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REVIEW

Industry 5.0: a review of emerging trends and transformative technologies in the next industrial revolution

Tarun Rijwani[1] · **Soni Kumari**[2] · **R Srinivas**[3] · **Kumar Abhishek**[1] · **Ganesh Iyer**[1] · **Harsh Vara**[1] · **Shreya Dubey**[4] · **V Revathi**[5] · **Manish Gupta**[6]

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Abstract

The emerging concept of Industry 5.0 centers on the collaboration between humans and machines within manufacturing. In contrast to prior studies, this paper thoroughly explores the essential technologies, implementation strategies, and potential applications of Industry 5.0. It offers fresh perspectives on various transformative approaches, emphasizing their capacity to boost efficiency, and conducts a comprehensive review of existing literature and case studies to illuminate the landscape of Industry 5.0. Additionally, the paper underscores the contributions of diverse technologies and strategies toward realizing the objectives of Industry 5.0. Moreover, it highlights the challenges requiring attention for successful integration and proposes future research directions to propel the field forward. Noteworthy technologies examined in this research include Edge computing, IoT, Blockchain, Artificial Intelligence, Cobots, Big Data Analysis, and 6G. This review is poised to catalyze further discourse, research, and development aimed at refining and integrating technologies for Industry 5.0 advancement.

Keywords Industry 5.0 · Cobots · IoT · Artificial intelligence · Big data analysis

1 Introduction

Starting in the late 18th century and extending into the 19th century, there was a profound shift from traditional agrarian and artisanal economies to a new paradigm of mechanized and factory-based production. This development referred to as the First Industrial Revolution, represents a transformative era in human history that laid the foundation for modern industrialization and fundamentally changed the way we live and work today [1]. Key to Industry 1.0 was the widespread adoption of steam power and the mechanization of labor-intensive tasks. Innovations such as the steam engine, textile machinery, and advancements in the iron and coal industries spurred a dramatic increase in productivity, enabling the production of goods on an unprecedented scale. This era saw the birth of factories, where workers operated machines to manufacture textiles, tools, and other goods, marking the beginning of mass production. Industry 1.0 not only transformed manufacturing processes but also had far-reaching impacts on society. This included urbanization, as people flocked to industrial centers seeking employment, and the development of transportation systems like railways to facilitate the movement of goods

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✉ Kumar Abhishek
krabhishek1987@gmail.com

R Srinivas
regonda.srinivas@gmail.com

[1] Department of Mechanical and Aerospace Engineering, Institute of Infrastructure Technology Research and Management, Ahmedabad, Gujarat, India

[2] Department of Mechanical Engineering, GLA University, Mathura, Uttar Pradesh, India

[3] Department of Mechanical Engineering, Institute of Aeronautical Engineering, Hyderabad, Telangana, India

[4] Department of Computer Science and Engineering, Shri Shankaracharya Institute of Engineering & Technology, Bhilai Durg, Chhattisgarh, India

[5] Department of Applied Sciences, New Horizon College of Engineering, Bangalore, India

[6] Division of Research and Development, Lovely Professional University, Phagwara, India

and people [2]. The First Industrial Revolution set the stage for subsequent waves of technological progress and continues to shape the world today. Following the First Industrial Revolution, a new wave of transformative technologies and industrial practices began during the late 19th century and continued until the early 20th century, known as the Second Industrial Revolution. Innovations in electricity, steel production, and the proliferation of internal combustion engines were the core enablers of this period. As a result of these breakthroughs, manufacturing, communication, and transportation saw significant transformations [3]. Electric power transformed manufacturing processes by enabling more adaptable and efficient production techniques. The emergence of steel as a multipurpose building material prompted the creation of bridges and skyscrapers, revolutionizing urban environments. Internal combustion engine-powered cars made mobility and transportation more widely available. Additionally, the emergence of mass manufacturing techniques, exemplified by Henry Ford's assembly line, marked Industry 2.0. These techniques drastically reduced costs and improved the availability of consumer products. Furthermore, the telephone and the telegraph emerged during this time, enabling quick long-distance communication. These advancements not only increased industrial efficiency but also sparked a surge of urbanization as people moved to cities in pursuit of better prospects [4]. Many of the economic, social, and technical advancements that we take for granted in the twenty-first century have their roots in the Second Industrial Revolution.

The Third Industrial Revolution is another significant era in human history, defined by the combination of industry and digital technology. This era, which began in the late 20th century and continues into the 21st, brought about a substantial transformation in automation, manufacturing, and communication, significantly impacting how we interact with one another and go about our daily lives [5]. Industry 3.0 was primarily driven by the widespread use of computerization and automation in industrial processes [6]. This wave of innovation introduced computers, software, and information technology to improve and expedite production. Programmable Logic Controllers (PLCs) are an example of an automation system that transformed manufacturing processes by enabling precise control and coordination of machinery. The growth of digital networks and the Internet during Industry 3.0 gave rise to the concept of the "Internet of Things" (IoT), which revolutionized the way data is gathered, analyzed, and used in industrial settings. This connectivity enabled seamless communication between systems, sensors, and devices, making real-time data exchange and decision-making essential for the smooth operation of smart factories and supply chains. Industry 3.0 also introduced the concept of "big data," referring to the vast amounts of information that can be collected and analyzed to predict maintenance needs, optimize production, and enhance overall efficiency. Furthermore, the integration of robotics and artificial intelligence advanced automation, allowing machines to perform tasks with a higher degree of autonomy and intelligence [7]. The Third Industrial Revolution significantly transformed the global economy and industry, leading to reduced costs, increased productivity, and the emergence of new business models. This era continued to drive innovation, impacting various sectors such as manufacturing, healthcare, transportation, and agriculture. Emerging in the 21st century, the fusion of digital, physical, and biological technologies characterized this period, signaling a shift in our approach to manufacturing, technology, and interconnected systems, and paving the way for the Fourth Industrial Revolution, known as Industry 4.0 [3].

