Emergency response and recovery AI can also help to automate the disaster management process, further optimizing the deployment of resources and supply chain logistics to make sure critical supplies, for example, get to affected areas promptly (Sobb et al., 2020; Bedi et al., 2021).

Environmental and sustainability resilience

Environmental and regulatory challenges have led to greater emphasis on sustainability as a crucial element of industrial resilience. By optimizing use of resources and reducing environmental impact, AI and ML technologies can make the world more environmentally resilient (Mumtaz et al., 2022; Chen, et al., 2023). With the help of AI, it possible to analyse different data sources such as sensors, satellite imagery and more - for tracking about environmental conditions and spotting requirement's particular locations (Aheleroff et al., 2022; Chen, et al., 2023). This includes applications where AI can help optimize water and power usage in industrial processes and thereby deliver a direct environmental benefit via reductions in waste and emissions. AI-based sustainability platforms, another tool for industries, can help businesses monitor and report on their environmental performance to ensure that they comply with regulations and improve their brand image. Businesses, including Unilever and Nestlé, are using AI to meet their sustainability targets and build their resilience.

Customer Relationship Management (CRM)

Customer relationships are critical as customer trust and loyalty have to be in place to help us manage through disruptions and maintain our industrial strength. Furthermore, with AI and ML customers use an additional tool for customer relationship management which offers personalized services and elevate customer satisfaction (Chatterjee et al., 2021; Marcucci et al., 2022; Bianco et al., 2023). Data analytics by the AI in CRM helps to hook and address customer's preferences and behaviour, which by that, the company can offer tailor cut products and deliver the more precise services to their customers. Moreover, AI chatbots and virtual assistants are capable of giving 24/7 customer answers/ solutions quickly (Marcucci et al., 2022; Bianco et al., 2023). It increases consumer satisfaction and also allows businesses to survive and maintain their revenue stream in hard times.

