Edge Computing for Industry 5.0: Fundamental, Applications, and Research Challenges

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***Abstract*—Industry 5.0 is the next stage in industrial evolution, collaborating between human ingenuity and intelligent technologies to provide manufacturing solutions. Integrating modern technology like artificial intelligence (AI), robotics, and the Internet of Things (IoT) into manufacturing and production processes characterizes Industry 5.0. On the other hand, edge computing provides real-time data processing and analysis at the network's edge, closer to the data source and a vital component of Industry 5.0. Edge computing enables Industry 5.0 to access and communicate information about their industrial sectors using more accessible, standard hardware and software resources. However, no recent survey papers have examined the importance of edge computing in Industry 5.0. This study aims to fill that gap by presenting a survey on the importance of edge computing in Industry 5.0 and discussing a variety of technologies that could be used to implement and support this new industrial paradigm. First, we outline an overview and fundamentals of edge computing in Industry 5.0 architecture. Then objectives of Industry 5.0 are summarized to address various research challenges, including privacy, human–robot co-working, sustainability, and robust networks. Afterward, this article provides an extensive overview of emerging technologies for Industry 5.0, such as collaborative robots, AI, Digital Twins, and many more. In addition, this survey highlights various open research challenges and potential solutions that should be addressed further to achieve Industry 5.0.**

***Index Terms*—Artificial intelligence (AI), collaborative robots (cobots), edge computing, Industry 5.0, Internet of Things (IoT), sustainability.**

I. Introduction

CURRENT industrial revolution, i.e., Industry 4.0, has prompted the automation of industrial processes and the integration of critical technologies, such as edge computing, cloud computing, Internet of Things (IoT), and artificial intelligence (AI) to achieve the vision of intelligent factories and enhance production [1]. It primarily aims to increase productivity and mass customization, transforming previous versions. Throughout the 1800s, Industry 1.0 developed by creating mechanical manufacturing infrastructures for water and steam-powered machines. The introduction of electric power and assembly line manufacturing marked the beginning of Industry 2.0 in 1870 as production capacity rose and the economy greatly benefited. In Industry 2.0, mass production and workload allocation play a significant role in boosting the productivity of manufacturing firms. As a result of the second industrial revolution, environmental pollution increased significantly throughout the world. Industry 3.0, the third industrial development, is frequently associated with computer technology, automation, transportation, and logistics development. As a result of Industry 3.0, manufacturing and production processes have significantly improved efficiency, precision, and personalization.

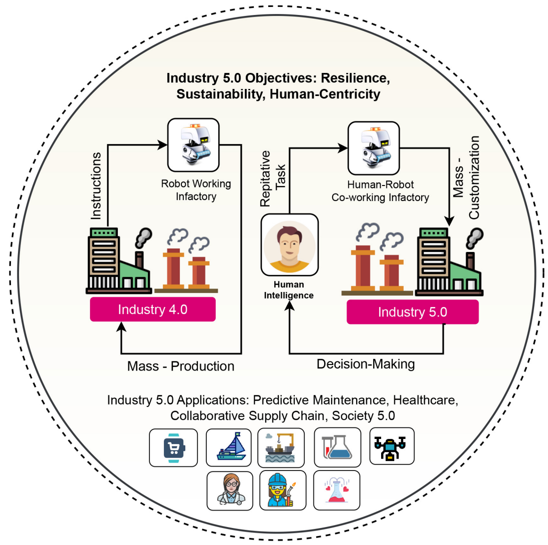

Fig. 1. Concept of Industry 5.0.

Later, in 2011, smart manufacturing for the future evolved into Industry 4.0 [2]. Aside from enhancing productivity and mass production, the basic goal of Industry 4.0 is to harness the power of emerging technology [3]. Industry 5.0 is the forthcoming industrial revolution, a cognitive control process based on Industry 4.0, where human–machine interactions are enhanced. This would result in a value-driven rather than a process-driven approach. In Industry 5.0, AI would combine human experience with cognitive abilities and precision control. Fig. 1 illustrates the key concepts behind the Industry 5.0 revolution. Industry 5.0 is envisioned to improve production quality by delegating repetitive and uninteresting tasks to robots while humans manage critical reasoning and intelligent duties. This would create a demand for skilled personnel [4].

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Since humans fully understand and can work with robotic colleagues, they can coexist in the workplace without fear or apprehension. As a result, production processes will be incredibly effective and value-added, trustworthy autonomy will flourish, waste will disappear, and associated costs will be lower [5].

Furthermore, this phase focuses on intelligent, linked, and autonomous systems that function efficiently and adapt to changing conditions [1], [6]. On the other hand, edge computing is essential for these systems to operate in real time, with minimal latency and outstanding reliability. One of the essential advantages of edge computing is the capacity to handle and industrial analyze data in real time. As Industry 5.0 develops, intelligent systems must be able to modify their response quickly based on real-time data and make decisions in real time. For example, edge computing can be used in a manufacturing plant to analyze real-time sensor data from production equipment. It can minimize downtime and increase efficiency by detecting potential problems and enabling predictive maintenance.

A. Why Edge Computing for Industry 5.0

Edge computing refers to the computational and networking operations carried out by IoT devices at the network's periphery while communicating with the distant cloud. Edge computing plays a crucial role in Industry 5.0 by enabling the implementation of AI algorithms and models directly at the edge. This allows for immediate data processing and decreases the need for cloud-based computing. It facilitates expedited response times, heightened security, and greater bandwidth optimization through localized data processing on edge devices or servers. For instance, edge computing is essential for ensuring fire safety in Industry 5.0 through its ability to offer real-time monitoring, data analysis, integration with the IoT, predictive maintenance, and improved safety features. These technologies aid in the identification and prevention of fire breaches, thereby guaranteeing a safer and more secure industrial setting.

The industry has favored edge computing and AI technologies more frequently in recent years. The driving forces behind this decision are the expansion of Industrial IoT (IIoT)-connected manufacturing, IIoT resources, data analysis techniques that necessitate computing equipment that uses less power, and the demand for real-time decision making in Industry 5.0 [7]. The idea is to process data more quickly and in larger quantities near the point of generation, resulting in more immediate and actionable answers. It has some distinctive features compared to conventional models, which centralize processing power in on-premise data centers. Edge computing has the ability to address the concerns of battery life, response time requirements, bandwidth cost savings, and end-to-end delay. Self-driving automobiles, autonomous robots, data from innovative equipment, and automated retail are examples of edge use cases [8].

In Industry 5.0, edge computing offers a variety of advantages, such as real-time communication between devices and low latency. Because of reduced latency, AI systems can respond rapidly, making them suited to activities that need quick decision making and control. AI algorithms implemented near the edge, such as autonomous vehicles or industrial robotics, can make split-second choices without relying on distant cloud servers. This can improve the performance of industrial systems, such as robotics, sensors, and automation, and minimize data loss risk. Second, in Industry 5.0, machines are expected to operate autonomously with minimal human intervention. However, this requires a high degree of reliability and resilience. Further, Fig. 2 illustrates the advantages of incorporating edge computing in Industry 5.0.

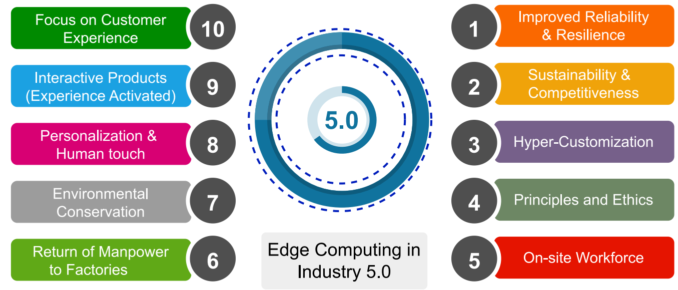

Fig. 2. Advantages of incorporating edge computing in Industry 5.0.

B. Edge Security

Edge security is a critical concern in Industry 5.0, where machines are expected to operate autonomously, and sensitive data is generated and transmitted. The privacy data of the end user must be partially or fully entrusted to third parties, such as cloud data centers or edge data centers, resulting in a separation of ownership and control. This arrangement increases the chances of data loss, leakage, unauthorized data operations (such as replication, publishing, and dissemination), and other data security issues. As a result, the confidentiality and integrity of the data cannot be ensured. Consequently, outsourcing data security is still a fundamental problem of edge computing data security. It enhances security by reducing sensitive data exposure to the Internet. Industries keep sensitive data within their networks, reducing the risk of data breaches and cyberattacks. It improves data quality by filtering and processing data nearby which helps to eliminate noise and irrelevant data and ensures that only high-quality data is transmitted to the cloud. This improves analytics and decision-making accuracy and reliability, leading to better products and services. For instance, various cryptographic approaches, including identity-based encryption, attribute-based encryption, proxy re-encryption, and homomorphic encryption, are integrated to develop multiple data encryption methods for a safe data storage system. These methods enable users to store their private data as ciphertext on untrusted edge servers. Edge servers primarily offer services to edge devices, which are widely recognized for their vulnerability to security issues due to their limited computational capabilities and diverse firmware. This helps industries adapt to changing business needs, improve agility, and reduce the time to market new products and services.

C. Survey Scope

Many reputed journals have published articles related to Industry 5.0, and these articles primarily focus on the definitions and state-of-the-art, enabling technologies, applications, challenges, and research directions in Industry 5.0 [9]. For example, Maddikunta et al. [5] have presented a survey on enabling technologies and potentials of Industry 5.0. Ghobakhloo et al. [10] have explained how Industry 5.0 could achieve sustainable development values, where authors mainly focused on the enabling technology and applications of Industry 5.0. Recently, Verma et al. [1] have presented a survey on blockchain as a possible enabler of Industry 5.0. Compared to existing survey articles, this study aims to fill that gap by providing a survey on the importance of edge computing in Industry 5.0 and discussing various technologies that could be used to implement and support this evolving industrial paradigm. Moreover, our research focuses on three main points, the research trend of Industry 5.0, Industry 5.0 objectives, and the edge-enabled Industry 5.0 architecture. Moreover, the primary research questions concerning edge computing in Industry 5.0 are as follows.

1) Can edge computing be successfully applied to Industry 5.0 in practical use cases?
2) What role does edge computing play in reducing latency and enhancing efficiency in Industry 5.0?
3) Can Industry 5.0 promote sustainable manufacturing while creating a resilient ecosystem?
4) Why should the Industrial 5.0 revolution adopt edge-enabled architecture as part of its strategy?

Existing research papers and articles fail to answer the above-mentioned questions. Unlike other surveys and existing studies, we reviewed popular open-source projects to analyze edge-enabled architecture. In this survey, we aim to answer the above-mentioned questions and constructive research directions toward the future of the Industry 5.0 revolution. Fig. 3 shows a detailed explanation of the survey scope.

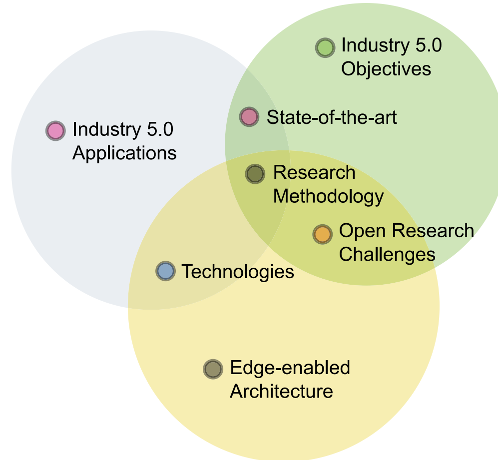

Fig. 3. Scope of this survey.

D. Motivation

By combining various technologies, including AI, IoT, cyber–physical system (CPS), cloud computing, and cognitive computing, Industry 4.0 has completely transformed the industrial landscape. Industry 4.0 represents the current stage in the industrial revolution where manufacturing systems and ICT, particularly the IoT, are integrated to form what is known as CPSs. Specifically, Industry 4.0 aims to enhance overall performance and production by utilizing machine learning (ML) to provide intelligence across equipment and applications. Industry 5.0 envisions a combination of powerful, smart, and precise machinery with human creativity. Several technical futurists believe that Industry 5.0 will add a more human touch to manufacturing. It is anticipated that Industry 5.0 will bring together human critical thinking and highly precise technology. Mass customization is another significant addition to Industry 5.0, allowing customers to select customized items based on their preferences and needs. Industry 5.0 will enable collaboration between humans and robots, significantly increasing industrial efficiency and fostering accountability for engagement and ongoing monitoring activities. The central focus of Industry 5.0 is mass customization, with humans controlling the robots. While Industry 4.0 already involves robots in mass production, Industry 5.0 is primarily focused on enhancing customer satisfaction. Industry 4.0 emphasizes CPS connectivity [11], whereas Industry 5.0 centers around customer satisfaction with the assistance of collaborative robots (cobots). Another intriguing advantage of Industry 5.0 is the availability of greener alternatives compared to the ongoing industrial changes, neither of which places a strong emphasis on environmental preservation.

E. Justification for Doing This Survey

Edge computing and Industry 5.0 are two emerging technologies that are getting substantial attention from academia and industries. Edge computing is a distributed computing approach that relocates processors and data storage closer to the points of use, improving application performance, reliability, and security. In contrast, Industry 5.0 is the latest industrial revolution that aspires to combine the benefits of Industry 4.0 (automation and digitization) with human-centric technologies like cobots, augmented reality (AR), and virtual reality (VR). Edge computing usage in Industry 5.0 can benefit significantly, including better productivity, faster decision making, and improved data security. This survey examines the rationale for edge computing and explores future research opportunities related to Industry 5.0. The primary goal of conducting this research and exploring edge computing in Industry 5.0 is to fill this knowledge gap and broaden the research scope. While several studies on the usage of edge computing in other industries have been conducted, there is a dearth of comprehensive studies on the specific use cases and benefits of edge computing in Industry 5.0. By undertaking research in this area, we can bridge this knowledge gap and provide more specific insights into the possible benefits of adopting edge computing in Industry 5.0. The performance of edge computing is being evaluated for various industrial applications. Our study also analyzes how edge computing impacts productivity, efficiency, and other key performance indicators.

F. Contributions

As industrial transformation continues to proliferate, Industry 5.0 is becoming more and more popular. However, there have not yet been any major review articles on the importance of edge computing in Industry 5.0, and none of them also discuss how Industry 5.0 can be enabled by edge computing technology. Motivated by this research gap, we intend to publish a comprehensive review article on combining edge computing in Industry 5.0 and highlight fundamental applications and research challenges for developing such a system. We have made the following contributions through our work.

1) We begin by presenting numerous definitions of Industry 5.0 from the accessible literature, which aids in developing a thorough grasp of Industry 5.0 from many angles.
2) Second, we compare Industry 5.0 to past industrial evolutions and highlight several additional features, where intelligent additive manufacturing, predictive maintenance and cyber–physical cognitive systems are thoroughly examined. We also discuss the essential component of Industry 5.0, i.e., edge computing and why it is necessary for Industry 5.0.
3) Our further section covers some of the most auspicious applications to be built and enabled in Industry 5.0, such as predictive maintenance, smart healthcare, production systems, collaborative supply chain management, the metaverse, and industrial transportation.
4) Additionally, we examine key Industry 5.0 technologies, such as zero-touch provisioning (ZTP), DT, IoE, quantum computing, cobots, and future 6G systems.
5) Subsequently, the Industry 5.0 architecture and Industry 5.0 objectives, namely, resilience, sustainability, and human-centricity, were deliberated upon. Eventually, we identify potential research challenges and future directions to achieve Industry 5.0.

G. Article Organization

The remainder of this article is organized as follows. Section II highlights the research methodology involving literature classification and existing tutorials on Industry 5.0. Section III provides an overview of the potential of Industry 5.0. Section IV discusses the objectives of Industry 5.0, which present new futuristic opportunities for Industry 5.0 applications. Section V discusses the enabling technologies of Industry 5.0 that entail enhanced communication and computation service requirements. Similarly, Section VI provides a discussion on edge-enabled architecture in Industry 5.0. In Section VII, we briefly outline the potential applications of Industry 5.0. Section VIII covers the lessons learned and recommendations. Section IX highlights the potential challenges and future opportunities in the context of Industry 5.0. Finally, Section X presents concluding remarks. For a better understanding, the organization of this article is also depicted in Fig. 4.