At the core of Industry 4.0 is the adoption of advanced technologies like the Internet of Things (IoT), artificial intelligence (AI), big data, cloud computing, and cyber-physical systems [4]. These advancements have facilitated the development of smart factories and supply chains, where machines, products, and systems interact and collaborate in real time. In this context, sensors embedded in machinery and products gather data that is immediately analyzed and acted upon [5]. A fundamental aspect of Industry 4.0 is "smart manufacturing," which leverages automation, robotics, and AI to optimize production processes. This not only improves efficiency but also enables more customized and flexible production, meeting the specific needs of individual customers [6 Industry 4.0 promotes a new era of connectivity and information exchange where cyber-physical systems and cloud computing enable seamless sharing of data and decision-making across organizations, making supply chains more adaptive and responsive. This, in turn, has led to advancements in predictive maintenance, reducing downtime and increasing the lifespan of machinery [7]. Moreover, the Fourth Industrial Revolution is changing our perception of products. The integration of technology into physical items, referred to as the Internet of Things, has led to the creation of "smart products" that can communicate with users and other products, opening up new possibilities in fields such as healthcare, transportation, and consumer goods [8].

The chronology and key components of industrial advancements are displayed in Fig. 1. where the latest and cutting-edge phase in the evolution of industry and production technology is Industry 5.0 referred to as The Fifth Industrial Revolution. Industry 5.0 builds upon the foundations of its predecessors while introducing groundbreaking advancements that emphasize the harmonious interaction between humans and machines [9]. The core of Industry 5.0 is the concept of "human-machine collaboration" for

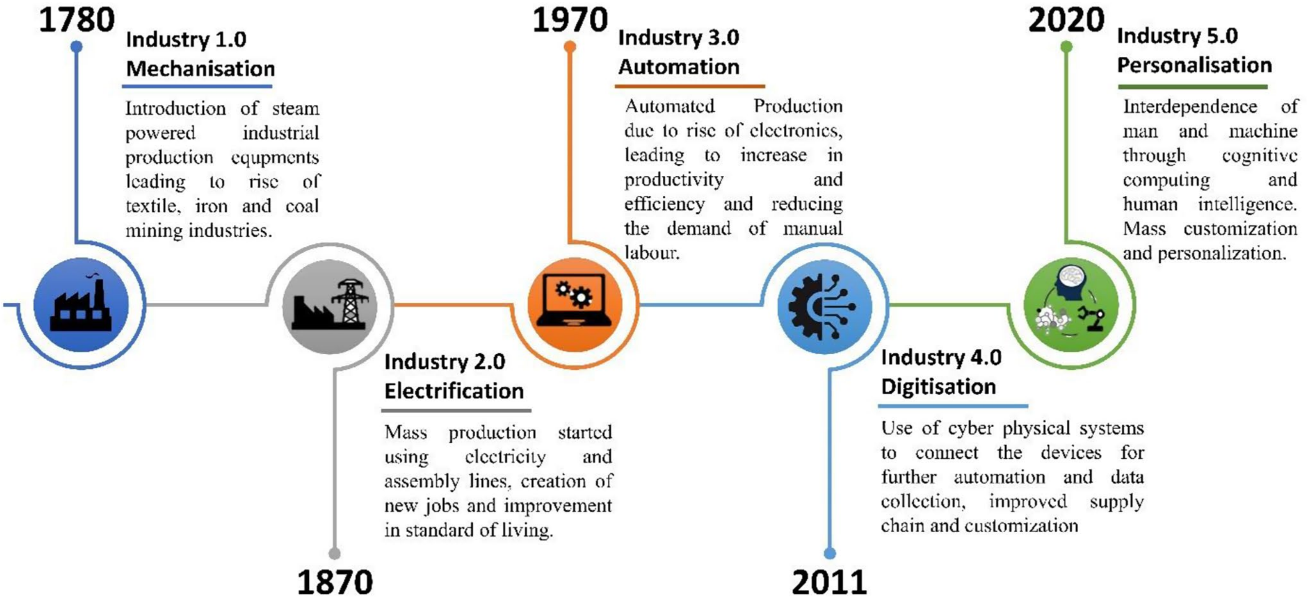


Fig. 1 Timeline and essentials of industrial revolutions

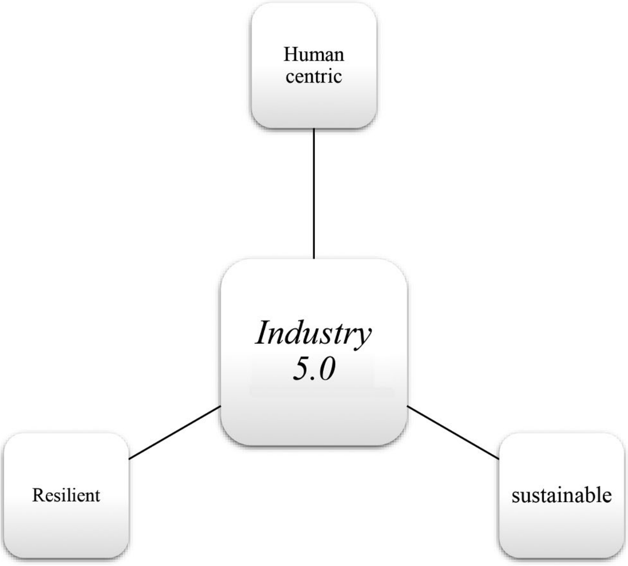


Fig. 2 Three core features of industry 5.0

resilient and sustainable human development. Acknowledging that although digitalization and automation have significantly increased industry efficiency and innovation, human creativity, skills, and problem-solving continue to be vital. Modern technology is made to enhance and supplement human abilities, encouraging a more diverse and well-rounded approach to work. Creating immersive and interactive work environments by utilising cutting-edge technologies like wearables, virtual reality (VR), and augmented reality (AR). By enabling more intuitive and natural interactions between workers and machines and digital systems, these technologies improve decision-making, training, and problem-solving abilities. The objective is to maintain high productivity levels while simultaneously improving worker well-being and job quality. These days, edge computing and the Internet of Things (IoT) are indispensable for facilitating real-time data collection and analysis that aids in decision-making. On the other hand, the focus moves from complete automation to a more cooperative and balanced strategy. Human ingenuity is employed to tackle complex, non-routine challenges, while automation and robots are utilised to handle repetitive and physically taxing tasks. Industry 5.0 is not just a technological revolution; it is a cultural and organizational shift. It underscores the importance of lifelong learning, adaptability, and the development of human skills to remain relevant in a rapidly evolving job landscape. As industries continue to transform, businesses and workers are rethinking their roles, responsibilities, and relationships with technology. Industry 5.0's three.

main characteristics are depicted in Fig. 2.