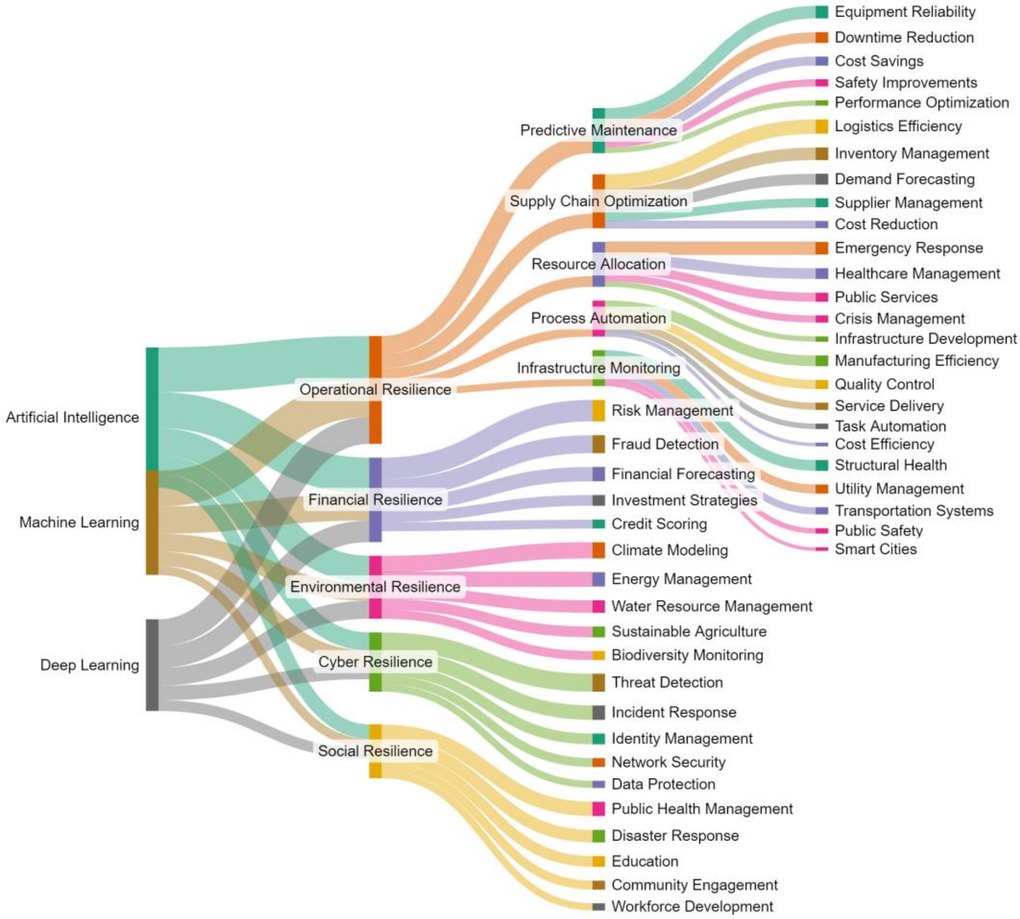

Fig. 3.2 Sankey diagram highlights how AI, ML, and DL contribute to different resilience, including operational, financial, environmental, cyber, and social resilience

Financial resilience

It is important that industries are financially resilient and are able to be in the game when things start not going their way. Financial forecasting, risk management and investment strategies), which are all contributed by, ML, and DL technologies (Burrell, 2024; Ali et al., 2024). AI algorithms can read historical financial data as well as market movements and economic indicators to deliver reliable predictions and pinpoint potential dangers. AI, for example, could forecast cash flow - allowing businesses to stay on top of liquidity management. AI-powered risk management systems can also look into the finances of suppliers and partners to determine areas of weakness in the supply chain. In investments AI trained trading algorithms can do portfolio optimizations in the investment sector reducing risk and maximizing returns.

Customer experience and satisfaction

Customer experience and satisfaction is crucial for industrial resilience, as it retains customers and ensures constant profit. AI and ML are efficient in enhancing customer experience (Chatterjee et al., 2021; Marcucci et al., 2022). AI can enable personalized customer interactions and proactive customer support. In terms of customer interactions, this can be achieved with AI-driven customer relationship management systems that can analyze customer data to understand customer preferences and behaviours and tailor product marketing to specific target customer groups (Chatterjee et al., 2021; Marcucci et al., 2022; Bianco et al., 2023). As for customer support, AI can enable chatbots and virtual assistants capable of providing support services 24/7. Thanks to these applications, customer inquiries and issues are addressed on the spot, which increases customer satisfaction. AI can also perform routine tasks, which frees up human capital for addressing more complex assignments. For instance, Amazon and Alibaba use AI to ensure a personalized shopping experience and for superior customer relationship management.

Energy management and sustainability

An important element of industrial resilience is sustainable energy management. Nowadays, industries face increasing regulatory, social, and competitive pressure to act in a sustainable manner and address environmental challenges. Accordingly, AI technologies, such as ML and DL, can be used to optimize energy use in accordance with sustainability requirements (Nessari et al., 2024; Behl et al., 2023). To use AI to optimize energy management, a company needs to collect data on energy consumption rate and patterns as well environmental conditions. With this information on hand, AI systems will identify areas where energy can be used in a sustainable manner and suggest optimizing energy usage by changing production schedule or using energy-saving technologies. Importantly, AI can be useful in guiding the use of renewable energy sources, for example, solar or wind energy, which may help achieve sustainability.

Human resources and workforce management

The safety of the human workforce is vital in maintaining productivity. Additionally, the protection can facilitate the limited outbreak, maintaining operational continuity. AI and ML can optimize workforce management by providing more sophisticated tools for talent management, employee training, and performance tracking (Flores et al., 2020). AI screens and automatically evaluates the applications received from different potential employees or volunteers and provides a list of all the resumes that meet the desired requirements. In this manner, businesses employ the most qualified and well-fitted person for the job, ensuring that they attract the best candidates and retain them for future projects. Additionally, AI-driven systems offer personalized courses to help employees gain specific skills and adapt to the requirements of any work. Furthermore, it tracks and provides feedback on both the performance and engagement levels of employees.