II. Research Methodology and Related Survey

Edge computing is a distributed computing paradigm that, rather than relying on centralized cloud computing platforms,

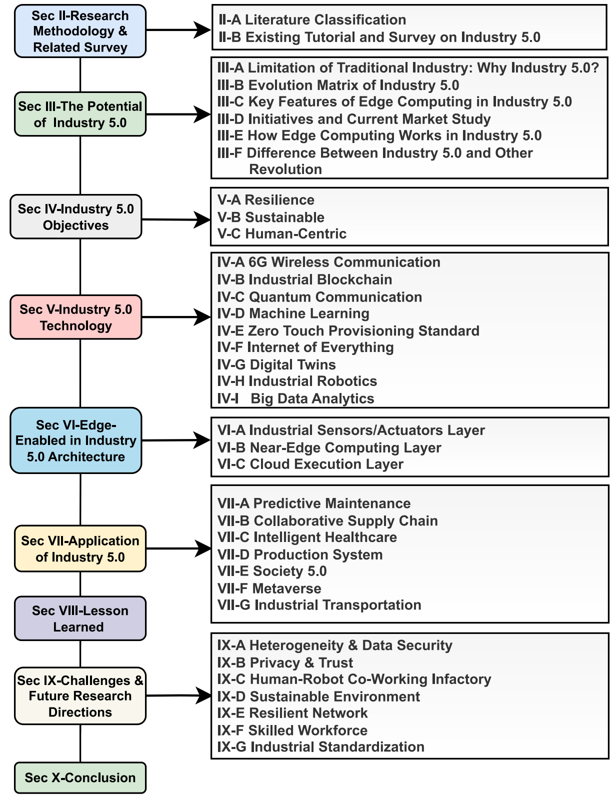

Fig. 4. Table of content and article organization.

brings computation and data storage closer to data sources, such as sensors, mobile devices, and IoT devices. It is designed to lower the latency and bandwidth of data sent to a remote cloud server for processing and analysis with numerous research avenues. Furthermore, edge computing in Industry 5.0 enables faster and more efficient data processing and decision making, particularly in industrial settings. It is becoming increasingly vital for industrial organizations looking to stay competitive in the fast-expanding Industry 5.0 scenario. It also includes a brief statistical overview of edge computing in Industry 5.0 research. In the following sections, we concisely analyze literature classification, existing tutorials, and surveys on Industry 5.0 targeting edge computing.

A. Literature Classification

We conducted a thorough literature review using four major scholarly databases (IEEE Xplore, Science Direct, ACM digital library, and Web of Science) to consider existing and future research prospects related to edge computing in Industry 5.0. Our search terms, edge computing, IoT, IIoT, Industry 5.0, AI, sustainability, human-centric, and resilient, provide us with a selection of more than 140 research publications published between 2015 and 2023, with a group of 110 papers published between 2016 and 2022, and a significant number of articles published in Elsevier (27) and IEEE (83) journals. This literature review examined 47 (30%) papers on edge computing. On the other hand, 51 (57%) papers addressed human–robot collaboration (HRC) approaches, whereas 30 (44%) articles addressed sustainability

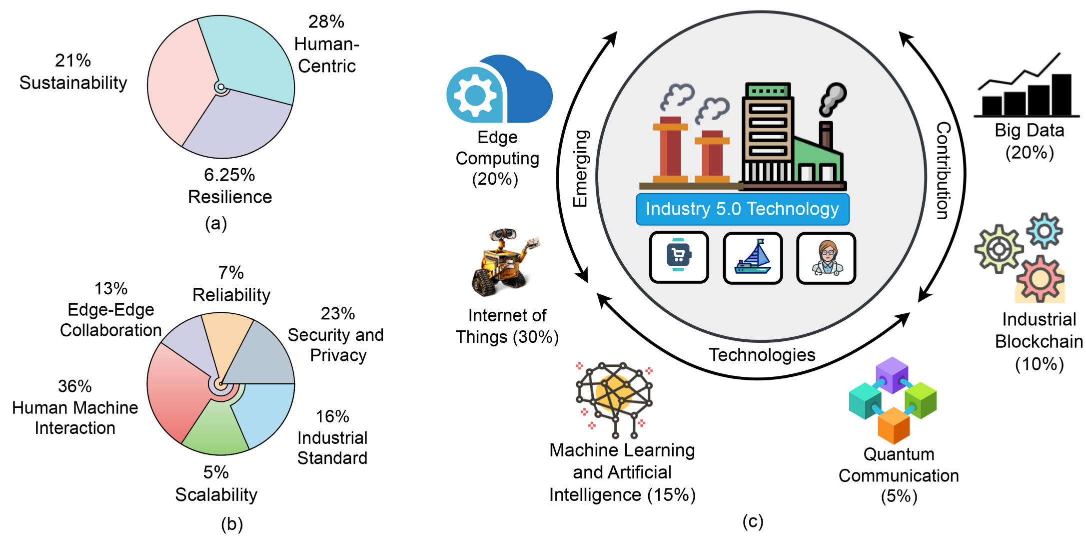

Fig. 5. Literature analysis on Industry 5.0 edge computing-based study. (a) Contributions to objective-specific Industry 5.0. (b) Domain-specific contributions. (c) Contribution of cutting-edge technologies.

strategies and corresponding implementations. These research activities give us a unique opportunity to describe our literature study from many angles. Specifically, the survey focuses on the previous five years (2019–2023) of related technologies and future research orientations associated with the *Edge Computing In Industry 5.0* revolution.

Fig. 5(a) illustrates the percentage of research effort done with different objectives of Industry 5.0, where human-centric approaches contribute 28% to Industry 5.0 development, sustainability strategies contribute approximately 21%, and resilience methods contribute approximately 6.25%. It is noteworthy to mention from Fig. 5(b) that human–machine intervention (36%) and security and privacy concerns (23%) are the most highlighted challenges in Industry 5.0. Similarly, 13% of the total contributions focused on minimizing communication latency over edge networks by edge-to-edge collaboration. In contrast, a small portion (i.e., 7%) of the research efforts were made on reliability-related issues. As expected, Industry 5.0 will rely on cutting-edge technologies (AI, ML, IoT, edge computing, big data analytics, and quantum computing) to stimulate innovation, boost productivity, and alter industrial processes while improving industrial architecture reliability. Further, Fig. 5(c) illustrates how each technology contributes significantly to the development of Industry 5.0, where researchers focus more on AI and ML, contributing approximately 15% to this development. These technologies allow intelligent automation, predictive analytics, optimization, and decision making. Additionally, contributions related to IoT and edge computing are approximately 20% and 30%, respectively, as they enable the interconnection of numerous devices, sensors, and systems and bring computational capacity closer to edge devices and sensors. On the other hand, 20% of the contributions are made using big data analytics for actionable insights, predictive modeling, and operational optimization. It is evident from all these statistical analyses that there is a demand for large-scale research initiatives and contributions from the private sector as well as from academic institutions in all of these industrial areas.

B. Existing Tutorials and Surveys on Industry 5.0

Several research articles on Industry 5.0 have been published in recent years, where the key goal is to boost productivity, customization, and innovation by combining new technologies with human experience while prioritizing worker safety, well-being, and skill development [23]. According to the survey [24], Industry 5.0 is a critical strategy that has the potential to reshape industries, inspire collaboration, and pave the way for a more efficient, sustainable, and successful future. Similarly, Maddikunta et al. [5] have discussed the potential uses of Industry 5.0, representing a substantial shift in how industries operate and integrate new technologies with human knowledge. However, this survey is very limited regarding architecture and enabling technologies like edge computing. On the other hand, Zeb et al. [12] have presented a study on the Intelligent NextG Wireless network. The concept aims to deliver zero waste, zero defect, and mass customization-based manufacturing solutions by combining human knowledge and creativity with intelligent, efficient, dependable cognitive cooperating robots. Chowdhury et al. [13] have discussed the possible applications and technologies for 6G connectivity and described potential hurdles and research directions to achieve 6G targets, and it will be implemented between 2027 and 2030 [25]. The main emphasis and essential contributions of the previous comprehensive surveys on Industry 5.0 are summarized in Table I.

III. Potential of Industry 5.0

Industry 5.0 has vast potential, marking a fundamental shift in our perception of the link between technology and work. It has the potential to generate creative forms of employment that are more fulfilling and meaningful. It also enhances productivity and efficiency by concentrating on human needs and capabilities. Edge computing involves the processing and analysis near the data source. This approach minimizes delays and eliminates the requirement for significant data transmission to centralized servers. It plays a crucial role in

TABLE I
COMPARISON AMONG THE EXISTING TUTORIAL AND SURVEY ON INDUSTRY 5.0

Publication	Short Summary	Survey Scope Architecture	Technologies	Applications	Edge Computing	Challenges
Maddikunta *et al.*[5]	A survey on potential application and challenges of Industry 5.0	✗	✓	✓	✗	✓
Mahmood *et al.*[12]	A comprehensive survey on connecting computational intelligence with wireless network architecture	✓	✓	✗	✗	✗
Ghobakhloo *et al.*[10]	Discussion on contributions to sustainable development by Industry 5.0	✓	✗	✗	✗	✗
Chowdhury *et al.*[13]	6G wireless communication with applications, requirements, technology challenges and research directions	✓	✓	✗	✗	✗
Ning *et al.*[14]	A short survey on metaverse, technologies application and challenges	✗	✓	✓	✗	✓
Huang *et al.*[15]	Comparison and coevolution of Industry 5.0 and Society 5.0	✗	✓	✗	✗	✗
Sukmono *et al.*[16]	Evaluation of proposed methods for preparing Industry 5.0 to deal with the crisis	✗	✗	✓	✗	✗
Hasegawa*et al.*[17]	Discussion on scope and implementation of industrial wireless standardization	✗	✓	✗	✗	✗
Sheridan *et al.*[18]	The current state of human-robot interaction and research challenges	✗	✓	✓	✗	✓
Deepa *et al.*[19]	Proposed an AI-based intelligent system for healthcare industry	✓	✗	✓	✗	✗
kopacek *et al.*[20]	Discussion on synchronisation of human and robot to make Industry 5.0 a success story	✗	✗	✓	✗	✗
Da Xu *et al.*[21]	Survey on key techniques, state-of-the-art and resource allocation of IoT	✗	✓	✗	✗	✗
Boskov *et al.*[22]	Evaluation of IoT devices using automated Zero-Touch Provision	✗	✓	✓	✗	✗
Our Survey	**A comprehensive survey on objectives and edge-enabled architecture of Industry 5.0 by incorporating edge computing**	✓	✓	✓	✓	✓

"✓" Signifies that the features are fully or partially considered in the research work.
"✗" Signifies that the features are not considered in the research work.

Industry 5.0 by enabling the implementation of AI algorithms and models at the edge, enabling real-time data processing, and lowering dependence on cloud-based computing. Moreover, it facilitates expedited response times, heightened security, and greater bandwidth optimization through localized data processing on edge devices or servers. Mattila et al. [26] have discussed an in-depth study of Industry 5.0, including its integration with IoT, AI, and big data. On the other hand, Javaid et al. [27] have discussed the use of Industry 5.0 to offer personalized therapy and patient diagnosis for Coronavirus disease (COVID). They deployed Industry 5.0 technology (such as humanoid robots, telemedicine, holography, 4-D scans, and intelligent inhalers) to combat the COVID-19 pandemic. According to a survey, ElFar et al. [28] have discussed the perspective of Industry 5.0 in algal biorefineries can customize algae creation and enable real-time algae growth monitoring, lowering operational expenses. This study Javaid and Haleem [29] demonstrates that Industry 5.0 would retain a favorable environmental impact while not damaging marine resources by properly deploying AI models.

A. Limitation of Traditional Industry: Why Industry 5.0?

Traditional industries have strict organizational structures and processes, which might limit their capacity to adjust swiftly to market changes or integrate emerging technologies, which results in limited flexibility. A lack of innovation and competitiveness is caused by traditional industries relying on tried-and-true strategies rather than adopting new ideas. Often, they require substantial capital investments in equipment and infrastructure, which may prevent new businesses from entering the market. Traditional industries can have a significant environmental impact as they rely on fossil fuels and non-renewable resources. They might have opaque supply chains or manufacturing methods, and consumers may need help understanding the sources and quality of the products they purchase. Traditional industries frequently depend on centralized decision-making procedures. Such circumstances can result in delays in addressing alterations or interruptions, constraining the system's ability to adjust. Industry 5.0 implements a system of decentralized decision making through the utilization of edge computing. Edge computing allows for rapid responses to dynamic environments, enhancing the agility and adaptability of systems. On the one hand, traditional industries encounter difficulties adjusting to evolving market requirements or unexpected disruptions due to inflexible procedures and structures.

On the other hand, Industry 5.0 prioritizes the use of flexible and responsive systems with the help of edge computing, which these goals facilitate rapid adaptation of industrial processes, allocation of resources, and decision making in response to dynamic conditions. Future industries must be functional in solving pressing societal concerns [12].

1) Circular production models, emerging enabling ICT technologies, and revision of energy consumption policies for efficient utilization of natural resources in the event of external shocks, such as the COVID-19 pandemic (resiliency).
2) Environmental and natural resource preservation and climate change (sustainability).

3) Digital hyperconnectivity and evolving digital skills for people empowerment and social stability (human-centric). Industry 5.0 vision components must realize and enable the 17 sustainable development goals (SDGs) or goals defined in the United Nations (UN) agenda 2030.

B. Evolution Matrix of Industry 5.0

The Industry 5.0 evolution matrix shows a roadmap of how the manufacturing sector will likely change over time, considering numerous technological advancements and innovations. This matrix's significance can be seen from various angles, including technological advancement, human–machine collaboration, personalization and customization, environmental impact, and other factors. It emphasizes the need for scalable solutions to support industrial processes' growth and expansion. This is especially crucial as businesses increasingly use digital technologies to optimize operations and boost productivity. The matrix emphasizes adopting technologies that scale sustainably and efficiently to enable industrial development. This includes creating technology to monitor and optimize various operations, such as manufacturing, shipping, and supply chain management. It also involves implementing technologies that allow industrial equipment to be monitored and controlled remotely, increasing efficiency and flexibility. Industry 5.0 will integrate sophisticated technologies, such as AI, robotics, and IoT to develop more collaborative and sustainable work environments that use human and machine strengths. We should expect to see the rise of cutting-edge technology and novel methods of industrial development that value both people's and the environment's well-being. Furthermore, Fig. 6 shows an overview of the evolution of Industry 5.0.

C. Key Feature of Edge Computing in Industry 5.0

Industry 5.0 is a manufacturing vision for the future that builds on earlier industrial revolutions while embracing modern technologies and human-centric techniques to produce a more sustainable, efficient, and flexible manufacturing ecosystem [5]. Among the primary elements of Industry 5.0 are as follows.

1) *Human–Machine Collaboration:* Rather than replacing humans with automation, Industry 5.0 emphasizes the necessity of synergy between humans and machines. This strategy recognizes human worker's unique skills to think creatively, solve issues, and judge while harnessing machine speed and precision. Edge computing provides various advantages, such as decreased bandwidth consumption, improved data privacy and security, offline functionality, and quicker response times. This enables immediate decision making and empowers edge devices to react promptly to critical events, reducing latency and enhancing operational efficiency.
2) *Advanced Technologies:* Industry 5.0 enables real-time monitoring, analysis, and optimization of production processes by utilizing cutting-edge technologies like ML, AI, robotics, edge computing, and the IoT. Maintenance prediction, quality control, and supply chain management are also possible with these technologies.

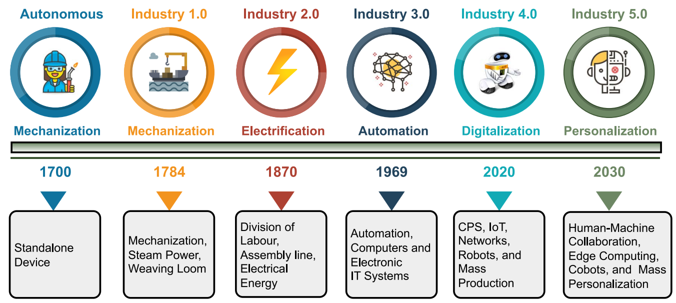

Fig. 6. Illustration of industrial revolutions and considered technologies.