2 Core Enabling technologies of Industry 5.0

Industry 5.0 is a manufacturing revolution that depends on a strong combination of key enabling technologies shown in Fig. 3. In smart factories core enabling technologies like edge computing become essential for processing data in real-time at the network's edge. This is especially important for applications that require low latency. The interconnectivity of devices through the Internet of Things (IoT) facilitates smooth communication and data exchange, hence empowering intelligent decision-making. Blockchain guarantees data

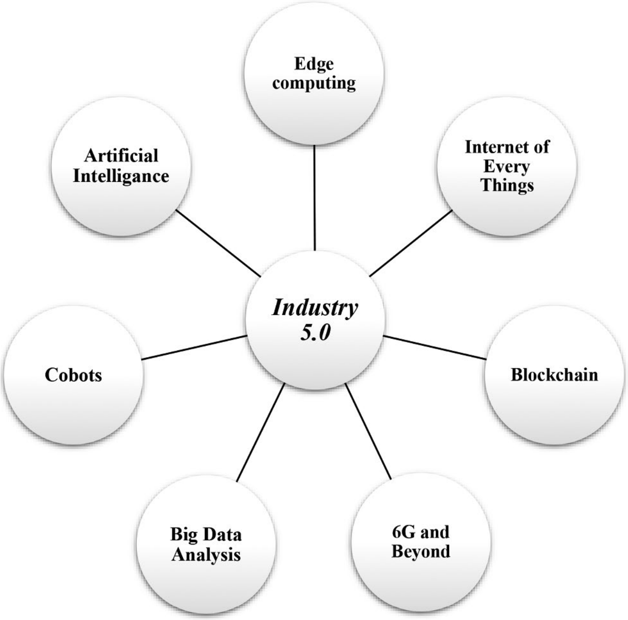


Fig. 3 Core Enabling Technologies of Industry 5.0

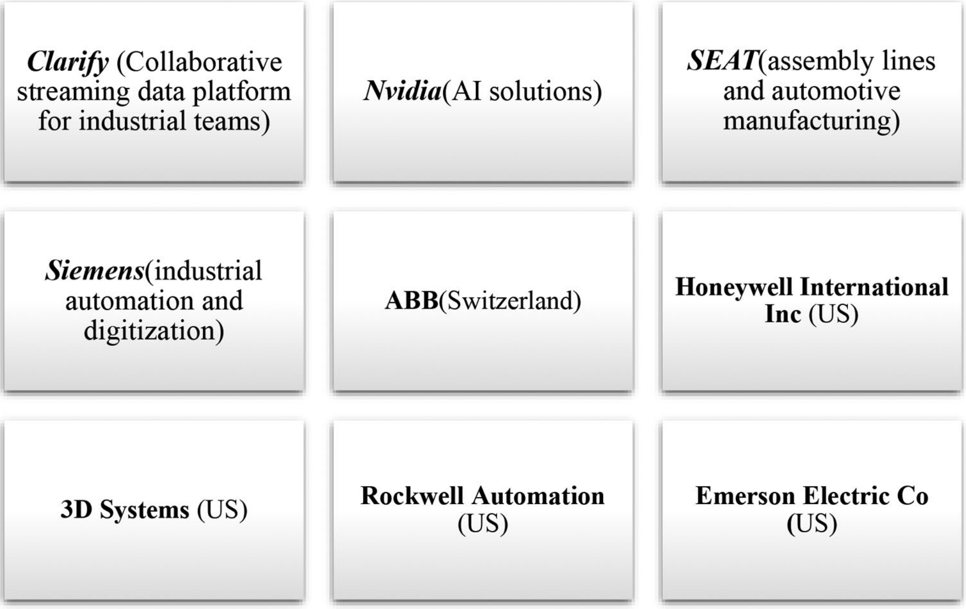
quality, transparency, and traceability throughout the supply chain with its decentralized and secure ledger system. Ultra-connectivity, ultra-reliability, and ultra-low latency are key components that will revolutionize communication networks and open up new application opportunities as we move closer to 6G and beyond. Cobots, or collaborative robots, are essential for improving efficiency and human-robot interaction. Massive datasets are sorted through big data analytics, which extracts priceless information that is essential for well-informed decision-making.

In the front is artificial intelligence (AI), promoting industry-wide innovation and improving operations through adaptive manufacturing, predictive maintenance, and autonomous systems. Together, these technologies drive Industry 5.0 toward previously unheard-of levels of creativity, flexibility, and efficiency.