Digital transformation and innovation

Industrial resilience is powered by digital transformation to help businesses respond to technological changes and shifts in market demand. AI-based automation, while handling non-core functions, enables saving of resources and money, allowing to focus on core strategic imperatives (Dilyard et al., 2021; Ghobakhloo et al., 2023). Moreover, AI-powered analytics would offer crucial information relative to business outcomes, consumer responses and market default, hence facilitating data-driven choices (Marcucci et al., 2022; Bianco et al., 2023). In this way, AI can also provide businesses with the means to innovate, allowing them to create new products, services and business models.

The Sankey diagram (Fig. 3.2) illustrates the complex interplay of relationships and contributions of these advanced technologies towards resilience across multiple spectra of resilience - operational, financial, environmental, cyber security, and social. The diagram starts with the broad overview of AI, ML, DL and their heavy contribution to various resilience arenas. AI is a deep root technology it gives opposite type of resilience such as operational, financial, environmental, cyber, and social. This shows how AI is being leveraged on a large scale to make different systems and processes more resilient and adaptable against the unforeseen circumstances. similar to AI, whose subset ML is used to design methods for systems to learn and improve from data, ML displays potential input values for operational, financial, environmental, cyber, and social resilience. This spread highlights the power of ML to streamline operations, control risk, and elevate decision making across multiple industries. Similarly, the notion of DL, a further refinement of ML using neural networks with numerous layers, is seen as very influential in the resilience capacity. DL helps to improve the robustness of systems through operational and financial, environmental, cyber and social resilience. The diagram goes on to line up more particular applications of resilience. To demonstrate the reach of open-source hardware, none of the applications listed in the example use a proprietary variant of Linux, nor are they specifically optimized for a cross-platform hardware setup. Operations resilience, for example, thrives on predictive maintenance, supply chain optimization, resource allocation, process automation, and infrastructure monitoring. The use cases for AI, ML and DL illustrated by these applications show that operations can not only be used to predict potential failures but also to improve logistics and allocate efficient resource, automate processes and track the health of in infrastructure long before they become production impediments.

Support for financial resilience could take the form of, amongst others, approaches to risk management, fraud detection, financial forecasting, investment strategies and credit scoring. These applications serve to illustrate the ways AI technologies can be used to identify and alleviate financial risks, identify cases of fraud, predict financial market trends, develop investment strategies, and determine creditworthiness in order to stabilize financial systems. Another important aspect is the support of resilience to environmental challenges, where tools can support the modeling of climate, energy, water resource, sustainable agriculture, and biodiversity. This only says to show the involvement of AI, ML and DL in addressing environmental issues, optimizing energy and water resources, promoting sustainable forms of agriculture and biodiversity relevant to the monitoring necessary to preserve ecosystems.

The cyber resilience essential in contributions to threat detection, incident response, identity management, network security and data protection. These applications highlight the critical role of AI in protecting digital infrastructures by detecting and responding to threat, managing identities, securing networks, and preventing data from breaches. Public health management, disaster response, education, community engagement and workforce development contribute to social resilience - the capacity of a population to support a community through any emergency. These examples illustrate how exciting uses of AI with widespread social impact may be embedded across a wide number of sectors including deployment in public health to make systems smarter, in disaster response to make outcomes more effective, in improving education, in community engagement and enabling the workforce to adapt in changing environments. In addition, the diagram maps these resilience building applications to the sustainability, socioecological, and application outcomes. Basically, the benefits of predictive maintenance result in increased equipment reliability, reduced downtime, cost savings, better-situation safety and more system performance. This includes logistics efficiency, inventory management, demand forecasting, supplier management, and of course, cost reduction. The deployment of resources improves emergency response, healthcare management, public service delivery, crisis management and infrastructure development. Increasing manufacturing efficiency, quality control, the delivery of services, task automation, lowering costs are the benefits of process automation.