3) *Sustainability:* Industry 5.0 emphasizes the importance of environmental effects and sustainability in manufacturing. This involves using renewable energy sources, reducing waste, and developing sustainable materials and goods. Edge computing improves sustainability by decreasing data transport and promoting immediate decision making, optimizing resource utilization, and minimizing environmental consequences.
4) *Cybersecurity and Data Privacy:* Industry 5.0 recognizes the need for cybersecurity and data privacy in manufacturing, particularly as more industrial processes become Internet-connected. Such measures include secure data transfer, encryption, and access control. Incorporating edge computing strengthens cybersecurity by locally processing sensitive data, minimizing vulnerability to centralized attacks, and improving data privacy through distributed storage, minimizing the dangers associated with large-scale data breaches.
5) *Customization and Personalization:* Industry 5.0 enables widespread product customization through digital design tools, flexible manufacturing processes, and enhanced supply chain management systems. This allows the mass creation of highly personalized products while maintaining efficiency and quality. Moreover, by providing up-to-date information and personalized interactions, edge computing improves the ability to customize and offer products or services, increasing user satisfaction and operational efficiency.

D. Initiatives and Current Market Study

The manufacturing industry had a modest growth rate of roughly 3.9% in 2022[1] compared to the output growth rate of 9.4% in 2021. Manufacturers have recognized that implementing changes to their digital strategy can enable them to recover and return to their growth rate before the epidemic. Consequently, manufacturers are increasingly adopting edge computing as a strategic move to enhance their overall efficiency and succeed in a highly competitive environment during the post-pandemic change. Edge computing is a decentralized

[1] https://www.controleng.com/articles/global-manufacturing-output-growth-at-3-9-in-2022/

information technology platform that enables the manipulation and retention of data near its source. Based on a recent market analysis conducted by IDC, the worldwide expenditure on edge computing was projected to reach U.S. $176 billion in 2022, indicating a significant increase of approximately 14.8% compared to 2021.[2]

Several countries contribute significantly to the development and implementation of Industry 5.0 [30]. These countries are investing in advanced technologies, infrastructure, research and development, and regulatory frameworks to support the growth of Industry 5.0. Japan has a long history of manufacturing, industrial development, and innovation. The country is home to some of the world's leading industrial robots and automation technology manufacturers. The Japanese government has actively promoted the development of smart factories and lights-out production systems, which rely primarily on digital technologies and automation to optimize manufacturing processes. As part of its overall strategy to become a global leader in advanced manufacturing and digital technologies, China has made significant investments in building Industry 5.0. The Chinese government has established various initiatives to encourage digital technologies in manufacturing, including the *Made in China 2025* plan, which aims to upgrade China's manufacturing industry by applying modern technology, such as robots, AI, and the IoT.[3] The United States (U.S.) has been actively promoting the development of Industry 5.0 and launched various initiatives to support adopting digital technologies in manufacturing, including the "Advanced Manufacturing Partnership" and the "National Network for Manufacturing Innovation."

Industry 5.0 is more comprehensive than just government initiatives or country-level developments. In addition, many industries invest heavily in developing and implementing Industry 5.0 technologies. As per Grand View Research, the global Industry 5.0 market was estimated at U.S. $95.4 billion in 2020 and is predicted to rise by 23.6% at a compound annual growth rate (CAGR) from 2021 to 2028.[4] Siemens invested over EUR 10 billion in research and development in 2020, with a significant portion of that investment going toward Industry 5.0 technologies.[5] ABB spent over U.S. $1.4 billion in research and development in 2020, focusing on developing automation and digital technologies for Industry 5.0. Intel has invested heavily in developing new microprocessors and other digital technologies that can power Industry 5.0 applications. In 2020, the company devoted over U.S. $13.6 billion to research and development.[6] According to a report by Statista, global spending on Industry 5.0 technologies is expected to reach U.S. $42.4 billion in 2021, up from U.S. $34.9 billion in 2020. In 2021, the manufacturing sector in Germany contributed 26.6% of gross value added. In comparison, France had 16.8%, the United States had 18.4%, and Japan had 29%.[7] The report notes that the Asia–Pacific region is the largest market for Industry 5.0 technologies, with China and Japan being the most prominent investors. The European Union (EU) recently announced a EUR 8 billion investment in developing Industry 5.0 technologies as part of its Horizon Europe research and innovation program.[8] The funding will mount the development of advanced manufacturing technologies, such as AI, robotics, and IoT, focusing on creating more sustainable and resilient manufacturing processes. These investment reports demonstrate that the Industry 5.0 market is rapidly growing, with companies and governments investing heavily in developing advanced manufacturing technologies worldwide.[9]

TABLE II
EDGE COMPUTING IN INDUSTRY 4.0 AND INDUSTRY 5.0

Edge-based Parameters	In Industry 4.0	In Industry 5.0
Customization	Low	High
Latency Concern	Moderate	High
Interconnectivity	Moderate	High
Security Concern	Moderate	High
Decision-Making	Low	High
Processing Power	Moderate	High
Sustainability	Low	High

E. How Edge Computing Works in Industry 5.0?

In Industry 5.0, edge computing has advanced to facilitate the implementation of AI algorithms and models at the edge. This allows for immediate data processing and decreases the need for cloud-based computing. This signifies a notable progression beyond prior industrial benchmarks, such as Industry 4.0 [31]. In Industry 4.0, edge computing was employed, but its significance was less prominent than in Industry 5.0. The emphasis was primarily on incorporating tangible resources with cutting-edge technology, such as IoT, cloud computing, and big data analytics. In Industry 5.0, edge computing goes beyond decentralizing decision-making processes, allowing for real-time decision making, improving data privacy and security, and offering offline capabilities. The increasing adoption of edge computing in Industry 5.0 is motivated by the necessity for quicker response times, decreased latency, higher operational efficiency, and heightened security. These factors are crucial for the human-centric and highly interconnected nature of Industry 5.0 systems. Table II summarizes the evolution of edge computing in Industry 5.0 [32].

F. Difference Between Industry 5.0 and Other Revolutions

The phrase *Industry 5.0* was recently coined to define the latest stage in the growth of industrial technology. It

[2]https://www.idc.com/

[3]https://cacm.acm.org/magazines/2021/11/256386-innovations-and-trends-in-chinas-digital-economy/abstract

[4]https://www.grandviewresearch.com/industry-analysis/global-telecom-services-market

[5]https://assets.new.siemens.com/siemens/assets/api/uuid:45446098-6c39-45ba-a5fc-e5f27ebfa875/siemens-ar2020.pdf

[6]https://www.statista.com/chart/27214/companies-that-spent-the-most-on-research-and-development-in-2020/

[7]https://www.deutschland.de/en/topic/business/germanys-industry-the-most-important-facts-and-figures

[8]https://www.ecb.europa.eu/pub/financial-stability/macroprudential-bulletin/focus/2021/html/ecb.mpbufocus2021103.en.html

[9]https://www.statista.com/statistics/320776/contribution-of-indian-it-industry-to-india-s-gdp/

TABLE III
COMPARISON AMONG DIFFERENT INDUSTRIAL REVOLUTIONS

Parameters	Industry 1.0	Industry 2.0	Industry 3.0	Industry 4.0	Industry 5.0
Time Period	Late 18th to early 19th centuries	Late 19th century to early 20th century	Late 20th century to early 21st century	Early 21st century to present day	Future (Not yet established)
Key Technologies	Steam engine, Mechanization	Mass production & Assembly line	Automation, Digitization & Computers	IoT, AI, and Big Data	AI, Nanotechnology, and Renewable Energy
Production Focus	Automation of manufacturing processes	Standardized mass-production of goods	Personalization of commodities on a large scale	Manufacturing that is smart and linked	Production that is both sustainable and ethical
Human Role	Machine operators & labourers	Operators & assemblers can work	Employees who are problem solvers and innovators	Advanced AI, Replacing human	Collaboration between humans and machine
Communication	Telegraph, Telephone	Radio, & Television	Internet, Mobile Devices, Social Media	IIoT, Real-time data sharing and analysis	Intelligent communication and collaboration
Manufacturing scale	Large factories and Mills	Large factories and Assembly lines	Decentralized production, flexible manufacturing	Smart factories, DT, 3D printing	Distributed manufacturing and production networks
Production speed	Standardized production speed	High-speed production	Real-time production and delivery	Flexible and adaptive production processes	On-demand production and delivery
Supply Chain	Local supply chains	Linear supply chains	Networked supply chain with real-time monitoring	Agile and responsive supply chains	Decentralized and autonomous supply chains
Key Industry	Textile, Iron and Steel, mining	Automotive, Steel, & Chemicals	Electronics, IT, Biotechnology	Industry 4.0 technologies across industries	Industries across sectors

began in the late 18th century with the introduction of mechanical power and resulted in significant changes in how we work and live. There have been multiple versions of the industrial revolution, each with technological advances and manufacturing process alterations. In the first industrial revolution, mechanical power was introduced, and the replacement of physical labor characterized this age. The manufacturing process became more standardized to boost efficiency, and assembly lines were implemented in Industry 2.0. The third industrial revolution, often known as Industry 3.0, began in the mid-20th century and lasted until the late 20th century. The current era is Industry 4.0, often called the fourth industrial revolution. It began in the early 21st century and is distinguished by incorporating digital technologies into production. Intelligent factories are highly automated and linked in this era.

Industry 5.0 is the ongoing development of the fourth industrial revolution. It is distinguished by incorporating both humans and machines into the manufacturing process. This epoch is dedicated to developing a more human-centered approach to manufacturing, in which machines and humans collaborate to manufacture items. This technique tries to blend mechanical efficiency and precision with human creativity and problem-solving abilities. Industry 5.0 strives to make production more sustainable and socially responsible, minimize waste and resource consumption, and can be reused, recycled, or repurposed at the end of their lifecycle. The main key differences are summarized in Table III.

IV. INDUSTRY 5.0 OBJECTIVES

Industry 5.0 emphasizes resilience, sustainability, and human-centricity. These characteristics are desirable and vital for the industry to remain relevant, competitive, and future-ready. That future may be nearer than many believe; in some ways, it may already be here. The digital revolution is well underway and shows no signs of abating. There have been enduring problems in many industries regarding finding new staff with the right skills and maintaining in-house skills. Companies must invest in technologies and employees to benefit from their relative capabilities. More robust collaboration is required between businesses on the one hand and education and training institutions on the other, as companies are well placed to identify skill gaps and foresee future skill needs [23]. Industry 5.0 achieves productivity and human-centered outcomes using cobots, AR/VR, and flexible manufacturing systems while prioritizing safety and working conditions.

Likewise, the industry can contribute to societal resilience by being robust, ensuring output is maintained and workers can continue working. It allows people empowerment (i.e., digital society and workforce) in conjunction with mass-customization goals in optimized supply chains, e.g., adaptability and scalable product varieties, resulting in positive impacts and benefits for various fields of society and bringing about the next industrial revolution. To enhance sustainability by establishing a more efficient and ecologically friendly manufacturing environment. To reduce waste and improve resource efficiency by embracing green technologies and sustainable practices. Therefore it is essential to discuss the objectives of Industry 5.0. Based on the existing literature, we can categorize the objectives of Industry 5.0 into three categories. These three fundamental objectives are resilience, sustainability, and human-centricity. The core values of Industry 5.0, as pictorially explained in Fig. 7.

A. Resilience

Resilience refers to the requirement to achieve a higher level of robustness in industrial production, equipping it better against disruptions and ensuring it can deliver and sustain critical infrastructure in times of crisis. System failures, cyber attacks, and supply chain disruptions make the manufacturing system more sensitive to disturbances. Hence, organizations must design resilience into their production systems to mitigate the impact of these interruptions and recover swiftly. Moreover, incorporating edge computing ensures that processing is distributed rather than centralized by processing

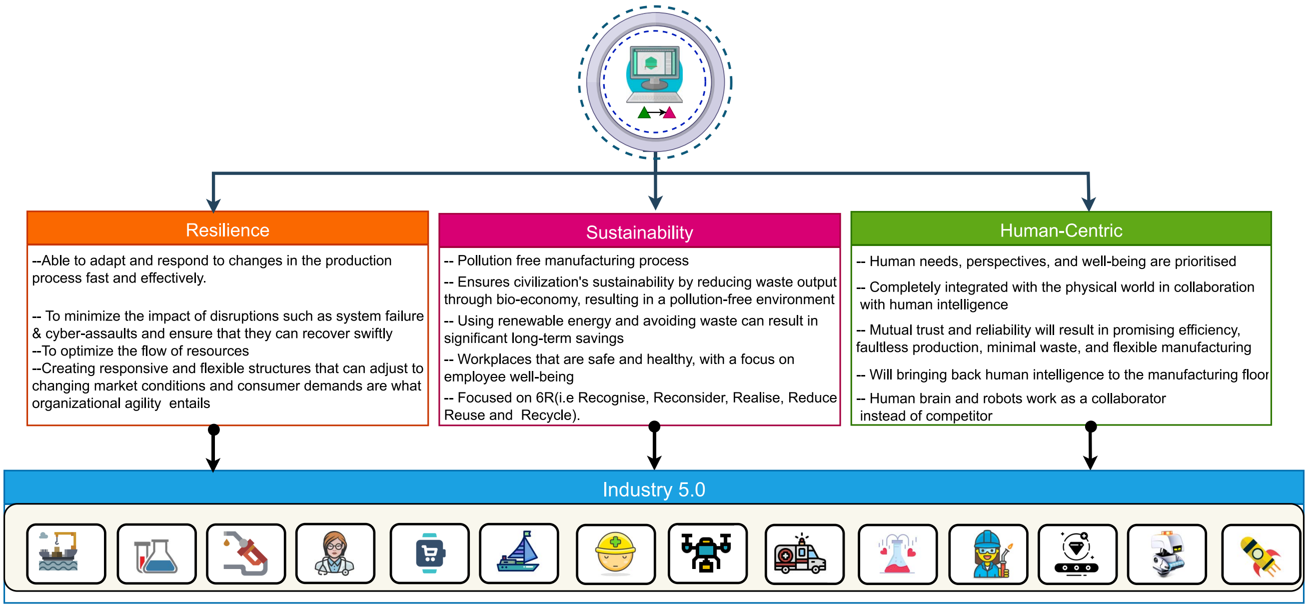

Fig. 7. Industry 5.0 objectives and their functionalities.

data at the network's edge. By doing this, data processing is continued, even if one or more nodes fail. Conversely, sensitive data is kept closer to the user, reducing the risk of data breaches. On the other hand, AI systems can analyze massive volumes of data from numerous sources to discover potential dangers and vulnerabilities in industrial operations. It helps assess and predict risks by recognizing patterns and correlations, enabling proactive risk management solutions to limit interruptions and assure business continuity. To implement resilience in Industry 5.0, organizations use various models and frameworks. One such model is the resilience engineering (RE) model, which provides a holistic approach to resilience and focuses on the interaction of humans, technology, and the environment. This model comprises four main components, such as anticipation, monitoring, response, and learning. Anticipation involves determining potential risks and preparing the organization to tackle them. The organization uses various tools, such as risk assessments, scenario planning, and simulation exercises to anticipate potential disruptions. Similarly, continuous monitoring of the system for changes and potential disruptions. Organizations can use various tools for monitoring, such as sensors, AI algorithms, and data analytics, to detect changes and potential disruptions. Organizations can learn from previous events and improve their resilience by implementing post-incident analyses, feedback loops, and continuous improvement processes. Therefore, by implementing these technical tools and approaches within the RE model, organizations can build a resilient system that adapts and responds to disruptions in Industry 5.0 [5].

B. Sustainability

In Industry 5.0, sustainability refers to the ability of the production system to meet current demands without jeopardizing the ability of future generations to meet their own needs. This requires optimizing the use of resources, such as energy, water, and raw materials to reduce waste and lessen the environmental effect of manufacturing operations [33], resulting in an emphasis on circular economy practices and resource-efficient design. Furthermore, AI can monitor and assess environmental conditions by analyzing data from sensors, satellites, and other sources. Industry 5.0 is the first industrial revolution led by humans based on the 6R (i.e., reduce, realize, reuse, recycle, reconsider, and recognize). It must establish circular methods for reusing, repurposing, and recycling natural resources, reducing waste and environmental impact, ultimately leading to a circular economy with improved resource efficiency and effectiveness. Incorporating edge computing contributes to sustainability by decreasing the need for large-scale data transfers to centralized data centers. Edge devices analyze and filter data locally, communicating only the essential insights rather than sending vast amounts of data across long distances. This method reduces network congestion, energy usage, and the carbon footprint associated with data transmission.