2.1 Edge computing

Sharma et al. [10] addressed the pivotal role of edge computing in enabling real-time data processing at the network's edge. Through a comprehensive survey, the paper fills a gap in recent literature by discussing the significance of edge computing and the supporting technologies. It addresses the challenges like privacy and sustainability. Miao et al. [11] discussed about integrating Industry 5.0 with edge computing reduces bottlenecks and delays, transitioning the industrial model from centralized to distributed. However, there will be privacy concerns arising with increased network interaction. The paper describes three-factor authentication and elliptic curve cryptography for anonymity, confidentiality, and integrity. Shruti et al. [12] highlighted how Fog computing plays a crucial role in facilitating real-time data processing for Industrial Internet of Things (IIOT) devices, enhancing security and efficiency. The research introduces a hierarchical fog computing-based architecture for smart energy-supplying systems, aiming to support numerous infrastructural architectures, highlighting the superiority of the proposed four-layer fog computing approach. Additionally, security measures employing Attribute-based encryption (ABE) ensure data confidentiality with minimal overhead, further enhancing the architecture's robustness. Cao et al. [13] have addressed the challenges posed by the growing number of Internet-connected smart devices due to the Internet of Everything (IoE). Traditional cloud

Fig. 4 Lists the Industry 5.0 ready companies and products



computing is struggling with issues like bandwidth, speed, security, and privacy. This has led to the emergence of edge computing, a paradigm that prioritizes proximity to users and data sources, focusing on local, lightweight data processing thereby reducing the latency and increasing the speed of decision-making. Mao et al. [14] discussed the shift in mobile computing from centralized mobile cloud computing to mobile edge computing (MEC) driven by IoT and 5G. MEC moves computation, network control, and storage to network edges to support latency-critical applications on resource-limited mobile devices. It promises reduced latency and energy consumption, aligning with 5G goals. The paper surveys current MEC research, emphasizing joint radio-and-computational resource management and addressing issues like system deployment, cache-enabled MEC, mobility management, green MEC, and privacy-aware MEC. It also mentions standardization efforts and typical MEC application scenarios. Chen et al. [15] have discussed the increasing use of deep learning in various applications, such as computer vision and natural language processing, where end devices like smartphones and IoT sensors generate data requiring real-time analysis or model training. However, deep learning demands substantial computation resources. Edge computing, deploying compute nodes near end devices, addresses the need for high computation and low latency, also enhancing privacy, bandwidth efficiency, and scalability. Edge computing bridges cloud computing to end users, enabling technologies like 5G, IoT, augmented reality, and vehicle-to-vehicle communication by offering low latency for delay-sensitive applications. The latest developments, including Mobile Edge Computing, Cloudlet, and Fog computing, highlight its core applications and significance in real-life scenarios where quick response time is crucial [16].

2.2 Big data analysis

Big Data offers both opportunities and challenges for modern society and data scientists. Big data analysis is useful where there are subtle population patterns and their massive size and complexity introduce unique computational and statistical obstacles, such as scalability, storage, noise, spurious correlation, endogeneity, and measurement errors. Gopal et al. [17] investigated the impact of big data analytics on the retail supply chain by evaluating various big data practices using TODIM (Interactive Multi-criteria Decision Making). The evaluation had involved nine practices, including data science, neural networks, and IoT, assessed according to seven supply chain performance criteria. Rinat et al. [18] compared the use of big data computing in Industry 4.0 and Industry 5.0, based on real-world data. The result reveals a 2% decrease in faculty item production and a 1% reduction in energy usage in highly automated companies in Industry 5.0. Notably, the study also presented that fault Type B had constituted 65% of defects in Industry 4.0, while their results had highlighted the benefits of Industry 5.0, emphasizing human-machine collaboration, data-driven processes, and personalized products and services. This shift had contributed to more efficient, sustainable, and quality-centric manufacturing. Fan et al. [19] have examined the salient features of Big Data, focusing on their effect on statistical and computational methods and computing architectures, and emphasized the importance of sparse solutions. They noted that incidental endogeneity prevents validation of many statistical assumptions, which can result in incorrect inferences and scientific conclusions. The concept of big data, characterized by large, diverse, and complex datasets posing challenges in storage, analysis, and visualization, is the foundation of big data analytics. This process involves uncovering hidden patterns and correlations within these datasets, ultimately providing valuable insights that can offer a competitive advantage to companies and organizations [20]. Das et al. [21] provided an overview of big data, including its content, scope, methods, advantages, challenges, and a discussion of privacy concerns.

2.3 Internet of things

With its ability to seamlessly exchange data and facilitate real-time communication between devices, the Internet of Things (IoT) is transforming the way we interact with our surroundings and boosting efficiency across industries. An era of networked gadgets and intelligent decision-making is ushered in by its integration, which powers smart systems that collect, evaluate, and act upon data. Deshpande et al. [22] have emphasized the pervasive influence of technology in daily life and its inevitable integration, stressing the importance of technology to intelligently simplify and enhance everyday tasks. The study also focused on examining the emergence and advancement of the Internet of Everything (IoET) as the next-generation communication tool. Singh et al. mentioned that in the era of Industry 5.0, the Integration of the Internet of Things (IoT) and sensor networks has emerged as a revolutionary force, reshaping connectivity in industrial processes. He has highlighted the essential role of IoT, its capability to link devices and machinery, thus enhancing efficiency and sustainability. With the increased adoption of smart sensors, IoT devices, and edge computing technologies, a digital ecosystem has evolved, facilitating data-driven decision-making and streamlining processes. Moreover, the section explores a variety of sensor types, including temperature, pressure, vision, and audio sensors, enabling continuous monitoring of crucial parameters for predictive maintenance and early detection [23]. Awouda et al. [24] emphasized the capability of digital twins for real-time asset monitoring and understanding system behavior through data-driven insights. Their research underscores the inadequacy of current IoT-based digital twin frameworks in addressing Industry 5.0 aspects like sustainability and human-centricity. They proposed a framework based on the IoT Architectural Reference Model (IoT-A or IoT-ARM) to standardize IoT development and implementation, showcasing its validity in vertical farming through a monitoring digital twin proof of concept. Additionally, they discuss potential applications of this framework in manufacturing and service sectors. Miraz et al. [25] discussed the comprehensive review of the current significance and potential of the Internet of Things (IoT), Internet of Everything (IoE), and Internet of Nano Things (IoNT). The paper provided a summary survey report, emphasizing the distinction between IoT and IoE, often mistakenly seen as identical. It also examined the current progress in these fields and outlines potential future applications and scenarios for their expansion. Xia et al. [26] discussed the emerging era of the Internet of Things (IoT), Internet of Everything (IoE), and Internet of Nano Things (IoNT). The work emphasized on the interconnectedness of everyday objects with embedded intelligence and its potential to enhance quality of life. It also highlights selected papers in the issue, addressing topics such as radio frequency identification, dynamic channel assignment, energy-efficient medium access control, localization algorithms, security measures, and more, while expressing gratitude to those involved in organizing the special issue and encouraging readers to explore its content. Mukhopadhyay et al. [27] have emphasized embedded devices with internet connectivity, enabling global interactions among devices, services, and people. The research highlights the potential of IoT connectivity to bolster reliability, sustainability, and efficiency by enabling enhanced information access across diverse applications such as environmental monitoring, home automation, and smart grids. Additionally, it explored into the prospect of IoT emerging as the principal source of internet-related data and introduces 6LoWPAN, a protocol specifically designed to facilitate efficient internet connectivity for low-powered wireless devices.