3.4 Conclusions

AI facilitates real-time data analysis, predictive modeling, and hence strengthens operational resilience. This enables the industries to predict and prevent the disruption while maintaining their operational processes in a shape. A decision is a choice, and a model is something that informs that choice based on our data, training (learnings), and experience. DL and advanced ML take it to the next level and perform better at an operational level. AI, ML and DL also play a major role in supply chain resilience. These integrate real-time visibility and predictive analytics to streamline logistics operations and mitigate the effects of disruptions. AI acts as a significant force for agility within the supply chain by using an AI-powered system of demand forecasting and inventory management to remain responsive within the supply chain to market fluctuations and disruption. In addition, AI driven supply chains are better equipped to respond to new constraints and re-route resources to be more sustainable and resilient in the presence of difficulties. AI and ML enable this through adaptive interfaces and collaborative robots (cobots) that work with humans, boosting efficiency and protecting jobs. Apart from its possible enhancement on industrial resilience, this synergy could increase workers' satisfaction and wellbeing. AI-led training and real time assistance systems help workers learn new skills on the fly and adapt to changing job roles, making the workforce more resilient. Societal resilience is thought to be an aspect of Society 5.0 with the goal of addressing societal challenges in a more sustainable and inclusive manner through digital transformation. AI and DL have an important role to play in smart city vision (including smart grid) by making the urban infrastructure smarter and energy efficient which is essential for urban resilience. Notably, AI-driven precision medicine and predictive analytics are saving lives and alleviating strain on our healthcare system by enabling earlier disease detection and more personalized treatment plans. Additionally, we are now able to use AI technology for smart energy management systems that reduce consumption and carbon footprints leading support for the environmental sustainability. As these fields grow and evolve, their applied synergy will be of key importance to navigating the nuances of the 21st century industrial and societal landscape and advancing not only economic, but social, environmental and health outcomes for a more resilient, sustainable and regenerative future.

References

Abdillah, A., Widianingsih, I., Buchari, R. A., & Nurasa, H. (2024). Big data security & individual (psychological) resilience: A review of social media risks and lessons learned from Indonesia. Array, 100336.

Aheleroff, S., Huang, H., Xu, X., & Zhong, R. Y. (2022). Toward sustainability and resilience with Industry 4.0 and Industry 5.0. Frontiers in Manufacturing Technology, 2, 951643.

Ahmed, T., Karmaker, C. L., Nasir, S. B., Moktadir, M. A., & Paul, S. K. (2023). Modeling the artificial intelligence-based imperatives of industry 5.0 towards resilient supply chains: A post-COVID-19 pandemic perspective. Computers & Industrial Engineering, 177, 109055.

Al-Banna, A., Rana, Z. A., Yaqot, M., & Menezes, B. (2023). Interconnectedness between Supply Chain Resilience, Industry 4.0, and Investment. Logistics, 7(3), 50.

Ali, M., Razaque, A., Yoo, J., Kabievna, U. R., Moldagulova, A., Ryskhan, S., ... & Kassymova, A. (2024). Designing an Intelligent Scoring System for Crediting Manufacturers and Importers of Goods in Industry 4.0. Logistics, 8(1), 33.

Bécue, A., Praça, I., & Gama, J. (2021). Artificial intelligence, cyber-threats and Industry 4.0: Challenges and opportunities. Artificial Intelligence Review, 54(5), 3849-3886.

Bedi, P., Upreti, K., Rajawat, A. S., Shaw, R. N., & Ghosh, A. (2021, September). Impact analysis of industry 4.0 on realtime smart production planning and supply chain management. In 2021 IEEE 4th International Conference on Computing, Power and Communication Technologies (GUCON) (pp. 1-6). IEEE.

Behl, A., Singh, R., Pereira, V., & Laker, B. (2023). Analysis of Industry 4.0 and circular economy enablers: A step towards resilient sustainable operations management. Technological Forecasting and Social Change, 189, 122363.

Bianco, D., Bueno, A., Godinho Filho, M., Latan, H., Ganga, G. M. D., Frank, A. G., & Jabbour, C. J. C. (2023). The role of Industry 4.0 in developing resilience for manufacturing companies during COVID-19. International Journal of Production Economics, 256, 108728.

Biard, G., & Nour, G. A. (2021). Industry 4.0 contribution to asset management in the electrical industry. Sustainability, 13(18), 10369.