There are many practical scenarios where sustainability has been implemented successfully. Some manufacturers have switched to renewable energy sources, such as solar and wind power for long-term development. Others have used closed-loop manufacturing systems to recycle waste materials into the manufacturing process, decreasing waste and conserving resources. Sustainable agriculture brings about resource conservation, environmental protection, and community support. Crop rotation, natural pest management, water conservation, and the usage of organic and locally sourced produce can all contribute to this. Others use conservation tillage practices, such as no-till farming to limit soil erosion and water use. Several buildings now feature green roofs and rainwater collection systems to reduce water consumption. Passive heating and cooling techniques, such as natural ventilation and shading, are also used in some facilities to reduce energy use. By adopting sustainable practices, industries reduce their environmental impact, conserve resources, and improve their bottom line.

C. Human-Centric

Human centricity refers to developing products, services, and systems focusing on human needs and capabilities. This approach recognizes that humans are the ultimate consumers of technology, and their requirements and preferences should be considered during the design process [34]. AI algorithms detect possible hazards, identify safety problems, and issue timely alerts or interventions. This proactive approach to safety decreases the likelihood of accidents and prioritizes worker's physical and mental well-being. On the other hand, incorporating edge computing enables real-time interactions and personalized experiences in human-centric applications. The delay between data collection and action considerably decreases when edge devices execute data processing and analysis at the network edge. This near-instant response time improves user experiences in various disciplines, including smart homes, cities, and healthcare. For instance, in smart homes, edge devices may swiftly analyze sensor data to modify ambient settings, giving inhabitants personalized comfort.

HRC has been popular in the previous decade for improving the working conditions and reproducible quality of manual task [34]. One futuristic perspective is expedited by an augmented robot, cognitive system, mixed reality, and co-intelligence by four enhanced human abilities (EHAs) to energize, advise, support, and empower (EASE) a human operator physically and intellectually. With the thoughts-driven assistance of brain robotics and sensing-enabled context awareness, the super operator implements their knowledge to carry out a human-centric assembly task best [35].

1) *Augmented Robot:* Due to fatigue, the human body has low and unsustainable muscle power over time. In contrast, weak muscles can be electrified by using an augmented robot, for instance, the exoskeleton with active and passive actuation. As a result, a human operator helped by an exoskeleton can execute long-term tasks beyond physical limits while maintaining continuous work precision and quality.
2) *Cognitive System:* Humans are generally capable of high levels of cognitive ability when given enough time. However, this skill is frequently constrained by tight boundary conditions (e.g., time constraints) and hindered by the lack of a holistic context view. To improve this skill, the operator can benefit from the assistance of a different cognitive system, such as an intelligent multiagent system, which will provide advice on making the best global decision possible.
3) *Mixed Reality:* Humans rely on direct senses to comprehend their surroundings but with fading memories of the past and decreasingly reliable future predictions. A mixed reality technology or a digital twin can help alleviate this incapacity. As a result, people will be able to see what is currently invisible as well as what may happen in the future, making it possible to avoid making bad decisions.
4) *Co-Intelligence:* Collaborative intelligence is built on the primitives of humans-assisting-robots (train, explain, and maintain) and robots-assisting-humans (amplify, interact, and embody). People must use their competencies to teach robots how to perform and explain how decisions are made to sustain. Robots must assist humans in self-adapting to interact with labor to their full (artificial and anthropological) potential.

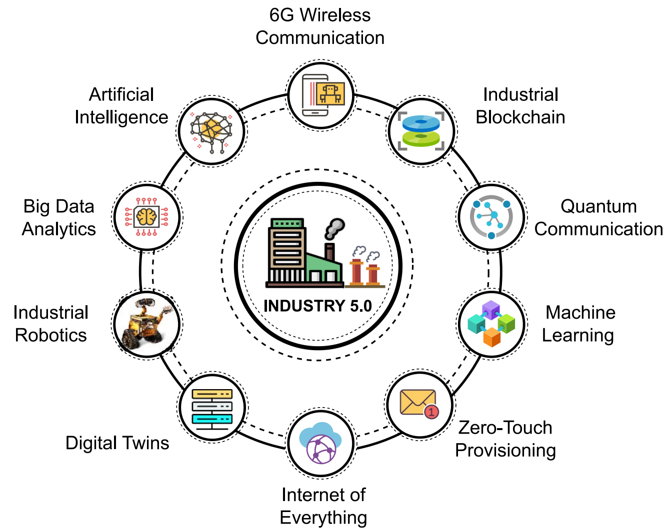

Fig. 8. Cutting-edge technologies powering Industry 5.0.

V. Industry 5.0 Technologies

Industry 5.0 technologies are crucial to the advancement and success of modern manufacturing. Advanced sensors and data analytics can assist manufacturers with real-time monitoring of manufacturing processes, allowing them to detect and correct quality issues. It helps to reduce waste and flaws and improve the overall quality of products. As illustrated in Fig. 8, various Industry 5.0 enabling technologies, such as DT, IoE, 6G, cobots, blockchain, and big data analytics, are consolidated with thought processes and creativity. These trends help industries to deliver customized products and increase productivity more rapidly. Industry 5.0 is a concept of energy sharing and peer-to-peer energy exchanges [5]. In this paradigm, industries use edge computing technology to build decentralized energy networks that exchange excess energy securely and transparently with other organizations. By engaging in energy-sharing networks, industries optimize energy usage, cut energy costs, and create a more sustainable and resilient energy ecosystem. It enables industries to interact and trade energy resources, resulting in efficient utilization and waste reduction. Industry 5.0 revolutionizes how energy is consumed, managed, and allocated by adopting energy sharing and peer-to-peer transactions, ultimately promoting economic growth while lowering total energy costs and environmental impact.

A. 6G Wireless Communications

Wireless communication is becoming increasingly vital as we shift toward a more human-centered approach to manufacturing. This is where 6G wireless connection comes in, with faster speeds, lower latency, and more reliability than previous generations. 6G can provide Industry 5.0 with multiple value-added services. For instance, it can offer better security features, such as network slicing, increasing network security, and customization while lowering cyber-assault risk. This is especially significant in Industry 5.0, where combining new technologies with traditional industrial processes might increase the danger of cyber assaults [13]. Its ability to transmit data at extremely high speeds. According to current research, 6G networks could provide data transfer rates up to 1 TB/s, significantly faster than the current maximum speed of 5G networks, around 20 GB/s. This increase in data transfer rates will enable new applications, such as real-time high-definition video streaming, VR experiences, and cloud gaming.

6G wireless communication is predicted to be more reliable. This dependability is achieved through advanced technologies, such as massive multiple-input–multiple-output (MIMO), which allows multiple antennas to send and receive data simultaneously, and beamforming, which allows specific devices or areas to be targeted with a focused signal. These technologies will allow 6G networks to provide improved coverage, especially in locations with high user density or environmental interference. Incorporating edge computing with 6G wireless communication has the potential to enable new applications and use cases in Industry 5.0. For example, in smart cities, edge computing could enable real-time monitoring and analysis of traffic patterns, air quality, and energy consumption, leading to more efficient use of resources and improved quality of life for citizens.

B. Industrial Blockchain

Industrial blockchain is significant in Industry 5.0, particularly with edge computing. In Industry 5.0, centralized control of many heterogeneous linked devices is a crucial challenge. By enabling distributed trust, blockchain can construct decentralized and distributed management platforms [36]. It has been shown that peer-to-peer communication using blockchain technology provides a permanent record-keeping system. Additionally, the immutable ledger promotes operational accountability and transparency for critical events in Industry 5.0 applications. Industrial blockchain technology creates a safe and transparent platform for collaboration and communication among producers, suppliers, and customers. This leads to better relationships and decision making. Smart contracts will be used in future Industry 5.0 apps to ensure security through authentication and automated service-oriented processes. On the one hand, industries will benefit from securing their data and privacy by incorporating edge networks. On the other hand, this cooperation enhances the distributed computing functionalities of the industrial environment, making the industrial environment resilient. Moreover, network access may be limited or unreliable in certain industrial situations. Therefore, incorporating edge computing allows edge devices to operate offline while synchronizing data with the central blockchain network when the connection is restored. This guarantees continuous operation and data integrity.

C. Quantum Communication

Quantum communication networks are groups of nodes linked via quantum communication channels. These networks are built with specialized hardware, such as single-photon sources, detectors, and quantum memory. The network's nodes are placed in data centers or at the network's edge. Quantum communication networks must integrate edge computing with sensors and mobile devices. This involves developing inter faces and protocols that enable edge devices to communicate securely with quantum communication networks. Quantum key distribution (QKD) helps to establish a shared key between two nodes in a secure manner. QKD is a revolutionary key distribution algorithm that uses quantum physics laws to distribute random secret keys between two users even when an eavesdropper is present. QKD is built around the principles of the no-cloning theorem and Heisenberg's uncertainty principle [37]. QKD involves sending single photons via a quantum channel. Any effort to measure or intercept these photons disturbs their quantum state, allowing the transmitter and receiver to detect the existence of an eavesdropper. Messages are encrypted and decrypted using a shared key. Edge computing applications that take advantage of quantum communication's secure and efficient data transport can be built. For instance, ML algorithms run on edge devices using data safely sent across the quantum communication network.

D. Machine Learning

Industry 5.0's primary accelerators include ML. Real-time data collecting and computation tasks are split between edge servers and devices for effective online ML training. Sending entire device data sets back to the cloud servers is too expensive and poses privacy issues. Integrating online ML training directly with edge or wireless devices, such as mobile phones, sensor networks, smart transportation, IIoT, etc., has received much attention in recent years. Edge learning framework, fog learning, and federated learning on vehicular nodes are just a few of the ML methods specifically developed for edge computing architectures by academia and industry [60]. Moreover, adopting and integrating ML algorithms is another emerging trend in industrial applications. These applications use ML algorithms for various purposes, for instance, decision making in ambient intelligence and smart environments, pattern recognition in objects and scene understanding in AR, face recognition for real-time identity verification, behavior prediction in mobile gaming and autonomous vehicles, and viewport prediction for video streaming.

E. Zero-Touch Provisioning Standard

As the number of IoT devices grows, the difficulties of quickly installing them, configuring them for the first time, and getting them to work have become more imperative. In next-generation IoT networks, manually setting up many different types of devices can slow things down and lead to mistakes and breakdowns. ZTP created a solution to these problems. It allows a wide range of devices to be set up automatically and without human intervention. The zero-touch network and service provisioning (ZNSP) standard, published by ETSI in 2019, aims to automate all manufacturing processes. It is still challenging to achieve zero-touch technology, even in Industry 5.0. The self-serving, self-fulfilling, and self-assuring nature of zero-touch services makes it a promising standard.

It is important to realize that achieving full automation, especially using self-learning features, brings new problems like collaborative intelligence, 5G network slicing, data protection, insufficient workforce training, customization, and more. Furthermore, ZNSP wants to fully automate production, while Industry 5.0 wants to include humans in the production process, making it difficult to understand the future of production. Key attributes of a ZTP approach include user-friendly usability, enabling provisioning by individuals without technical knowledge; interoperability, ensuring compatibility across different vendors and systems; robust security measures to safeguard the integrity of credentials during the provisioning process; ease of implementation, requiring minimal additional equipment or complex infrastructure; and scalability, allowing the network to seamlessly adapt to changes, such as the inclusion of new devices or the expansion of capacity [22].

F. Internet of Everything

IoE is a network that connects people, processes, information, and things [21]. It brings various functions like a better user experience and anticipated advantages for sectors and countries. It increases customer satisfaction and loyalty and creates customized experiences using data supplied by IoE [61]. It enables the real-time collection of enormous amounts of data from various sources, such as consumer feedback, social media, and device usage trends. ML algorithms help to analyze this data and uncover patterns and trends to improve consumer experiences. For example, an IoE-enabled intelligent home system can analyze user behavior and preferences to recommend personalized products and services. By removing congestion from communication lines and lowering latency, Industry 5.0's use of IoE offers the chance to cut operating costs. As time has passed, humans have shared information wirelessly, primarily with wireless sensors. For instance, the medical field connects sensors to the patient. These sensors identify patient irregularities and send information to the doctor or nurse. Based on the findings, doctors will take proper action. Indeed, incorporating edge computing into IoE involves deploying edge devices, such as gateways or edge servers, to process data locally. These edge devices are outfitted with sensors and processing power, such as graphics processing units (GPUs), for real-time data processing and analysis.

G. Digital Twin

A DT is a digital replication of a physical system or object. It helps to represent wind farms, industries, jet engines, buildings, and even larger systems such as smart cities digitally [62]. Although the notion of DT was proposed in 2002, it has only recently become a reality because of the growth of IoT. IoT reduced the cost of DT, making it more accessible and economical to a wide range of sectors. Data from physical things are transmitted to their digital counterparts for simulation via IoT devices. This digital mapping of real-time objects/systems via DT allows for monitoring, analysis, and prevention of issues before they occur in the real world. Due to the rapidly growing use of cutting-edge technologies, DT has decreased maintenance costs and increased system performance. This is done using software that simulates the behavior of the equipment or system. The model should capture all the parameters and variables affecting the equipment or system's performance. Afterward, connect DT to an edge computing system to process the data in real time. This is done using various connectivity options like Wi-Fi, Ethernet, or Bluetooth. The data is collected from a physical object or system via sensors. As the data from the physical equipment or systems are collected, they are sent to the edge computing system for analysis with the help of ML algorithms.

H. Industrial Robotics

Industrial robotics refers to using advanced robotic systems in manufacturing and industrial processes. In just a few decades, robots completely transformed the industrial environment. The concept of designing and building creatures or equipment that might perform repetitive or heavy duties, thus freeing men of this burden, reaches back to ancient times. They are normally made up of a controller, a power supply, a manipulator, and an end effector. They are programmed with sophisticated software that allows them to do a wide range of tasks with high precision and accuracy [63]. They are outfitted with a range of sensors, such as cameras, lasers, and proximity sensors, which allow them to detect and respond to changes in their surroundings. They can also be programmed with complex algorithms for collision avoidance, path planning, and other critical functions. With the tremendous and rapid advances in AI technology, it is evident that all gadgets with computational capabilities have become more intelligent. Collaboration between humans and robots helps make human capabilities more efficient and straightforward [64].

I. Big Data Analytics

The industrial environment has undergone a phenomenal change due to the rapid development of information and communication technology. The introduction of cutting-edge technology leads to changes in the manufacturing processes that transform manual production methods into machine-driven ones. This manufacturing process automation brought on the Industrial Revolution. The massive amount of data (big data) has been generated as a result of the development of the social Web, and its effective use has helped to shape the fifth industrial revolution [65]. Big data analytics is essential in developing an intelligent and sustainable industry. Big data analytics makes real-time analysis possible through sophisticated algorithms, delivering actionable insights to enhance product quality, reduce downtime, and optimize manufacturing processes. It also helps with predictive maintenance, enabling proactive servicing of equipment prior to breakdowns. A brief discussion on enabling technologies for Industry 5.0 is presented in Table IV.