2.4 Blockchain

Blockchain technology operates as a decentralized, secure ledger system, ensuring transparent, tamper-proof records across transactions or data exchanges. Its cryptographic principles and distributed nature bolster trust, enabling a wide array of applications beyond finance, including supply chain management, healthcare, and secure digital identities. Wust et al. [28] highlighted the potential of blockchain technology in revolutionizing trade and societal interactions, emphasizing key features like trustless transactions, integrity-protected data storage, and process transparency without a trusted third party. They also analyzed blockchain as a suitable solution for specific scenarios, differentiating between permissionless and permissioned blockchains and comparing them to centralized databases. Additionally, they present a structured methodology to determine the best technical solution for a given application problem. Akanfe et al. [29] examined the challenges arising from the intersection of Blockchain Technology (BCT) and privacy regulations, particularly the General Data Protection Regulation (GDPR). The study highlighted the conflict between blockchain technology's decentralized and immutable nature and GDPR's stringent privacy requirements. The research had explored tensions and opportunities for synergy to ensure privacy regulatory compliance usingTechnology-Organization-Environment (TOE) theoretical lens. It had identified areas of friction and proposed nine research propositions focusing on six key GDPR data privacy requirements through an analysis of 71 multidisciplinary research studies. The study aimed to contribute to the discourse on privacy-compliant blockchain solutions, offering a theoretical foundation for future investigations. It had suggested that reconciling blockchain technology and privacy regulations would unleash blockchain's full potential, fostering a secure and privacy-conscious technology infrastructure with practical implications for policymakers. Babu et al. [30] explored the potential of IoT in various applications and addressed its challenges, such as data security and energy efficiency, due to resource constraints and device diversity. They proposed a novel approach combining a genetic algorithm (GA) for energy optimization and mixed integer linear programming (MILP) for strategic node deployment, integrated with blockchain technology for data privacy. The proposed method demonstrated superior performance in network longevity and throughput compared to existing models, offering reliable and efficient IoT operations while ensuring data security. Nofer et al. [31] provided analysis of three use cases: Supply Chain Management, Interbank and International Payments, and Decentralized Autonomous Organizations, concluding with an outlook on future opportunities.

2.5 6G and beyond

Devi et al. [32] discussed about Next-Generation Networks, especially 5G, have transformed the telecommunications sector by combining networks and services, offering faster speeds, and meeting evolving consumer and business needs. These networks, known for their scalability and reliability, have rapidly evolved from 1G to 6G, with 5G driving advancements in AI, IoT, and augmented reality. The research also discussed about the potential of 6G networks, which will provide high-speed connectivity and support a wide range of devices. The study also highlights the possibilities of 7G, which aims to achieve seamless, wireless connectivity with enhanced bandwidth and coverage, enabling uninterrupted services and lowering costs for users. Alsharif et al. [33] mentioned as the global quest for sustainable energy solutions continues, incorporating cutting-edge technologies into smart energy grid management (SEGM) becomes increasingly vital. The emergence of Sixth Generation (6G) wireless networks offers an exciting opportunity to revolutionize how we monitor, control, and optimize energy grids. The paper explored the potential of 6G networks in SEGM, discussing envisioned capabilities and techniques. The research also addressed key challenges and opportunities such as scalability, security, real-time monitoring, and dynamic spectrum access. Additionally, it examined about the integration of 6G networks to technologies like Blockchain and Cybertwin to enhance resilience, emphasizing their transformative potential in paving the way for a sustainable and intelligent future in energy grid management. Chen et al. [34] stated that Frequency Selective Surfaces (FSSs) have garnered significant attention for their ability to reduce interference and enhance channel quality in wireless communication networks by selectively manipulating electromagnetic waves within specific frequency ranges. The research also highlighted FSS technology, alongside Intelligent Reflective Surfaces (IRSs), is being considered for future 6G communication system. The study also compared FSS and IRS technologies for 6G networks.

Strinati et al. [35] advocated incorporating semantic and goal-oriented aspects in 6G networks to enhance system effectiveness and sustainability. It emphasized the importance of conveying meaning and achieving goals in communication, focusing on relevant information, and leveraging semantic learning strategies. These strategies mentioned in literature can improve interpretation and counter adversarial attacks, benefiting the 6G network. Akyildiz et al. [36] outlined the vision for 6G and beyond, aiming to provide ubiquitous wireless connectivity for a fully connected world. They discussed the major technological advancements required, including THz band networks, intelligent communication environments, AI, network automation, dynamic spectrum access, energy-efficient communications, and space-based networks. Liu et al. [37] highlighted use cases and recent developments in emerging technologies, addressing open challenges and providing a development timeline for 6G efforts. The study also explored promising early-stage technologies, such as the Internet of NanoThings, the Internet of BioNanoThings, and quantum communications, which will shape the future of wireless communication.