Bongomin, O., Yemane, A., Kembabazi, B., Malanda, C., Chikonkolo Mwape, M., Sheron Mpofu, N., & Tigalana, D. (2020). Industry 4.0 disruption and its neologisms in major industrial sectors: A state of the art. Journal of Engineering, 2020(1), 8090521.

Bradu, P., Biswas, A., Nair, C., Sreevalsakumar, S., Patil, M., Kannampuzha, S., ... & Gopalakrishnan, A. V. (2023). Recent advances in green technology and Industrial Revolution 4.0 for a sustainable future. Environmental Science and Pollution Research, 30(60), 124488-124519.

Burrell, D. N. (Ed.). (2024). Innovations, Securities, and Case Studies Across Healthcare, Business, and Technology. IGI Global.

Chatterjee, S. R., Shukla, V. K., Wanganoo, L., & Dubey, S. (2021, September). Transforming Supply chain Management through Industry 4.0. In 2021 9th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions)(ICRITO) (pp. 1-6). IEEE.

Chen, L., Chen, Z., Zhang, Y., Liu, Y., Osman, A. I., Farghali, M., ... & Yap, P. S. (2023). Artificial intelligence-based solutions for climate change: a review. Environmental Chemistry Letters, 21(5), 2525-2557.

Chen, Y. T., Sun, E. W., Chang, M. F., & Lin, Y. B. (2021). Pragmatic real-time logistics management with traffic IoT infrastructure: Big data predictive analytics of freight travel time for Logistics 4.0. International Journal of Production Economics, 238, 108157.

Compare, M., Baraldi, P., & Zio, E. (2019). Challenges to IoT-enabled predictive maintenance for industry 4.0. IEEE Internet of things journal, 7(5), 4585-4597.

Dilyard, J., Zhao, S., & You, J. J. (2021). Digital innovation and Industry 4.0 for global value chain resilience: Lessons learned and ways forward. Thunderbird International Business Review, 63(5), 577-584.

Ferrag, M. A., Shu, L., Friha, O., & Yang, X. (2021). Cyber security intrusion detection for agriculture 4.0: Machine learning-based solutions, datasets, and future directions. IEEE/CAA Journal of Automatica Sinica, 9(3), 407-436.

Flores, E., Xu, X., & Lu, Y. (2020). Human Capital 4.0: a workforce competence typology for Industry 4.0. Journal of Manufacturing Technology Management, 31(4), 687-703.

Futai, M. M., Bittencourt, T. N., Carvalho, H., & Ribeiro, D. M. (2022). Challenges in the application of digital transformation to inspection and maintenance of bridges. Structure and Infrastructure Engineering, 18(10-11), 1581-1600.

Ghobakhloo, M., Iranmanesh, M., Foroughi, B., Tseng, M. L., Nikbin, D., & Khanfar, A. A. (2023). Industry 4.0 digital transformation and opportunities for supply chain resilience: a comprehensive review and a strategic roadmap. Production Planning & Control, 1-31.

Golovianko, M., Terziyan, V., Branytskyi, V., & Malyk, D. (2023). Industry 4.0 vs. Industry 5.0: co-existence, Transition, or a Hybrid. Procedia Computer Science, 217, 102-113.

Grabowska, S., Saniuk, S., & Gajdzik, B. (2022). Industry 5.0: improving humanization and sustainability of Industry 4.0. Scientometrics, 127(6), 3117-3144.

Grybauskas, A., Stefanini, A., & Ghobakhloo, M. (2022). Social sustainability in the age of digitalization: A systematic literature Review on the social implications of industry 4.0. Technology in Society, 70, 101997.

Habibi Rad, M., Mojtahedi, M., & Ostwald, M. J. (2021). Industry 4.0, disaster risk management and infrastructure resilience: a systematic review and bibliometric analysis. Buildings, 11(9), 411.

Hsu, C. H., Zeng, J. Y., Chang, A. Y., & Cai, S. Q. (2022). Deploying Industry 4.0 enablers to strengthen supply chain resilience to mitigate ripple effects: an empirical study of top relay manufacturer in China. IEEE Access, 10, 114829-114855.