VI. Edge-Enabled Industry 5.0 Architecture

An edge-enabled architecture provides an efficient computing environment and control near the network's edge to address scalability and latency challenges. It will divide

TABLE IV
ENABLING TECHNOLOGIES, EXISTING CONTRIBUTIONS, AND CORRESPONDING INITIATIVES TOWARD INDUSTRY 5.0 REVOLUTION

Enabling Technologies	Ref	Short Summary	Research Challenges				
			Energy	Latency	Cost	Reliability	Customzation
6G Wireless Communication	[13]	Discussed the goal of 6G wireless communication	✓	✓	✗	✗	✓
	[38]	Discussed vision and future strategies of 6G	✗	✓	✗	✓	✗
	[39]	To attain sustainability through the use of digital tools	✗	✗	✓	✓	✗
Industrial Blockchain	[40]	Demonstrated the benefits of industrial blockchain	✓	✗	✗	✓	✓
	[41]	Blockchain applicability in IIoT-specific industries	✗	✗	✗	✓	✓
	[42]	Discussion on architecture of the industrial blockchain	✗	✓	✗	✓	✓
Quantum Communication	[43]	Presented development of quantum communication	✗	✓	✓	✓	✗
	[44]	The implementation of cryptographic beyond QKD	✓	✓	✗	✓	✗
	[42]	Understood data in encoded form in quantum systems	✗	✗	✓	✓	✗
Machine Learning	[45]	Securing, predicting, and improving supply chain	✗	✗	✓	✓	✓
	[46]	Monitoring and diagnosis fault of industrial machines	✗	✓	✗	✓	✓
	[39]	To attain sustainability through the use of digital tools	✗	✗	✓	✓	✗
Zero Touch Provision	[47]	Discussed zero touch framework usability	✓	✓	✓	✓	✗
	[48]	Purposed current state-of-the-art of ZTP	✓	✓	✗	✓	✓
	[48]	Incorporate ZTP into heterogeneous devices	✗	✓	✓	✓	✗
Internet of Everything	[49]	An Analysis of the Internet of Everything	✗	✗	✓	✗	✓
	[50]	Secure solution for dynamic environments	✓	✓	✗	✓	✗
	[51]	Designed a scheduling model in the IoE	✓	✓	✗	✗	✓
Digital Twins	[52]	Discussion on present state-of-the-art of DT	✗	✓	✗	✓	✗
	[53]	Proposed a multi-dimensional taxonomy of a DT	✗	✓	✗	✓	✓
	[54]	Discussed improvement of manufacturing processes	✗	✓	✗	✓	✗
Industrial Robotics	[55]	Task performed by robot in manufacturing process	✗	✓	✗	✓	✓
	[55]	Human-robot interaction for future industrial robotics	✓	✗	✗	✓	✓
	[56]	Programming method for industrial robotics	✓	✗	✓	✓	✗
Big Data Analytics	[57]	Focussed optimization of data by edge computing	✓	✓	✗	✓	✓
	[58]	Integrate AI and Edge computing for Industry 5.0	✓	✓	✓	✓	✓
	[59]	Discussed development of Edge-AI enabled IoT system	✓	✓	✓	✓	✓

"✓" Signifies that the features are fully or partially considered in the research work.
"✗" Signifies that the features are not considered in the research work.

complex computational processes into small components and execute them on local edge devices/nodes rather than dumping large amounts of data and workloads to a remote cloud data center. Edge devices/nodes can be any computing, storage, and network connectivity device at the Internet's outskirts. Sensors, surveillance cameras, and cellphones (e.g., routers, access points (APs), and base stations) are not only data producers but also communication gateways. This architecture's significant focus is offloading computational processes near the data source on devices that create data or neighboring gateways. As a result, data transmission over the Internet would be eliminated, saving bandwidth and lowering Internet traffic. Without large-scale communication costs, edge computing-based applications enable edge nodes/devices to react locally and significantly reduce system latency [66].

Hence, edge-enabled architecture is ideal for time-sensitive applications requiring complex data processing/algorithms to produce actionable and immediate results based on resource-constrained device readings. For instance, smart factory monitoring and control where various devices and sensors are positioned throughout the production line to monitor performance, detect anomalies, and optimize production. Therefore, a three-tiered architecture is required for Industry 5.0, in which devices are grouped into layers based on their function [67]. A flow of offloaded tasks appears on the top of this architecture, as some lower capacity devices send tasks to more powerful devices for processing. We define a task as an inseparable computation generated by a particular application, with its characteristics and constraints, such as maximum latency, data size, and computational resources needed. The architecture consists of three layers. Industrial sensors/actuators are located in the first layer, usually at the edge. The second layer is the near-edge computing (NEC) layer, widely known as the fog layer, and the third layer is the cloud execution layer (CEL) [7]. The architectural depiction of edge-enabled in Industry 5.0 is illustrated in Fig. 9.

A. Industrial Sensors/Actuators Layer

The industrial sensors/actuators layer (ISAL) is a fundamental component of an edge-enabled industrial architecture. This layer is closest to the user, consisting of heterogeneous edge devices with a recurrent connection and dynamic position. This layer has minimal latency and computational capacity and generates tasks from edge devices that host IoT applications. Depending on the offloading algorithm, a task can be processed locally or sent to IoT devices in any of the three layers. Wired and wireless connections are used to connect the layers together. Using wireless access technologies, such as 3G, 4G, Wi-Fi, wireless local area networks (WLAN), ZigBee,

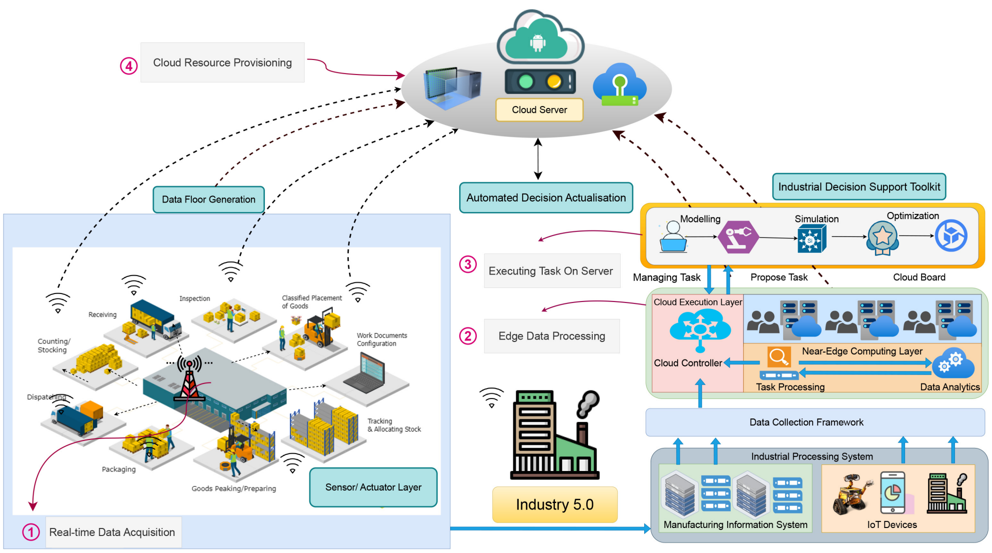

Fig. 9. Edge-enabled Industry 5.0 architecture.

Bluetooth, etc., and cable connections, each end device or smart object is connected to one of the fog nodes in this architecture.

The CEL and the NEC layer are connected via cable. In contrast, radio links connect the edge layer to the NEC layer and other edge devices. Each connection between levels has a maximum bandwidth. In the edge layer, each IoT device executes an offloading algorithm that decides, using the local information of the device, where it offloads the tasks it generates [68]. This layer consists of IoT-enabled devices, such as sensor nodes, end users' smart hand-held devices (e.g., smart cards, smartphones, tablets, autonomous vehicles, and smart watches), and many more. These end devices are known as terminal nodes. Fig. 9 shows the proposed Edge-enabled in Industry 5.0 architecture, where sensors measure physical quantities, such as temperature, pressure, humidity, and vibration. AI algorithms can provide a holistic perspective of the system by combining input from numerous sensors, enabling better decision making and more precise control operations.

In this layer, various sensors are deployed throughout the production environment to collect real-time data about equipment, machines, and other operational parameters. These sensors are embedded in machinery to monitor critical points in the production process. On the other hand, actuators are devices that allow physical systems to be controlled based on input received from sensors or decision-making algorithms. Decisions and analyses are made at the edge, and actuators act accordingly. These actions include adjusting machine settings, initiating maintenance chores, triggering safety processes, or managing material flow. Sensors collect data from surrounding environments and transmit it to IoT devices. Edge devices act as an intermediate between sensors and the higher level system, processing and analyzing the data collected from the sensors. Moreover, actuators can control and automate various processes based on analysis and decisions made at the edge.

B. Near-Edge Computing Layer

The NEC layer is another critical component of an Edge-enabled industrial architecture. This layer is also termed a fog computing layer. The middle layer is where fog servers are deployed. Fog servers are small data centers with intermediate processing capability between edge devices and the cloud, resulting in medium latency as shown in Fig. 9. This layer comprises network devices, such as a router, gateway, switch, and APs. These devices can be interconnected and intercommunicated by wired or wireless communication technologies. This architecture widely distributes fog nodes between the end devices and the cloud. They are static at a fixed location or mobile on a moving carrier. The end devices auspiciously connect with fog nodes to obtain services and can compute, transmit, and temporarily store the received sensed data. While real-time analysis and latency-sensitive applications can be accomplished in the fog layer.

Furthermore, by an IP core network, fog nodes are connected to the cloud data center and are responsible for interaction and cooperation with the cloud to obtain more powerful computing and storage capabilities [69]. Hence, deploying computing resources and services closer to edge devices, often within the range of a local network, helps fast and efficient industrial operations decision making. Furthermore, lowering the amount of data that must be transported to the centralized cloud or data center optimized the network's bandwidth. On the other hand, data processing and filtering take place, allowing only relevant or summarized information to be broadcast. This helps reduce network load, latency, and the costs of transferring vast data over long distances. Local data analysis by AI systems might trigger rapid responses or activities based on predefined rules or learned patterns. This functionality is especially useful in time-sensitive situations where real-time decision making is vital. The advantage of the NEC layer is that it enables greater flexibility and agility in industrial operations. It is feasible to adjust quickly to changing conditions and requirements by placing computing resources and equipment near the network's edge, for instance, in industrial contexts where conditions, such as production or logistics, might change.

C. Cloud Execution Layer

The CEL comprises several high-performance servers and storage devices offering various application services, such as smart home, smart transportation, smart factory, etc. It has powerful computing and storage capabilities that allow for intensive calculation analysis and long-term storage of massive amounts of data. The decision to offload a computation-intensive task to the cloud is typically based on factors, such as the computational requirements of a task, accessible resources on the local machine, and the network's connectivity. The task is considered for offloading if the local machine lacks adequate resources or the cloud provides better performance or cost-effectiveness. Furthermore, the task may be broken into smaller subtasks or data pieces before offloading. This partitioning allows efficient work distribution between the local machine and the cloud. Subtasks requiring significant computational resources are chosen for offloading.

On the other hand, local machines handle various components of the task. If the task being offloaded requires data processing, the required data is transmitted from the local machine to the cloud. This transmission can occur over a secure network connection, ensuring data integrity and privacy. It enables large-scale AI model deployment and inference. AI models that have been trained can be put in the cloud, allowing for real-time inference and prediction of incoming data. Cloud platforms provide the resources required for AI algorithms to run and predictions to be delivered to client apps, as shown in Fig. 9. The cloud service provider allocates the computing resources needed to complete the activity. Cloud computing provides numerous advantages for both organizations and individuals. The first advantage is that it can be scaled up or down according to the required processing power. This flexibility ensures resources are used efficiently, improving performance and saving money. Second, it saves money because hardware and infrastructure are not needed upfront. Users pay for cloud services on a pay-as-you-go basis, reducing capital costs.

However, there are some limitations to consider. Cloud computing relies on Internet connectivity, and any disturbances, such as Internet outages or limited bandwidth, can impair access to cloud services, reducing productivity and accessibility. Data security and privacy are significant issues, as organizations must entrust sensitive data to cloud service providers. While cloud providers often have robust security measures in place, there is still a risk of unauthorized access or data breaches. Eventually, collaborative edge–cloud resource federation holds significant potential for the future of computing and network infrastructure. For instance, it involves real-time allocating of tasks and resources across the edge–cloud continuum. Hence, service orchestration optimizes task execution by considering task requirements, resource availability, and network circumstances.

Fig. 10. Emerging Industry 5.0 applications.

VII. Applications of Industry 5.0

The application of Industry 5.0 offers several benefits, such as emphasizing collaboration between humans and advanced technologies. The goal is to establish a harmonious working atmosphere that merges human skills, creativity, and problem-solving abilities with automation accuracy and efficiency. Furthermore, it improves manufacturing safety, decreases accidents and injuries, and makes production operations more efficient and productive. It helps to reduce costs by optimizing manufacturing processes and increasing productivity. Moreover, Industry 5.0 applications contribute to sustainable practices by eliminating waste and optimizing resources. IoT and data analytics integration allow real-time monitoring and control of energy consumption, material utilization, and manufacturing processes. This results in better resource allocation, less environmental impact, and economic savings. Various potential applications of Industry 5.0 are shown in Fig. 10, their challenges and how Industry 5.0 can help to solve these challenges are shown in Table V.

A. Predictive Maintenance

Predictive maintenance is one of the emerging application areas in Industry 5.0, also known as online monitoring, condition-based maintenance, or risk-based maintenance. When equipment starts to fail, it may show signals that can be identified if sharp eyes, ears, and noses are utilized to detect the failure precursors. Fortunately, sensors are now available to detect degradations and malfunctions of devices before they cause damage. This helps to save money by avoiding

TABLE V
APPLICATIONS, CHALLENGES, AND THE ROLE OF INDUSTRY 5.0

Applications	Challenges	How Industry 5.0 can help
Predictive Maintenance	The availability of high-quality data is critical for predictive maintenance. Obtaining meaningful and trustworthy data from numerous sensors, equipment, and systems is difficult, especially in older or less-connected infrastructure.	Industry 5.0 allows the smooth integration of data from many sources by introducing standardised protocols and data exchange frameworks. This facilitates access to essential data for predictive maintenance analysis and reduces data availability and integration problems. Connect devices, sensors, and systems securely using industry-standard protocols. By deploying an edge computing infrastructure, ensure connectivity between edge devices and the central data infrastructure.
Collaborative Supply Chain	Building confidence and developing cooperation among supply chain partners are quite challenging, especially when several organisations are engaged with diverse aims, cultures, and priorities.	Industry 5.0 emphasizes the need for trust and security in collaborative supply chains. Edge computing improves the collaborative supply chain's security and privacy. Edge devices use encryption, access controls, and security protocols to protect data and prevent unauthorised access. Improved security and privacy safeguards foster trust among partners while assisting in compliance with data protection standards.
Intelligent Healthcare	Interoperability is the ability of several systems and devices to communicate information and work in unison. A major challenge for the healthcare industry is the lack of interoperability between healthcare systems.	Edge data processing decreases delays and promotes real-time interoperability. With the help of smartwatches and smart sensors, healthcare data can be continuously recorded in real-time and stored in the cloud. Patients' medical conditions can be diagnosed using ML algorithms. Smart gadgets can communicate with each other, and if a doctor's attention is needed, these devices can let the doctor know the patient's current condition.
Production System	Fluctuations in customer demand present obstacles to production systems. Rapid fluctuations in demand volume or mix can lead to underutilization or overutilization of manufacturing capacity, resulting in inefficiencies and cost increases.	Design flexible or modular manufacturing systems that easily accommodate product variants and variable production volumes. Edge computing enables distributed processing and scalability in commercial systems. Additional edge devices can be deployed as needed to meet rising production demands. This gives flexibility and agility in increasing manufacturing operations without relying only on centralised systems. Monitor inventory levels, lead times, and reorder points using advanced management tools and procedures.
Society 5.0	With Industry 5.0, the benefits of Society 5.0 may be dispersed relatively across society. Adopting modern technology may result in more automation and job displacement, disproportionately impacting low-skilled employees.	Industry 5.0 helps to resolve concerns about unequal benefit distribution. Edge computing brings computing resources closer to end-users and devices, lowering latency and improving connectivity. Edge devices offer smooth and uninterrupted interaction between humans, devices, and systems by processing data locally. By supporting sustainable development, innovation, cooperation, digital inclusion, and a human-centred approach, Industry 5.0 can help tackle numerous problems in Society 5.0.
Metaverse	The metaverse requires a robust, high-speed network architecture for real-time data transfer. Universal access to such infrastructure worldwide is challenging, particularly in impoverished or isolated areas.	Including high-speed internet access, 5G networks, and edge computing will help to face the challenges. The time it takes for interactions and actions to be processed and reflected in the virtual environment is reduced by processing data locally on edge devices or servers. This enhances the user experience by making metaverse interactions more responsive and immersive.
Industrial Transportation	Industrial transportation contributes to carbon emissions and environmental contamination. Managing transportation operations sustainably is becoming increasingly challenging.	Industry 5.0 encourages modern technologies such as electric vehicles, hybrid systems, and alternative fuels to enhance fuel efficiency and minimise carbon emissions. Edge devices eliminate the need for huge volumes of data to be transmitted to centralised systems or the cloud by processing data locally at the edge, which consumes significant network bandwidth and energy.

unnecessary equipment replacement and improving process safety, availability, and efficiency. This technique works in that the targeted asset is the source of the imported data, which is subsequently synthesized and aggregated with many other data sources. Once a substantial amount of data has been thoroughly cleansed, data analysis is undertaken to discern prevailing trends and patterns. Ultimately, the system can produce predictive models to anticipate forthcoming occurrences by employing ML and AI methodologies. A manufacturing industry that depends on a fleet of industrial machinery for production. A crucial machine in the industry is outfitted with sensors to oversee many characteristics, including temperature, vibration, and pressure. Sensor data would be consistently transmitted to a centralized cloud server for analysis in a conventional configuration without edge computing. The data would be processed by predictive maintenance algorithms operating on the cloud, utilizing historical trends to forecast the timing of repair needs. Afterward, the outcomes and notifications would be transmitted back to the industries. The machine has been upgraded with edge computing, which integrates edge devices that can process data locally. ML models are implemented on these edge devices to analyze the real-time sensor data. The edge devices do local data processing instead of sending all raw data to the cloud, transmitting pertinent insights or alarms.