2.6 Cobots

Li Liu [38 discussed the significant impact of rapid advancements in robot technology on manufacturing, particularly focusing on collaborative robots (cobots) as promising solutions for productivity and ergonomics challenges. The paper explored effects of cobot on safety, system and workspace design, task scheduling, productivity, and ergonomics, providing a comprehensive understanding of their manufacturing applications. The study also outlined the future research opportunities and directions to stimulate further inquiry, offering novel insights into cobot applications and potential developments in human-cobot interaction. Prabhakaran [39] discussed the rising prevalence of collaborative robots, or cobots, in modern society, emphasizing their role in simplifying and enhancing efficiency in various tasks. The paper surveyed industrial applications of cobots and identifies leading manufacturing companies leveraging this technology. Furthermore, it offers insights into future trends, indicating the trajectory of cobot technology. Sotirios Panagou [40] explored the rise of humans and robots interaction in the workplace especially with the rise of Industry 4.0 and Industry 5.0. The study revealed various design aspects and their effects on operators. These findings offer invaluable insights for designers and practitioners, highlighting the significance of operator involvement in implementation, understanding robots' capabilities, and providing sufficient training. Robots, known as "cobots," are designed for direct interaction with human workers while handling a shared payload. They differ from autonomous industrial robots, which must be separated from humans for safety, and from teleoperators, where a human operator remotely controls a robot. Cobots use software-defined "virtual surfaces" to guide the motion of the shared payload, without adding substantial power. By combining the strength and computer interface of the cobot with the sensing and dexterity of the human worker, they offer ergonomic and productivity benefits. Peshkin et al. [41] introduce cobots as part of the Intelligent Assist Devices (IADs) category for materials handling equipment and describe two cobots currently in industrial testbeds. Future applications include tool guidance in image-guided surgery and haptic displays for feeling CAD model surfaces. Colgate et al. [42] used "steerable" nonholonomic joints for constraint, making them suitable for safety-critical tasks and high-force applications, and demonstrated the simplest cobot with a single joint (a steerable wheel) and explored two control modes: "virtual caster" and "virtual wall" control, providing experimental results for further insight. Recent research and development of autonomous mobile service robots are referred to as Collaborative Robots or CoBots. Over the past three years, these CoBots have autonomously navigated through multi-floor office buildings, covering over 1,000 km. Their functionality relies on various perceptual, cognitive, and actuation representations and algorithms. The key aspects highlighted include episodic non-Markov localization for reliable mobility, a scheduler for handling user-requested service tasks with various constraints, and symbiotic autonomy, where the CoBots proactively seek external assistance to overcome occasional limitations [43].

2.7 Artificial intelligence

The definition of artificial intelligence (AI) is a challenging aspect of the field. It involves understanding both the artificial and the intelligence components. "Artificial" in AI refers to the origin of AI systems, created by human ingenuity rather than naturally occurring through biological or evolutionary processes [44]. Artificial intelligence systems possess certain properties of intelligence as a result of human design, making them distinct from naturally intelligent entities. In essence, AI is about creating intelligent systems through human intervention and design rather than relying on natural processes [45]. In a past study by Leng et al., the evolution of manufacturing towards Industry 5.0 was explored, revealing how Artificial Intelligence (AI) opened new opportunities and features within the industrial landscape. Despite the prevailing influence of Industry 4.0 at the time, the practical implementation of Industrial Artificial Intelligence (IndAI) often failed to meet expectations. The study aimed to offer insights into designing appropriate models and algorithms for industry upgrades by categorizing IndAI according to intelligence levels and outlining four implementation principles. It identified three significant opportunities of IndAI—collaborative intelligence, self-learning intelligence, and crowd intelligence—in advancing Industry 5.0 objectives. The study also discussed pathways for implementing IndAI in Industry 5.0, along with key empowering techniques. Additionally, it addressed social barriers, technology challenges, and future research directions for IndAI, with the aim of laying the groundwork for its effective utilization in past Industry 5.0 research and engineering practices [46]. Srinivasan [47] explained that "Industry 5.0" was coined to address personalized production and human empowerment in manufacturing, responding to Industry 4.0's shortcomings in customization. The study adopted a new proof of concept for enhanced Process Mining incorporating AI techniques to automate decision-making, optimize machine settings, and conduct maintenance, providing a novel method for modeling production management. The research also emphasized on comprehensive evaluations of decision support systems (DSS) to reveal future research trends and suggesting directions for overcoming identified obstacles. Russel and Norvig [48] emphasized the development of human-centered management applications for maintenance scheduling, cost reduction, improved production yield, and the creation of a human-machine cyberspace. They concluded that this approach offers a pathway to global standardization of operational processes, enabling the design of an intelligent system with near-zero failures, capable of self-learning and continuous improvement. Foresti et al. [49] discussed the integration of artificial intelligence in smart societies, emphasizing the need for automated data analysis and smart applications. The study also introduced a method focused on reducing the gap between training and operational processes by providing advanced diagnostics for smart management. This method is adaptable to the context of Society 5.0, reducing risk factors and ensuring quality and sustainability.

2.8 Insights of industry 5.0

The shift from Industry 4.0 to Industry 5.0 has emerged as a response to the challenges faced by modern society, such as neglect of worker welfare and environmental degradation. While Industry 5.0 holds promise, its practical implementation is still a work in progress. This paper introduces a fresh perspective by presenting a new framework that delves into the intricate web of factors driving the development of Industry 5.0. Through thorough research and interviews with experts, the study identifies three crucial dimensions and 18 key factors shaping the trajectory of Industry 5.0. Notably, sustainable development emerges as the most influential dimension, with factors like renewable energy and data-driven analysis technologies playing pivotal roles. By leveraging innovative methodologies like Fermatean Fuzzy sets and DEMATEL, the study sheds light on the complex relationships among these factors, offering actionable insights for decision-makers to craft effective improvement strategies [50]. The research of Madani Bezoui explored the transition toward Industry 5.0, emphasizing its core principles of sustainability, human-centricity, and resilience in industrial advancement. Recognizing the pivotal role of advanced technology alongside human expertise, the study underscored the need to strike a balance between efficiency, cost, quality, and sustainability. Central to this exploration was the utilization of Multi-Objective Optimization (MOO) to address the intricate challenges posed by contemporary manufacturing systems. The research introduced an innovative methodology that merged mathematical modeling with swarm intelligence to tackle multifaceted optimization issues. A comprehensive Multi-Objective Mixed Integer Linear Programming (MILP) model was crafted, and its efficacy was showcased through the application of Multi-Objective Particle Swarm Optimization (MOPSO). By analyzing synthetic data, the study juxtaposed the performance of MOPSO against traditional optimization methods. The findings not only underscored the potential of MOPSO in modern manufacturing contexts but also laid the groundwork for future investigations aimed at integrating human ergonomics into the optimization framework. This holistic approach was envisioned to propel the evolution of Industry 5.0, aligning with its overarching objectives of sustainability, human-centricity, and resilience [51]. Manufacturing firms in developing economies like India faced the challenge and opportunity of integrating cleaner production practices with emerging technological innovations during Industry 5.0. This study aimed to explore this integration and identify effective implementation methods. Methodologies such as the Best Worst Method (BWM), Grey DEMATEL, and GRID Framework were used to examine transformative strategies. The study identified key strategies such as “Leveraging AI & IoT for optimization (STG B)” and “Incorporating Blockchain technology (STG D),” categorizing them into cause-and-effect groups. “Leveraging AI & IoT for optimization (STG B)” was found to be the most influential strategy. The implications extended to stakeholders like policymakers, government bodies, and academia, providing insights for aligning with global sustainability goals. The study served as a guide for manufacturing firms navigating the complex landscape of technological innovation and sustainability in Industry 5.0 [52]. .