Ivanov, D. (2023). The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives. International Journal of Production Research, 61(5), 1683-1695.

Khalid, M. (2024). Energy 4.0: AI-enabled digital transformation for sustainable power networks. Computers & Industrial Engineering, 110253.

Lee, J., Ni, J., Singh, J., Jiang, B., Azamfar, M., & Feng, J. (2020). Intelligent maintenance systems and predictive manufacturing. Journal of Manufacturing Science and Engineering, 142(11), 110805.

Leng, J., Zhong, Y., Lin, Z., Xu, K., Mourtzis, D., Zhou, X., ... & Shen, W. (2023). Towards resilience in Industry 5.0: A decentralized autonomous manufacturing paradigm. Journal of Manufacturing Systems, 71, 95-114.

Mallioris, P., Aivazidou, E., & Bechtsis, D. (2024). Predictive maintenance in Industry 4.0: A systematic multi-sector mapping. CIRP Journal of Manufacturing Science and Technology, 50, 80-103.

Marcucci, G., Antomarioni, S., Ciarapica, F. E., & Bevilacqua, M. (2022). The impact of Operations and IT-related Industry 4.0 key technologies on organizational resilience. Production Planning & Control, 33(15), 1417-1431.

Marinagi, C., Reklitis, P., Trivellas, P., & Sakas, D. (2023). The impact of industry 4.0 technologies on key performance indicators for a resilient supply chain 4.0. Sustainability, 15(6), 5185.

Mata, J., Santos, J., & Barateiro, J. (2021). Using emergent technologies on the structural health monitoring and control of critical infrastructures. In Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills (pp. 541-567). Cham: Springer International Publishing.

Morelli, G., Magazzino, C., Gurrieri, A. R., Pozzi, C., & Mele, M. (2022). Designing smart energy systems in an industry 4.0 paradigm towards sustainable environment. Sustainability, 14(6), 3315.

Moustafa, N., Koroniotis, N., Keshk, M., Zomaya, A. Y., & Tari, Z. (2023). Explainable intrusion detection for cyber defences in the internet of things: Opportunities and solutions. IEEE Communications Surveys & Tutorials.

Mumtaz, N., Izhar, T., Pandey, G., & Labhasetwar, P. K. (2022). Utilizing artificial intelligence for environmental sustainability. In Artificial Intelligence for Renewable Energy Systems (pp. 259-279). Woodhead Publishing.

Nessari, S., Ghanavati-Nejad, M., Jolai, F., Bozorgi-Amiri, A., & Rajabizadeh, S. (2024). A data-driven decision-making approach for evaluating the projects according to resilience, circular economy and industry 4.0 dimension. Engineering Applications of Artificial Intelligence, 134, 108608.

Pandey, V., Sircar, A., Bist, N., Solanki, K., & Yadav, K. (2023). Accelerating the renewable energy sector through Industry 4.0: Optimization opportunities in the digital revolution. International Journal of Innovation Studies, 7(2), 171-188.

Peres, R. S., Jia, X., Lee, J., Sun, K., Colombo, A. W., & Barata, J. (2020). Industrial artificial intelligence in industry 4.0-systematic review, challenges and outlook. IEEE access, 8, 220121-220139.

Paramesha, M., Rane, N. L., & Rane, J. (2024a). Artificial Intelligence, Machine Learning, Deep Learning, and Blockchain in Financial and Banking Services: A Comprehensive Review. Partners Universal Multidisciplinary Research Journal, 1(2), 51-67.

Paramesha, M., Rane, N., & Rane, J. (2024b). Trustworthy Artificial Intelligence: Enhancing Trustworthiness Through Explainable AI (XAI). Available at SSRN 4880090.

Paramesha, M., Rane, N., & Rane, J. (2024c). Artificial intelligence in transportation: applications, technologies, challenges, and ethical considerations. Available at SSRN 4869714.