B. Collaborative Supply Chain

Globalized and highly competitive business environments have led manufacturers to realize they must provide the highest customer value at the lowest possible cost to maintain a competitive advantage. Customers increasingly seek faster reaction times, shorter product cycles, and customized products and services. Central servers frequently experience information overload, leading to expensive processing delays. Therefore, edge computing enhances supply chain efficiency by optimizing resource allocation, reducing dependence on human oversight, and significantly improving the response time for time-critical operations. With the increasing investment in IoT devices and the growing need for faster outcomes in warehousing and transportation operations, edge computing emerges as a profitable choice for companies seeking logistics management solutions. Additionally, collaboration between supply chain partners allows organizations to pursue business goals. As a result, cooperative behavior and activities in supply chain management have grown in relevance [70]. Industry 5.0 collaborative supply chains prioritize system, process, and data format standardization and interoperability. This allows smooth integration and communication among various entities in the supply chain, promoting effective collaboration. Organizations may optimize resource utilization, eliminate waste, and design more sustainable goods and processes by working closely with suppliers and customers. Furthermore, incorporating edge computing helps in such a way that collaborative supply chains frequently operate in various settings, including rural or isolated places. When connectivity is restricted or sporadic, edge computing allows offline capability by enabling edge devices to process and store data locally. Even under difficult network conditions, this ensures uninterrupted operations and data integrity.

C. Intelligent Healthcare

Intelligent healthcare plays a crucial role in Industry 5.0, merging digital and conventional industries to drive innovation, efficiency, and sustainability. It allows for remote consultations, telemedicine, and remote patient monitoring, bridging geographical and socioeconomic inequalities in healthcare access. This is particularly critical in Industry 5.0, where connectivity and digital infrastructure allow equitable healthcare access regardless of geography or socioeconomic position. Doctors use ML models to diagnose illnesses, saving time and money [19]. Nevertheless, it is not enough in the present day to address personalized patient needs, like monitoring blood pressure and sugar levels and providing tailored treatment with doctors' assistance. For instance, healthcare presents numerous cutting-edge prospects. Currently, monitoring devices, such as glucose monitors, health tools, and other sensors, are either not linked together or if they are, significant quantities of unprocessed data from these devices would have to be kept on an external cloud service. This poses security risks for healthcare practitioners. The medical facility might utilize edge computing to process data locally, ensuring data privacy preservation. Edge also facilitates real-time notifications to healthcare professionals regarding atypical patient patterns or behaviors (using analytics and AI) and the development of comprehensive patient dashboards for complete visibility.

Smart wearables, such as smartwatches and wearable sensors, can continuously capture and analyze patient data through ML methods. These smart gadgets may communicate with one another, allowing doctors to observe the patient's current state and alert them if intervention is required. Surgeons are using robots that communicate with one another to assist them in operating on patients with the help of cobots [5]. In telemedicine and distant care settings, edge computing is critical. Healthcare providers distantly diagnose and treat patients by delivering computational capability to the edge rather than depending primarily on centralized servers. Edge technologies can process high-resolution medical imaging, facilitate real-time video consultations, and support remote monitoring, allowing patients to obtain prompt care from their homes. This functionality is especially useful for people living in distant places or having limited healthcare access. Moreover, industrial healthcare keeps workers safe by detecting and controlling occupational hazards. This includes risk assessments, implementing safety protocols, providing personal protection equipment (PPE), and training staff on safe practices.

D. Production System

The production system in Industry 5.0 turns traditional manufacturing into an intelligent, collaborative, and sustainable ecosystem. Intelligent manufacturing relies heavily on production systems. Industrial resources are created and developed with virtual (digital) resources associated with physical resources throughout their existence. With the recent rise of ICTs, such as big data, VR, and the IoT, the interconnection and interaction of physical and virtual resources in production systems have become conceivable. Furthermore, edge computing improves the reliability and resilience of production systems. Local processing and storage capabilities at edge devices ensure that critical production operations can continue even if the network is disrupted or there is a latency issue. Edge devices are self-contained and make decisions based on local data, maintaining continuous production and minimizing downtime [71]. For instance, in an Industry 5.0 setting, edge devices could analyze product surfaces for imperfections or ensure precise assembly. Any deviations from quality standards trigger immediate corrective actions, reducing waste and improving overall product quality.

E. Society 5.0

Society 5.0 is the creation of an open society guided by technological and scientific innovation, whose focus is to create a human-centered, super-smart, and lean society, which was initiated by the Japanese government in the year January 2016 [15]. Society 5.0 was implemented in Japan to balance economic growth and address social issues (such as the aging population, low birth rates, and lack of competitiveness). In Society 5.0, edge computing enables decentralized systems and peer-to-peer networks. Edge computing allows distributed applications and services by allowing edge devices to communicate and share resources without relying on centralized servers. Due to this decentralization, individuals and communities benefit from increased autonomy, resilience, and collaborative decision making. Society 5.0 aims to ensure that all its citizens have access to high-quality lives that are comfortable and full of vitality by providing the essential goods and services for specific individuals at the necessary level when needed by fusing cyberspace and physical space with advanced technologies. In actuality, human society has gone through four changes, namely, hunter-gatherer society (Society 1.0), agricultural society (Society 2.0), industrial society (Society 3.0), and information society (Society 4.0), and is currently entering a smart civilization valuing humans (Society 5.0). Human centricity is the essential element in both Society 5.0 and Industry 5.0. Individualized service systems, intelligent manufacturing systems, and other systems will all contribute to the value of Society 5.0.

F. Metaverse

Metaverse is the futuristic type of Internet application and social form that consolidates a variety of new technology [14]. The metaverse is a computer-generated environment with a consistent value system and an independent economic system connected to the real world. The name comes from the combination of the word *meta* (which means transcendence) with the suffix *verse*, which is short for the *universe*. It generates a mirror picture of the natural world using DT technology. It enables users to create content and edit the world by integrating the real and virtual worlds into social, economic, and identification systems. In the future, the metaverse will have a lot of potential for use in virtual manufacturing and simulation. For instance, manufacturers use the metaverse to create virtual replicas of their production lines, equipment, and procedures, making it easier to simulate and prove their processes. This enables virtual testing, optimization, and simulation of manufacturing activities, eliminating the need for actual prototypes and expensive trial-and-error methods. Manufacturers can enhance and optimize their processes in the metaverse before adopting them in the physical world [72]. As a result, many researchers and practitioners have begun to deploy the metaverse in industrial services. For example, a Japanese airline started offering virtual flights from Tokyo to numerous locations (e.g., Rome, Paris, and New York). Moreover, edge computing enables deploying edge AI models to power intelligent virtual agents in the metaverse. Edge devices may process user inputs in real time, analyze the context, and provide dynamic answers, resulting in more engaging and personalized experiences. Edge AI also enables virtual agents to adapt and learn from human behaviors, increasing the realism and intelligence of metaverse avatars.

G. Industrial Transportation

Transport plays a very important role within Industry 5.0, which focuses on integrating sophisticated technology and collaborative production practices to integrate manufacturing and production processes into one seamless process. The traditional transportation industry is being transformed by Industry 5.0, which uses cutting-edge technologies to improve efficiency, sustainability, and responsiveness through advanced technologies. Transporting commodities from distribution centers to end users is one of the most important aspects of the industrial transportation industry. Technologies, such as drone deliveries, self-driving cars, and crowd-shipping platforms, are aiding last-mile delivery efficiency, cutting delivery times, and increasing customer satisfaction. Furthermore, autonomous transportation, which refers to cars that can operate without human intervention, is gaining popularity and is expected to impact the industry significantly. For instance, autonomous platooning of truck convoys is expected to be among the initial applications of autonomous vehicles. Here, a truck fleet closely follows each other in a convoy, reducing fuel expenses and alleviating traffic congestion. Edge computing eliminates drivers in all trucks except the front one by facilitating seamless communication between the trucks with minimal delay. Moreover, the transportation sectors could lessen their carbon footprint by optimizing routes, reducing traffic, and reducing parking demand. Electric automobiles driving themselves may also become more prevalent, reducing pollution [73].

VIII. Lesson Learned

This section summarizes the lessons learned from current state-of-the-art studies and summarizes research issues that need to be addressed to ensure an effective Industry 5.0 environment. Section I introduced Industry 5.0 and its industrial development and automation stages based on the preceding steps in the industry. In the section, we addressed the solution to this question *What role does edge computing play in reducing latency and enhancing efficiency in Industry 5.0?* by discussing the idea of processing data more quickly and in larger quantities near the point of generation results in more immediate and actionable answers. Furthermore, one significant drawback is the increased energy consumption linked to the implementation and maintenance of edge devices. Acquiring additional hardware and software is necessary to achieve optimal performance and store data locally, which can result in increased energy consumption and operational expenses. Moreover, the widespread use of edge devices in different local areas can increase costs, impacting the overall cost-efficiency of edge computing solutions. Furthermore, the management and maintenance of numerous dispersed edge devices present operational difficulties, necessitating a sturdy infrastructure and allocation of resources. Notwithstanding these disadvantages, the advantages of edge computing include reduced latency by processing data locally, enabling devices to communicate with one another in real time without depending on a central data center, and persistently propelling its implementation in Industry 5.0 applications [74]. Section II discussed research methodology, literature classification, and existing tutorials. Section III addressed the potentials of Industry 5.0. It holds immense potential to transform manufacturing and production processes through human–machine collaboration.

Combining the benefits of advanced technology, such as AI, robotics, and edge computing with human creativity, problem-solving skills, and adaptability and fostering a deeper interaction with machines, ensures resource efficiency and increased productivity and addresses social and environmental issues. In Section V, we examined the various supporting technologies of Industry 5.0, which are critical to its effective implementation and realization. Moreover, we addressed the solution to this question *Can edge computing be successfully applied to Industry 5.0 in practical use cases?* by discussing edge computing computational capacity closer to the data source, allowing real-time data processing and analysis at the network's edge. Later on, in Section IV, we addressed the solution to this question *Can Industry 5.0 promote sustainable manufacturing while creating a resilient ecosystem?* by emphasizing the core objective of Industry 5.0, recognizing the unique strength of cobots, and unleashing unprecedented levels of production, creativity, and societal well-being.

In Section VI, we addressed the solution to this question *Why should the Industrial 5.0 revolution adopt edge-enabled architecture as a strategy?* by discussing edge-enabled architecture in Industry 5.0. Edge-enabled reduces data transmission to the cloud by filtering and processing data at the edge. It also improves security and privacy by limiting data exposure and giving you more control over sensitive data. Eventually, in Section VII, we addressed the solution to this question *What are some practical use cases where edge computing is being successfully applied in Industry 5.0?* by discussing supporting applications of Industry 5.0, critical for developing smart manufacturing processes in which advanced technologies are used to optimize production, monitor equipment performance, predictive maintenance, and enhance product quality. These applications provide real-time data gathering, analysis, and integration across the manufacturing ecosystem, allowing machines, systems, and human operators to communicate and collaborate in real time. By exploiting these technologies, industries can improve operational efficiency, minimize downtime, and improve product customization. This will increase competitiveness and long-term growth in the industrial landscape.

IX. Challenges and Future Research Directions

Industry 5.0 completely transforms production, benefiting businesses, workers, and consumers. This section will examine some potential challenges and research directions for Industry 5.0. As modern technology becomes more integrated into industrial processes, the workforce must learn various skills and adapt to changing employment needs. To ensure a smooth transition, this shift may result in job displacement and the need for retraining and upskilling programs. Therefore, the workforce's adaptability to new technologies and working techniques is one of the most severe problems of Industry 5.0.

Future research directions for developing human–robot co-operation technologies are one of the primary research objectives for Industry 5.0. These technologies will allow robots to operate alongside people in a safe environment, increasing production and efficiency while ensuring safety and reducing the chance of accidents. Industry 5.0 intends to build smart factories that are ultimately linked, automated, and flexible. Smart factories will require advanced IoT technology, such as sensors, connectivity, and data analytics to enable real-time monitoring and optimization of production processes. AI and ML will be meaningful in Industry 5.0, allowing robots to learn from data and improve their performance over time. Developing advanced algorithms and ML models that learn from massive data sets will be critical to realizing Industry 5.0's full potential. Table VI explains the potential challenges and future research directions in Industry 5.0.

A. Heterogeneity and Data Security

Heterogeneity pertains to the presence of diverse platforms, architectures, infrastructures, computing, and communication technologies utilized by the elements of edge computing (such as end devices, edge servers, and networks). The main factors contributing to end-device heterogeneity are software, hardware, and technology variations. The primary cause of heterogeneity on the edge server side is the presence of APIs, custom-designed policies, and platforms. These differences lead to interoperability problems, making it a primary challenge to implement edge computing in Industry 5.0 effectively. During deployments, Industry 5.0 will experience serious security problems. Industry 5.0 must fulfill security requirements, including integrity, availability, authentication, and audit elements, just like conventional CPSs do. Building confidence in the ecosystem is essential to authenticating many stakeholders, including machines, IoT nodes, fog nodes, collaborative partner nodes, and communication nodes [75].

Industries rely so heavily on wireless communication that they are susceptible to jamming attacks. Additionally, the interconnectedness of IoT devices amplifies the potential damage, necessitating the implementation of strong security measures by industries to mitigate this susceptibility [76]. Industry 5.0 authentication solutions should be lightweight to deploy with IoT nodes, scalable to connect billions of devices, and quantum-resistant to fend off future quantum computing applications. Utilizing AI and automation in Industry 5.0 will introduce a novel vulnerability. Trusted execution is crucial for ensuring security in AI/ML operations. It is essential to safeguard the integrity of the data set utilized for training ML models and AI algorithms to ensure their effective functioning in Industry 5.0. For example, in Industry 5.0, various tenants should securely exchange empirical data to train AI models or make incremental updates to the models, similar to the concept of federated learning. Furthermore, the notable applications of Industry 5.0 heavily rely on ICT systems, resulting in new security needs, including implementing proactive security measures and preventing zero-day attacks. Furthermore, the advancement of quantum computing could enable Industry 5.0 to function in the era of quantum computing. A quantum computer will greatly simplify the safeguarding of traditional security methods. In such circumstances, Industry 5.0 systems ought to employ quantum-resistant encryption or post-quantum cryptography mechanisms to ensure the necessary level of security.

B. Privacy and Trust

Privacy is essential for Industry 5.0 applications since the entire ecosystem relies on pricey intellectual property, expensive manufacturing components, and subscription management. Data is transmitted through the Internet in Industry 5.0 to connect machines and people, designers, and other partners, and to convey monitoring and control information [77]. Transparency, responsibility, and moral behavior are the cornerstones of Industry 5.0 trust. Industries must be open and honest about gathering and utilizing data, giving brief and comprehensible justifications for each step in the process. Integrate differential privacy techniques into edge computing systems to secure the privacy of individual data. It introduces noise or disturbances into data to ensure privacy while allowing correct aggregate analysis. Personal information can be secured while allowing for relevant analysis and insights by implementing differential privacy at the edge.