Yavari et al. [53] represented the evolution of manufacturing, enabling collaboration between humans and machines for increased productivity. It enhances customer satisfaction by enabling personalized product manufacturing. Digital technologies are at the core of Industry 5.0, reshaping manufacturing, and supply chain management. Machine learning and artificial intelligence are harnessed to analyse big data, addressing complex manufacturing challenges. Industry 5.0’s integration of IoT and robots is essential for competitive advantage and economic growth, revolutionizing mass personalization and smart manufacturing. Souza et al. [54] focused on bringing workers back to the center of decision-making in the implementation of new technologies. The key emphasis is on making technology-driven information meaningful and eliminating waste, aligning with Lean principles and exploring the evolution of Industry 4.0 and Industry 5.0 while using the Lean approach to analyse and emphasize human-centric process improvements. Demir et al. [55] explored the potential of Industry 5.0, focusing on human-robot co-working as an emerging theme, reflects a significant advancements in robotics and AI. The study highlighted a lack of research on organizational issues related to human-robot co-working and aims to address this gap. The text suggests that these issues will likely be the subject of future research in the field of organizational robotics. Xu et al. [56] evaluated the evolution from Industry 4.0 to Industry 5.0, with Industry 4.0 being a globally adopted technology-driven initiative and Industry 5.0 being value-driven. This transition prompts questions and discussions about the coexistence of these two industrial revolutions. Outlining a structured approach using five key questions to facilitate unbiased discussions and information sources, aiming to stimulate ongoing debate and discourse on these topics. Leng et al. [57] prioritized human well-being in manufacturing, striving for social goals beyond mere growth and emphasizing prosperity for all. However, research on Industry 5.0 is currently limited. The paper reviews its evolution and core characteristics, including human-centricity, sustainability, and resiliency. Presenting a three-dimensional system architecture for Industry 5.0 implementation and discusses key enablers, future paths, potential applications, and challenges. The paper acknowledges current research limitations and suggests future research directions, aiming to foster discussions and collaboration in building a comprehensive Industry 5.0 system. Skobelev et al. [58] presented the concept of Industry 4.0, integrating the physical and virtual worlds, and then shifted focus to the emerging paradigm of Industry 5.0. Industry 5.0 envisions collaboration between Artificial Intelligence and humans to enhance human capabilities and place humanity back at the center. They outlined various modern technologies, including IoT and emerging intelligence, suggesting that their convergence will drive the transformation from Industry 4.0 to Industry 5.0 Al Faruqi [59] highlights the significance of Industry 4.0 in technological research and development, driving innovations across sectors. It introduces the concept of Society 5.0, which envisions a revolution in people’s lives through the fourth industrial revolution’s development. The main idea is to showcase a societal revolution that combines technology utilization with a focus on human aspects. Various sectors are embracing digitalization, incorporating technologies like Artificial Intelligence, Big Data, Robotics, Automation, Machine Learning, and the Internet of Things to enhance human life and address societal needs. Paschek et al. [60] provides a path for the transition from Industry 4.0 to Industry 5.0, analysing the business impact of Industry 5.0, and evaluating the strengths and weaknesses of Industry 4.0 through expert interviews. It identifies gaps, opportunities, and threats, offering suggestions for businesses to navigate this new revolution. Additionally, the paper explores the idea of reintegrating human workers into the supply chain alongside automation, emphasizing the need for improved entrepreneurship and transformation capacity in recognizing and adapting to Industry 5.0. Nahavandi [61] highlights the increasing challenges of staying competitive in a rapidly evolving tech-driven world. It emphasizes the growing role of robots and their integration with the human mind through brain-machine interfaces and AI. The research introduces Industry 5.0, focusing on human-robot collaboration rather than competition, addressing the need for increased productivity while retaining human workers. It discusses key features and concerns related to Industry 5.0, presents research developments, and argues that it will create more jobs than it displaces, benefiting the manufacturing industry and the economy. Zhou et al. [62] The research describes an intelligent manufacturing system known as a human-cyber-physical system (HCPS) involving humans, cyber systems, and physical systems to achieve manufacturing goals efficiently. It emphasizes the role of HCPS in the evolution of intelligent manufacturing, from digital manufacturing to new-generation intelligent manufacturing (NGIM). NGIM combines new-generation AI technology with advanced manufacturing technology and is considered the driving force of the new industrial revolution. it reviews the evolution of intelligent manufacturing through the lens of HCPS, discusses its characteristics and key technologies in the context of NGIM, and outlines the major challenges for HCPS in future manufacturing. Fukuda [63], brought light to Society 5.0, a human-centered vision in Japan's fifth stage of development. It focuses on the science, technology, and innovation (STI) ecosystem in this context. The paper conducts a comparative analysis of Germany and the United States to understand the historical transformation of Japan's STI ecosystem. It identifies major socio-economic risks related to labor, capital, and space. To address these risks and enhance productivity and growth in Society 5.0, the shift from a push-based to a pull-based .