Paramesha, M., Rane, N., & Rane, J. (2024d). Generative artificial intelligence such as ChatGPT in transportation system: A comprehensive review. Available at SSRN 4869724.

Paramesha, M., Rane, N., & Rane, J. (2024e). Big data analytics, artificial intelligence, machine learning, internet of things, and blockchain for enhanced business intelligence. Available at SSRN 4855856.

Qader, G., Junaid, M., Abbas, Q., & Mubarik, M. S. (2022). Industry 4.0 enables supply chain resilience and supply chain performance. Technological Forecasting and Social Change, 185, 122026.

Qiu, D., Lv, B., & Chan, C. M. (2022). How digital platforms enhance urban resilience. Sustainability, 14(3), 1285.

Raja Santhi, A., & Muthuswamy, P. (2022). Pandemic, war, natural calamities, and sustainability: Industry 4.0 technologies to overcome traditional and contemporary supply chain challenges. Logistics, 6(4), 81.

Raja Santhi, A., & Muthuswamy, P. (2023). Industry 5.0 or industry 4.0 S? Introduction to industry 4.0 and a peek into the prospective industry 5.0 technologies. International Journal on Interactive Design and Manufacturing (IJIDeM), 17(2), 947-979.

Ralston, P., & Blackhurst, J. (2020). Industry 4.0 and resilience in the supply chain: a driver of capability enhancement or capability loss?. International Journal of Production Research, 58(16), 5006-5019.

Ramírez-Márquez, C., Posadas-Paredes, T., Raya-Tapia, A. Y., & Ponce-Ortega, J. M. (2024). Natural Resource Optimization and Sustainability in Society 5.0: A Comprehensive Review. Resources, 13(2), 19.

Rane, N., Choudhary, S., & Rane, J. (2024a). Integrating deep learning with machine learning: technological approaches, methodologies, applications, opportunities, and challenges. Available at SSRN 4850000.

Rane, N., Choudhary, S., & Rane, J. (2024b). Artificial Intelligence (AI), Internet of Things (IoT), and blockchain-powered chatbots for improved customer satisfaction, experience, and loyalty (May 29, 2024). http://dx.doi.org/10.2139/ssrn.4847274

Rane, N., Choudhary, S., & Rane, J. (2024c). Artificial intelligence and machine learning for resilient and sustainable logistics and supply chain management. Available at SSRN 4847087.

Ricciardelli, A., Del Vecchio, P., Ventura, M., & Reina, R. (2023). How digitalization saved 2020 European Capitals of Culture. European Journal of Innovation Management.

Romão, X., & Pereira, F. L. (2021). Smart Disaster Risk Reduction and Emergency Management in the Built Environment. In Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills (pp. 315-340). Cham: Springer International Publishing.

Saefudin, A., Triharwanto, F., Farida, Y. E., Mahalli, M., Rozaq, A., & Yulistianti, H. D. (2022, January). The Socio-Cultural Resilience of Islamic Boarding School: Supporting and Inhibiting Factors. In International Conference on Madrasah Reform 2021 (ICMR 2021) (pp. 207-214). Atlantis Press.

Saha, H. N., Chakraborty, S., Paul, S., Ghosh, R., & Bhattacharya, D. C. (2022). Impact of healthcare 4.0 technologies for future capacity building to control epidemic diseases. Smart healthcare system design: Security and privacy aspects, 115-142.

Sindhwani, R., Afridi, S., Kumar, A., Banaitis, A., Luthra, S., & Singh, P. L. (2022). Can industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers. Technology in Society, 68, 101887.

Sobb, T., Turnbull, B., & Moustafa, N. (2020). Supply chain 4.0: A survey of cyber security challenges, solutions and future directions. Electronics, 9(11), 1864.

Tortorella, G. L., Fogliatto, F. S., Saurin, T. A., Tonetto, L. M., & McFarlane, D. (2022). Contributions of Healthcare 4.0 digital applications to the resilience of healthcare organizations during the COVID-19 outbreak. Technovation, 111, 102379.

Williams, D., & Tang, H. (2020). Data quality management for industry 4.0: A survey. Software Quality Professional, 22(2), 26-35.