Blockchain is a decentralized technology that utilizes a distributed ledger to store information in a transparent, unchangeable, and highly secure manner. Additionally, it is more resource-intensive as it requires more energy to extract the data from its nodes. However, it guarantees data security by employing digital hashes of the preceding records. Blockchain

TABLE VI
INDUSTRY 5.0 CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Research Challenge	Ref	Short Summary	Technology Consideration	Potential Solutions	Future Directions
Heterogeneity and Data Security	[78]	Presented interoperability and security requirements for the IoT	• Message Queue • Data Virtualization	• Middleware Integration • Industry Collaboration	• Semantic Interoperability • Distributed Interoperability
	[79]	Addressing the need for interoperability in CPS at large scale	• Cloud Computing • Web Services	• Data Transformation • Programming Interface	• Smart IoT Ecosystem • Federated Interoperability
	[80]	Discussed implementation of interoperability for Industry 4.0	• Edge Computing • Cloud Computing	• Collaborative Partnership • Data Integration	• User-Centered • Autonomous Systems
Data Privacy	[81]	Observed the impact of robustness by agent-based model	• Quantum Computing • Industrial IoT	• Fault-Tolorent Architecture • Recovery Planning	• Resilient System • Self-Healing Systems
	[82]	Proposed a model for improvement of existing attacks in Industry	• AR & VR • Industrial AIoT	• Regular Maintenance • Robust Infrastructure	• Autonomous Systems • Regular Testing
	[83]	Framework to examine robustness in the manufacturing Industry	• Digital Twins • Cognitive Computing	• AR & VR • Monitoring & Alerting	• Adaptive Systems • Self-Configuring Systems
Trust and Ownership	[84]	Discussed the various privacy attack occurred in Industry 4.0	• Encryption • Data Masking	• Data Minimization • Access Control	• Privacy-preserving ML • Enhanced user control
	[85]	Discussed specific measures to deal with customer's data privacy	• Secure Shell (SSH) • Zero-knowledge Proofs	• Consent Policy • Authentication	• Differential Privacy • Ethical data use
	[86]	Provide privacy protection in the field of Industrial IoT (IIoT)	• Real-Time Transportation • Cryptography	• Anonymization • Pseudonymization	• Privacy enhancing • Increased Regulation
Human-Robot Co-working	[87]	Fostering a positive attitude of decision-making towards Industry	• Robotics • AR	• Change Facilitation • Worker Empowerment	• Global Competence • Cognitive Abilities
	[88]	Discussed the various potential of adaptation to Industry 4.0	• VR • AI	• Agile Workforce Development • Continuous Communication	• Upskilling & Reskilling • Social Inclusion
	[89]	Development of new workforce adaptability in the industry	• IoT • Cloud Computing	• Public Awarness • Collaborative Ecosystem	• Responsible Automation • Safety in Smart factories
Sustainable Environment	[90]	Discussed the impact of Industry 4.0 on environmental sustainability	• Advanced Robotics • Automation	• Green Building • Sustainable Infrastructure	• Biodiversity Conservation • Ecosystem Restoration
	[91]	Discussed the impact of the proliferation of ICT in the Industry	• Green Chemistry • 3D Printing	• Environmental Monitoring • Sensor Technologies	• Green and Clean Industry • Sustainable Cities
	[39]	To attain sustainability through the use of numerous digital tools	• Cloud Computing • Data Centers	• Collaborative Platforms • Sharing Economy	• Environmental Education • Mitigation & Adaptation
Resilient Network	[92]	Proposed the methods to improve supply chain resilience	• Cloud Computing • Virtualization	• Data Redundancy • Diversify Supply Chain	• Technology Fusion • Ecosystem Resilience
	[93]	Discussed resilience for industrial ecosystems and smart cities	• IoT & Automation • Orchestration	• Risk Assessment • Risk Mitigation	• Resilience in Smart Cities • Data-driven Resilience
	[94]	Discussed new resilient supply chain management in Industry	• Edge Computing • AI & ML	• Resilient Infrastructure • Data Backup	• International Collaboration • Resilience in Healthcare Crisis
Skilled Workforce	[95]	Improving cognitive support humans at work with new technologies	• AI, Robotics • NLP	• Personalization • Customization	• Empowering Workers • Augmenting Workers
	[96]	Discussed data dissemination and information within Industry	• Data Analytics • Robotics	• User-Centered • Rapid Prototyping	• Ethical Considerations • Trustworthy System
	[97]	Proposed human-centred dimension of digital industrial revolution	• Digitalization • Social Robotics	• Continuous Feedback • Iterative Design	• Co-creation, Innovation • Personalization

technology has the potential to make a substantial impact on privacy concerns in Industry 5.0. Due to the resource-intensive nature of the blockchain, a rise in the number of nodes in Industry 5.0 applications based on blockchain technology may result in a slowdown. To mitigate this issue, one can implement a lightweight blockchain structure by separating infrequently utilized data from the main blockchain and placing it in a separate sidechain. Moreover, quantum computing can enhance the security of the CPS or CPPS without experiencing any periods of system unavailability. To ensure the necessary level of security, it is advisable to employ either quantum-resistant cryptography or post-quantum cryptography mechanisms.

C. Human–Robot Co-Working Infactory

Humans will again work alongside cobots on the production floor with the evolution of Industry 5.0. Although it appears to be a productive technique for creating customized products, specific concerns about the interaction between humans and robots must be considered. Additionally, job loss anxiety will be reduced when humans and robots share labor. The cobot will do the routine tasks, freeing the human to focus entirely on innovation and creativity. It will be preferable for cobots to support humans than the other way around, which might lead to organizational instability and complicate the company's long-standing job competitiveness culture. Additionally, cobot workers are skilled and may have higher expectations than a traditional workplace culture [18]. Use edge computing to optimize resource allocation in the production between people and robots. Edge devices can monitor human and robot workloads, availability, and capabilities, allowing for dynamic task allocation based on efficiency, skill sets, and real-time situations. This guarantees that tasks are assigned to the best entity for the job, increasing efficiency and reducing bottlenecks.

D. Sustainable Environment

Industry 5.0 has the potential to advance productivity beyond the profit-centered productivity of Industry 4.0 and to advance sustainable development objectives, including human-centricity, socio-environmental sustainability, and resilience [10]. By integrating environmentally friendly practices into the design, development, and use of industrial processes and systems, sustainability in Industry 5.0 can be realized. Using clean and renewable energy sources like solar, wind, and hydropower can be encouraged through Industry 5.0. Using renewable energy systems in industrial operations can lessen carbon emissions and contribute to developing a sustainable energy future. Adopting circular economy concepts, which aim to reduce waste and promote resource reuse, can enhance resource efficiency. Industrial processes can be less environmentally impactful using sustainable materials. They can facilitate the use of sustainable materials like bioplastics and recycled materials, which can help minimize waste and preserve natural resources. Use edge computing to monitor factory emissions in real time. Edge devices collect emission sensor data, analyze emission trends, and provide alerts or feedback on emission levels. By monitoring emissions at the edge proactively, factories may identify areas for improvement, implement emission reduction initiatives, and comply with environmental standards.

E. Resilient Network

The ability of the industrial network to withstand and recover from disturbances brought on by internal or external forces is referred to as resilience in Industry 5.0. Industry 5.0 calls for adopting technology and practices that guarantee business continuity and reduce downtime. Some strategies can promote stability by implementing redundancy and backup systems that guarantee ongoing operation in the case of disruptions. By implementing strong cybersecurity measures that guard against online dangers like hacking, malware, and ransomware assaults. Advanced encryption techniques, secure networks, and firewalls can all be used to accomplish this by embracing interoperable technologies and systems that can easily interface with other systems [23]. In the event of disruptions, this can reduce downtime and ensure company continuity by providing predictive maintenance solutions that employ data analytics and AI to find and fix equipment issues before they happen. This helps to reduce downtime and ensure uninterrupted operation.

F. Skilled-Workforce

Standardization and legal standards must be enforced to tackle technology, societal, and management challenges because a skilled worker in Industry 5.0 must offer a high-value production task. Providing a qualified workforce involves several considerations for management, employees, company culture, management infrastructure, and general policies. Various industries would readily embrace the emerging technology, while management may need more comprehension of its implications. The proficient staff and the prevailing culture have the potential to take advantage of the management's lack of knowledge. In addition, if the employees lack forward-thinking abilities, it will result in significant training expenses from a managerial standpoint. The senior employee may require more time to adjust, and reengineering efforts may also be necessary. Furthermore, several organizations may need more infrastructure to support the implementation of the new technology. Therefore, it is essential to consider these factors while establishing a transparent corporate culture and ensuring the long-term acquisition of talented staff. Consequently, this will expedite future business changes. Consistent and efficient training for humans and cobots will prevent most collaborative work problems. In addition, providing ongoing training for operational workers will guarantee a highly skilled workforce. To ensure the necessary level of security, it is advisable to employ either quantum-resistant cryptography or post-quantum cryptography mechanisms.

G. Industrial Standardization

The creation and implementation of uniform standards for the planning, creating, and managing industrial systems and procedures are referred to as standardization in Industry 5.0. Interoperability, cost savings, and increased productivity can all be achieved by standardization in industrial operations. The General Data Protection Regulation (GDPR) and the California Consumer Privacy Act (CCPA) are important industry data protection legislation. Global GDPR enforces strict data processing regulations, and California's CCPA protects consumers' privacy rights and affects industries that operate in the state. Moreover, the International Society of Automation (ISA) is the leading organization for establishing standards and rules and providing industry experts with training and education in automation to improve operational excellence. The objectives of ISA are to increase safety, simplify component integration, and offer unwavering instrumentation. The American National Standards Institute (ANSI) is a noncommercial organization that manages global agreement standards development, collaborating with ISA to produce standards for industrial control systems [17]. ANSI and ISA have developed various industrial control system standards. It includes practices for the alarm system in industrial processes (ISA18), safety and practical application of hazardous environment equipment (ISA12) [17]. Moreover, Germany has a long history of maintaining strong manufacturing standards for emphasizing quality, efficiency, and innovation across various businesses. Germany takes an active role in creating and using International Organization for Standardization (ISO) standards. German industry frequently uses ISO 9001 (Quality Management Systems) and ISO 14001 (Environmental Management Systems) to ensure quality control and sustainability.[10]

X. Conclusion

This article provides a comprehensive survey of Industry 5.0 enabling technologies and future applications. We begin by defining the notion of Industry 5.0 from an industrial and academic perspective. Then, we discuss the concept of edge computing and why it plays a vital role in Industry 5.0. Simultaneously, we highlight the edge-enabled architecture of Industry 5.0 and its different layers. Next, we discuss some potential applications of Industry 5.0, including smart healthcare, production systems, smart education, the metaverse, industrial transportation, etc., followed by a discussion of some key supporting technologies for Industry 5.0. The concept of Industry 5.0 can be summed up as a way to consistently coordinate human and robot workspaces to improve their efficiency and productivity, respectively. Industry 5.0, facilitated by various emerging applications and supporting technology, is predicted to boost manufacturing output and consumer satisfaction. Also, we discuss several obstacles and important topics, such as privacy, scalability, human–robot synergy in a factory, security, and trained labor that should be addressed as soon as possible to achieve Industry 5.0.

[10]https://www.iso.org/standard/60857.html

REFERENCES

[1] A. Verma et al., "Blockchain for industry 5.0: Vision, opportunities, key enablers, and future directions," *IEEE Access*, vol. 10, pp. 69160–69199, 2022.

[2] G. Aceto, V. Persico, and A. Pescape, "A survey on information and communication technologies for industry 4.0: State-of-the-art, taxonomies, perspectives, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3467–3501, 4th Quart., 2019.

[3] L. D. Xu, E. L. Xu, and L. Li, "Industry 4.0: State of the art and future trends," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2941–2962, 2018.

[4] O. A. ElFar, C.-K. Chang, H. Y. Leong, A. P. Peter, K. W. Chew, and P. L. Show, "Prospects of industry 5.0 in algae: Customization of production and new advance technology for clean bioenergy generation," *Energy Convers. Manag., X*, vol. 10, Jun. 2021, Art. no. 100048.

[5] P. K. R. Maddikunta et al., "Industry 5.0: A survey on enabling technologies and potential applications," *J. Ind. Inf. Integr.*, vol. 26, Mar. 2022, Art. no. 100257.

[6] A. Hazra and P. Choudhary, "An advance forward pointer-based routing in wireless mesh network," in *Proc. Appl. Artif. Intell. Techn. Eng.*, 2019, pp. 153–164.

[7] A. Hazra, P. Rana, M. Adhikari, and T. Amgoth, "Fog computing for next-generation Internet of Things: Fundamental, state-of-the-art and research challenges," *Comput. Sci. Rev.*, vol. 48, May 2023, Art. no. 100549.

[8] A. Hazra, M. Adhikari, S. Nandy, K. Doulani, and V. G. Menon, "Federated-learning-aided next-generation edge networks for intelligent services," *IEEE Netw.*, vol. 36, no. 3, pp. 56–64, May/Jun. 2022.

[9] H. R. Chi, C. K. Wu, N.-F. Huang, K.-F. Tsang, and A. Radwan, "A survey of network automation for Industrial Internet-of-Things toward industry 5.0," *IEEE Trans. Ind. Informat.*, vol. 19, no. 2, pp. 2065–2077, Feb. 2023.

[10] M. Ghobakhloo, M. Iranmanesh, M. F. Mubarak, M. Mubarik, A. Rejeb, and M. Nilashi, "Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values," *Sustain. Prod. Consum.*, vol. 33, pp. 716–737, Sep. 2022.

[11] L. Cavanini et al., "A preliminary study of a cyber physical system for industry 4.0: Modelling and co-simulation of an AGV for smart factories," in *Proc. Workshop Metrol. Ind.*, 2018, pp. 169–174.

[12] S. Zeb et al., "Industry 5.0 is coming: A survey on intelligent NextG wireless networks as technological enablers," 2022, *arXiv:2205.09084*.

[13] M. Z. Chowdhury, M. Shahjalal, S. Ahmed, and Y. M. Jang, "6G wireless communication systems: Applications, requirements, technologies, challenges, and research directions," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 957–975, 2020.

[14] H. Ning et al., "A survey on metaverse: The state-of-the-art, technologies, applications, and challenges," 2021, *arXiv:2111.09673*.

[15] S. Huang, B. Wang, X. Li, P. Zheng, D. Mourtzis, and L. Wang, "Industry 5.0 and society 5.0—Comparison, complementation and coevolution," *J. Manuf. Syst.*, vol. 64, pp. 424–428, Jul. 2022.

[16] F. G. Sukmono and F. Junaedi, "Towards industry 5.0 in disaster mitigation in Lombok Island, Indonesia," *Jurnal Studi Komunikasi*, vol. 4, no. 3, pp. 553–564, 2020.

[17] T. Hasegawa, H. Hayashi, T. Kitai, and H. Sasajima, "Industrial wireless standardization—Scope and implementation of ISA SP100 standard," in *Proc. SICE Annu. Conf.*, 2011, pp. 2059–2064.

[18] T. B. Sheridan, "Human–robot interaction: Status and challenges," *Human Factors*, vol. 58, no. 4, pp. 525–532, 2016.

[19] N. Deepa et al., "An AI-based intelligent system for health-care analysis using ridge-Adaline stochastic gradient descent classifier," *J. Supercomput.*, vol. 77, pp. 1998–2017, Feb. 2021.

[20] M. D. Kent and P. Kopacek, "Do we need synchronization of the human and robotics to make industry 5.0 a success story?" in *Proc. Int. Symp. Prod. Res.*, 2021, pp. 302–311.

[21] X. Li and L. D. Xu, "A review of Internet of Things—Resource allocation," *IEEE Internet Things J.*, vol. 8, no. 11, pp. 8657–8666, Jun. 2021.

[22] I. Boškov, H. Yetgin, M. Vucnik, C. Fortuna, and M. Mohorcic, "Time-to-provision evaluation of IoT devices using automated zero-touch provisioning," in *Proc. IEEE Global Commun. Conf.*, 2020, pp. 1–7.

[23] A. Hazra, M. Adhikari, T. Amgoth, and S. N. Srirama, "A comprehensive survey on interoperability for IIoT: Taxonomy, standards, and future directions," *ACM Comput. Surv.*, vol. 55, no. 1, pp. 1–35, Nov. 2021. [Online]. Available: https://doi.org/10.1145/3485130

[24] E. Loizaga, A. T. Eyam, L. Bastida, and J. l. M. Lastra, "A comprehensive study of human factors, sensory principles, and commercial solutions for future human-centered working operations in industry 5.0," *IEEE Access*, vol. 11, pp. 53806–53829, 2023.

[25] C. Yeh, G. Do Jo, Y.-J. Ko, and H. K. Chung, "Perspectives on 6G wireless communications," *ICT Exp.*, vol. 9, no. 1, pp. 82–91, 2023.

[26] V. Mattila, P. Gauri, P. Dwivedi, and D. Dadhich, "The fifth industrial revolution: Enlightenment of 5ire towards industry 5.0," *Int. J. Creat. Res. Thoughts*, vol. 10, no. 8, pp. 178–180, 2022.

[27] M. Javaid, A. Haleem, R. P. Singh, M. I. U. Haq, A. Raina, and R. Suman, "Industry 5.0: Potential applications in COVID-19," *J. Ind. Integr. Manag.*, vol. 5, no. 04, pp. 507–530, 2020.

[28] O. A. ElFar, C.-K. Chang, H. Y. Leong, A. P. Peter, K. W. Chew, and P. L. Show, "Prospects of industry 5.0 in algae: Customization of production and new advance technology for clean bioenergy generation," *Energy Convers. Manag., X*, vol. 10, Jun. 2021, Art. no. 100048.

[29] M. Javaid and A. Haleem, "Critical components of industry 5.0 towards a successful adoption in the field of manufacturing," *J. Ind. Integr. Manag.*, vol. 5, no. 03, pp. 327–348, 2020.

[30] L. S. Dalenogare, G. B. Benitez, N. F. Ayala, and A. G. Frank, "The expected contribution of industry 4.0 technologies for industrial performance," *Int. J. Prod. Econ.*, vol. 204, pp. 383–394, Oct. 2018.

[31] K. Voulgaridis, T. Lagkas, and P. Sarigiannidis, "Towards industry 5.0 and digital circular economy: Current research and application trends," in *Proc. 18th Int. Conf. Distrib. Comput. Sens. Syst. (DCOSS)*, 2022, pp. 153–158.

[32] K. Tange, M. De Donno, X. Fafoutis, and N. Dragoni, "A systematic survey of Industrial Internet of Things security: Requirements and fog computing opportunities," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2489–2520, 4th Quart., 2020.

[33] D. K. Sah, A. Hazra, R. Kumar, and T. Amgoth, "Harvested energy prediction technique for solar-powered wireless sensor networks," *IEEE Sensors J.*, vol. 23, no. 8, pp. 8932–8940, Apr. 2023.

[34] F. Longo, A. Padovano, and S. Umbrello, "Value-oriented and ethical technology engineering in industry 5.0: A human-centric perspective for the design of the factory of the future," *Appl. Sci.*, vol. 10, no. 12, p. 4182, 2020.

[35] M. Breque, L. De Nul, and A. Petridis, *Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry*, Eur. Comm., Dir. Gener. Res. Innov., Brussels, U.K., 2021.

[36] W. Viriyasitavat and D. Hoonsopon, "Blockchain characteristics and consensus in modern business processes," *J. Ind. Inf. Integr.*, vol. 13, pp. 32–39, Mar. 2019.

[37] R. Liu, G. G. Rozenman, N. K. Kundu, D. Chandra, and D. De, "Towards the industrialisation of quantum key distribution in communication networks: A short survey," *IET Quantum Commun.*, vol. 3, no. 3, pp. 151–163, 2022.

[38] P. Yang, Y. Xiao, M. Xiao, and S. Li, "6G wireless communications: Vision and potential techniques," *IEEE Netw.*, vol. 33, no. 4, pp. 70–75, Jul./Aug. 2019.

[39] B. Rathore, "Digital transformation 4.0: Integration of artificial intelligence & metaverse in marketing," *Eduzone, Int. Peer Rev./Refereed Multidiscip. J.*, vol. 12, no. 1, pp. 42–48, 2023.

[40] J. Al-Jaroodi and N. Mohamed, "Blockchain in industries: A survey," *IEEE Access*, vol. 7, pp. 36500–36515, 2019.

[41] T. Alladi, V. Chamola, R. M. Parizi, and K.-K. R. Choo, "Blockchain applications for industry 4.0 and Industrial IoT: A review," *IEEE Access*, vol. 7, pp. 176935–176951, 2019.

[42] X. Liu, W. M. Wang, H. Guo, A. V. Barenji, Z. Li, and G. Q. Huang, "Industrial blockchain based framework for product lifecycle management in industry 4.0," *Robot. Comput.-Integr. Manuf.*, vol. 63, Jun. 2020, Art. no. 101897.

[43] S. Song and C. Wang, "Recent development in quantum communication," *Chin. Sci. Bull.*, vol. 57, pp. 4694–4700, Dec. 2012.

[44] D. A. Vajner, L. Rickert, T. Gao, K. Kaymazlar, and T. Heindel, "Quantum communication using semiconductor quantum dots," *Adv. Quantum Technol.*, vol. 5, no. 7, 2022, Art. no. 2100116.

[45] P. Radanliev and D. De Roure, "Disease X vaccine production and supply chains: Risk assessing healthcare systems operating with artificial intelligence and industry 4.0," *Health Technol.*, vol. 13, pp. 11–15, Jan. 2023.

[46] V. Singh, P. Gangsar, R. Porwal, and A. Atulkar, "Artificial intelligence application in fault diagnostics of rotating industrial machines: A state-of-the-art review," *J. Intell. Manuf.*, vol. 34, no. 3, pp. 931–960, 2023.

[47] L. Bonati, M. Polese, S. D'Oro, S. Basagni, and T. Melodia, "NeutRAN: An open RAN neutral host architecture for zero-touch RAN and spectrum sharing," 2023, *arXiv:2301.07653*,

[48] S. L. Correa et al., "Supporting MANOaaS and heterogenous MANOaaS deployment within the zero-touch network and service management framework," *IEEE Commun. Stand. Mag.*, to be published.

[49] R. Qamar and B. A. Zardari, "An analysis of the Internet of Everything," *Mesop. J. CyberSecur.*, vol. 2023, pp. 86–93, Apr. 2023.

[50] T. Saba, A. Rehman, K. Haseeb, T. Alam, and G. Jeon, "Cloud-edge load balancing distributed protocol for IoE services using swarm intelligence," *Clust. Comput.*, vol. 26, pp. 1–11, Jan. 2023.

[51] Z. Tong, B. Liu, J. Mei, J. Wang, W. Li, and K. Li, "D2OP: A fair dual-objective weighted scheduling scheme in Internet of Everything," *IEEE Internet Things J.*, vol. 10, no. 10, pp. 9206–9219, May 2023.

[52] Y. Jiang, S. Yin, K. Li, H. Luo, and O. Kaynak, "Industrial applications of digital twins," *Philos. Trans. Royal Soc. A*, vol. 379, no. 2207, 2021, Art. no. 20200360.

[53] H. Van der Valk, H. Haße, F. Möller, M. Arbter, J.-L. Henning, and B. Otto, "A taxonomy of digital twins," in *Proc. AMCIS*, 2020, pp. 1–10.

[54] A. El Saddik, "Digital twins: The convergence of multimedia technologies," *IEEE MultiMedia*, vol. 25, no. 2, pp. 87–92, Apr.–Jun. 2018.

[55] A. Dzedzickis, J. Subaciute-Žemaitiene, E. Šutinys, U. Samukaite-Bubniene, and V. Bucinskas "Advanced applications of industrial robotics: New trends and possibilities," *Appl. Sci.*, vol. 12, no. 1, p. 135, 2021.

[56] Z. Pan, J. Polden, N. Larkin, S. Van Duin, and J. Norrish, "Recent progress on programming methods for industrial robots," *Robot. Comput.-Integr. Manuf.*, vol. 28, no. 2, pp. 87–94, 2012.

[57] B. Bajic, N. Suzic, S. Moraca, M. Stefanovic, M. Jovicic, and A. Rikalovic, "Edge computing data optimization for smart quality management: Industry 5.0 perspective," *Sustainability*, vol. 15, no. 7, p. 6032, 2023.

[58] F. Khan, R. L. Kumar, M. H. Abidi, S. Kadry, H. Alkhalefah, and M. K. Aboudaif, "Federated split learning model for industry 5.0: A data poisoning defense for edge computing," *Electronics*, vol. 11, no. 15, p. 2393, 2022.

[59] P. Fraga-Lamas, S. I. Lopes, and T. M. Fernández-Caramés, "Green IoT and edge AI as key technological enablers for a sustainable digital transition towards a smart circular economy: An industry 5.0 use case," *Sensors*, vol. 21, no. 17, p. 5745, 2021.

[60] R. S. Peres, X. Jia, J. Lee, K. Sun, A. W. Colombo, and J. Barata, "Industrial artificial intelligence in industry 4.0—Systematic review, challenges and outlook," *IEEE Access*, vol. 8, pp. 220121–220139, 2020.

[61] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2347–2376, 4th Quart., 2015.

[62] Y. Lu, C. Liu, I. Kevin, K. Wang, H. Huang, and X. Xu, "Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues," *Robot. Comput.-Integr. Manuf.*, vol. 61, Feb. 2020, Art. no. 101837.

[63] A. C. Simões, A. L. Soares, and A. C. Barros, "Factors [influencing the] intention of managers to adopt collaborative robots (cobots) in manufacturing organizations," *J. Eng. Technol. Manag.*, vol. 57, Jul.–Sep. 2020, Art. no. 101574.

[64] K. Sowa, A. Przegalinska, and L. Ciechanowski, "Cobots in knowledge work: Human–AI collaboration in managerial professions," *J. Bus. Res.*, vol. 125, pp. 135–142, Mar. 2021.

[65] A. Sharma and H. Pandey, "Big data and analytics in industry 4.0," in *A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development*. New York, NY, USA: Springer, 2020, pp. 57–72.

[66] X. Wu, R. Dunne, Q. Zhang, and W. Shi, "Edge computing enabled smart firefighting: Opportunities and challenges," in *Proc. 5th ACM/IEEE Workshop Hot Topics Web Syst. Technol.*, 2017, pp. 1–6.

[67] A. Robles-Enciso and A. F. Skarmeta, "A multi-layer guided reinforcement learning-based tasks offloading in edge computing," *Comput. Netw.*, vol. 220, Jan. 2023, Art. no. 109476.

[68] R. Sanketh, Y. MohanaRoopa, and P. N. Reddy, "A survey of fog computing: Fundamental, architecture, applications and challenges," in *Proc. 3rdInt. Conf. I-SMAC (IoT Soc., Mobile, Anal. Cloud) (I-SMAC)*, 2019, pp. 512–516.

[69] P. Hu, S. Dhelim, H. Ning, and T. Qiu, "Survey on fog computing: Architecture, key technologies, applications and open issues," *J. Netw. Comput. Appl.*, vol. 98, pp. 27–42, Nov. 2017.

[70] M. Hudnurkar, S. Jakhar, and U. Rathod, "Factors affecting collaboration in supply chain: A literature review," *Procedia-Soc. Behav. Sci.*, vol. 133, pp. 189–202, May 2014.

[71] H. Zhang, Q. Yan, and Z. Wen, "Information modeling for cyber-physical production system based on digital twin and automationML," *Int. J. Adv. Manuf. Technol.*, vol. 107, pp. 1927–1945, Mar. 2020.

[72] Y. Wang et al., "A survey on metaverse: Fundamentals, security, and privacy," *IEEE Commun. Surveys Tuts.*, vol. 25, no. 1, pp. 319–352, 1st Quart., 2023.

[73] D. Sportillo, A. Paljic, and L. Ojeda, "On-road evaluation of autonomous driving training," in *Proc. 14th ACM/IEEE Int. Conf. Human–Robot Inter. (HRI)*, 2019, pp. 182–190.

[74] Y. Xiao, Y. Jia, C. Liu, X. Cheng, J. Yu, and W. Lv, "Edge computing security: State of the art and challenges," *Proc. IEEE*, vol. 107, no. 8, pp. 1608–1631, Aug. 2019.

[75] M. Liyanage, A. Braeken, P. Kumar, and M. Ylianttila, *IoT Security: Advances in Authentication*. Hoboken, NJ, USA: Wiley, 2020.

[76] D. Tosh, O. Galindo, V. Kreinovich, and O. Kosheleva, "Towards security of cyber-physical systems using quantum computing algorithms," in *Proc. IEEE 15th Int. Conf. Syst. Syst. Eng. (SoSE)*, 2020, pp. 313–320.

[77] C. Esposito, A. Castiglione, B. Martini, and K.-K. R. Choo, "Cloud manufacturing: Security, privacy, and forensic concerns," *IEEE Cloud Comput.*, vol. 3, no. 4, pp. 16–22, Jul./Aug. 2016.

[78] E. Lee, Y.-D. Seo, S.-R. Oh, and Y.-G. Kim, "A survey on standards for interoperability and security in the Internet of Things," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 1020–1047, 2nd Quart., 2021.

[79] J. Nilsson and F. Sandin, "Semantic interoperability in industry 4.0: Survey of recent developments and outlook," in *Proc. IEEE 16th Int. Conf. Ind. Inf. (INDIN)*, 2018, pp. 127–132.

[80] T. Burns, J. Cosgrove, and F. Doyle, "A review of interoperability standards for industry 4.0," *Procedia Manuf.*, vol. 38, pp. 646–653, Jan. 2019.

[81] K. Lange, G. Korevaar, I. Nikolic, and P. Herder, "Actor behaviour and robustness of industrial symbiosis networks: An agent-based modelling approach," *J. Artif. Soc. Soc. Simul.*, vol. 24, no. 3, pp. 1–28, 2021.

[82] Y. Wang, Y.-A. Tan, T. Baker, N. Kumar, and Q. Zhang, "Deep fusion: Crafting transferable adversarial examples and improving robustness of industrial artificial intelligence of things," *IEEE Trans. Ind. Informat.*, vol. 19, no. 6, pp. 7480–7488, Jun. 2023.

[83] A. Brintrup, A. Ledwoch, and J. Barros, "Topological robustness of the global automotive industry," *Log. Res.*, vol. 9, pp. 1–17, Dec. 2016.

[84] M. M. H. Onik, K. Chul-Soo, and Y. Jinhong, "Personal data privacy challenges of the fourth industrial revolution," in *Proc. 21st Int. Conf. Adv. Commun. Technol. (ICACT)*, 2019, pp. 635–638.

[85] H. Gimpel, D. Kleindienst, N. Nüske, D. Rau, and F. Schmied, "The upside of data privacy–delighting customers by implementing data privacy measures," *Electron. Mark.*, vol. 28, pp. 437–452, May 2018.

[86] B. Jiang, J. Li, G. Yue, and H. Song, "Differential privacy for Industrial Internet of Things: Opportunities, applications, and challenges," *IEEE Internet Things J.*, vol. 8, no. 13, pp. 10430–10451, Jul. 2021.

[87] T. Hamada, "Determinants of decision-makers' attitudes toward industry 4.0 adaptation," *Soc. Sci.*, vol. 8, no. 5, p. 140, 2019.

[88] F. Sözbilir, "Development and validation of an industry 4.0 adaptation potential scale (4IRAPS)," *Technol. Econ. Develop. Econ.*, vol. 27, no. 3, pp. 704–721, 2021.

[89] R. C. Santos and J. L. Martinho, "An industry 4.0 maturity model proposal," *J. Manuf. Technol. Manag.*, vol. 31, no. 5, pp. 1023–1043, 2020.

[90] J. Oláh, N. Aburumman, J. Popp, M. A. Khan, H. Haddad, and N. Kitukutha, "Impact of industry 4.0 on environmental sustainability," *Sustainability*, vol. 12, no. 11, p. 4674, 2020.

[91] S. Kunkel and M. Matthess, "Digital transformation and environmental sustainability in industry: Putting expectations in Asian and African policies into perspective," *Environ. Sci. Policy*, vol. 112, pp. 318–329, Oct. 2020.

[92] A. Spieske and H. Birkel, "Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the COVID-19 pandemic," *Comput. Ind. Eng.*, vol. 158, Aug. 2021, Art. no. 107452.

[93] J. Zhu and M. Ruth, "Exploring the resilience of industrial ecosystems," *J. Environ. Manag.*, vol. 122, pp. 65–75, Jun. 2013.

[94] P. Wicher, D. Staš, M. Karkula, R. Lenort, and P. Besta, "A computer simulation-based analysis of supply chains resilience in industrial environment," *Metalurgija*, vol. 54, no. 4, pp. 703–706, 2015.

[95] H. N. Ngoc, G. Lasa, and I. Iriarte, "Human-centred design in industry 4.0: case study review and opportunities for future research," *J. Intell. Manuf.*, vol. 33, no. 1, pp. 35–76, 2022.

[96] D. Li, A. Landström, Å. Fast-Berglund, and P Almström, "Human-centred dissemination of data, information and knowledge in industry 4.0," *Procedia CIRP*, vol. 84, pp. 380–386, Jan. 2019.

[97] F. Celaschi, "Advanced design-driven approaches for an industry 4.0 framework: The human-centred dimension of the digital industrial revolution," *Strateg. Design Res. J.*, vol. 10, no. 2, pp. 1–8, 2017.