Golovianko et al. [64] provided insights into the evolution of smart manufacturing through two paradigms: Industry 4.0 focuses on digitalization and automation, while Industry 5.0 emphasizes human-centricity. The shift is driven by contemporary challenges like climate change, pandemics, and warfare, necessitating sustainable and resilient decision-making involving humans. The study proposes a hybrid approach, combining the efficiency of Industry 4.0 with the sustainability of Industry 5.0. Digital cognitive clones mimicking human decision-making are presented as a key technology to enable this hybrid model, accelerating the convergence of digital and human realms. Lu et al. [65], suggested dedicated manufacturing systems are giving way to ultra-flexible smart manufacturing systems, driven by the demands of Industry 4.0. These systems must adapt to varying batch sizes of personalized products and dynamically reconfigure in near-real-time on the shop floor. Collaboration between machines and humans, often powered by artificial intelligence, is a key trend in achieving this flexibility. The impact of this collaboration goes beyond changing how work is done; it's about enhancing human capabilities and well-being. The vision is of a future where humans and machines work together harmoniously, combining human cognitive strengths with the unique abilities of smart machines to form adaptive and intelligent teams in rapidly changing circumstances.

Coelho et al. [66], suggested that the term Industry 5.0 has emerged with various interpretations. The lack of a clear definition prompted a bibliographic analysis. Many associate it with the fifth industrial revolution, aiming to promote a more just and sustainable society through a collaborative relationship between humans and machines/robots. These values align with the European Union's vision for the future of the industry but still lack a unifying idea to categorize Industry 5.0 as a distinct industrial revolution. Maddikunta et al. [67] provide an introductory overview of Industry 5.0, presenting various industry practitioners' and researchers' perspectives and definitions. It explores potential applications, including intelligent healthcare, cloud manufacturing, supply chain management, and manufacturing production. Additionally, the paper discusses supporting technologies such as edge computing, digital twins, collaborative robots, the Internet of Things, blockchain, and advanced networks like 6G. It concludes by outlining research challenges and open issues that must be addressed to fully realize the potential of Industry 5.0. Golovianko et al. [64] presented a hybrid approach that combines the efficiency of Industry 4.0 with the sustainability of Industry 5.0, using digital cognitive clones to enable the convergence of digital and human realms and enhance resilience [64].

3 Industry 5.0 ready company and products

Businesses and products that are prepared for Industry 5.0 demonstrate a deep integration of cutting-edge technologies to improve production and operational effectiveness. Businesses that are leaders in their fields include Siemens, which offers digital enterprise solutions, and ABB, which uses robotics and automation. Industry 5.0 readiness is demonstrated by products like IBM's Watson AI platform and Bosch's IoT-enabled industrial solutions, which provide intelligent decision-making and interconnected systems. Furthermore, cutting-edge companies responding to the changing demands of contemporary manufacturing and industrial landscapes, such as Veo robots specializing in collaborative robots, and Augury specializing in predictive maintenance, demonstrate innovation in line with Industry 5.0 principles. The organizations and their merchandise exemplify preparedness for the upcoming industrial revolution, prioritizing automation, connection, and data-driven insights to propel unmatched productivity and creativity [68–70].

3.1 Challenges in the implementation of industry 5.0

Despite its potential, Industry 5.0 has a number of obstacles that prevent its widespread adoption and smooth integration. The major financial outlay needed to redesign the current infrastructure in order to incorporate cutting-edge technologies is one of the main obstacles. Compatibility problems with legacy systems make integration a difficult and expensive task. Concerns regarding data protection and cyber risks are also raised by privacy and security issues, which are particularly pressing given the massive volumes of data produced by connected devices. The workforce needs to be upskilled to function in a technologically advanced environment, which presents another problem and calls for intensive training and retraining programs.

The success of Industry 5.0 depends on flawless communication and data interchange across various systems, so interoperability among multiple technologies continues to be a challenge. While still in progress, standardization initiatives necessitate close cooperation between many parties. Significant obstacles also arise from the ethical issues surrounding the use of AI, the influence of automation on jobs, and the societal ramifications of widespread technology adoption. To overcome these obstacles and ensure a more seamless transition to Industry 5.0, industries, governments, and technology developers must work together to address technical, ethical, and socioeconomic issues.

In the past decade, smart technologies have made significant strides in early disease diagnosis and healthcare delivery. However, with Industry 5.0's focus on social justice and sustainability, along with digitalization and smart technologies, there has been a shift towards even more efficient outcomes. Industry 5.0 technologies offer intelligent solutions for human employees, enhancing productivity, flexibility, safety, and performance across various applications. This research centered on the healthcare sector, highlighting how Industry 5.0 technologies offer several advantages. These include automated and precise disease prediction, support for medical personnel through continuous surveillance and monitoring, and the successful digital automation of smart equipment. The study aimed to evaluate these advantages using a hybrid multi-criteria decision-making approach in a neutrosophic environment. The primary value of Industry 5.0 is to create human-centric, sustainable, and resilient industries. Sub-values specific to the healthcare sector were identified based on existing literature. Methodologies such as the Analytical Hierarchy Process (AHP) were employed to evaluate main values and sub-values, followed by the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to rank the effectiveness of Industry 5.0 technologies. The approach was designed to accommodate uncertainty using a neutrosophic environment to ensure accuracy in the evaluation process. The results indicated that AI and cloud computing were the most influential technologies in healthcare, while nanotechnology, drone technology, and robots ranked lower. Through outcome comparisons and sensitivity studies, the efficacy of the methodologies was validated, demonstrating the benefits of the approach in evaluating Industry 5.0 technologies for healthcare [71].

4 Conclusion

The study clearly depicts the evolving landscape of the industrial sector, transitioning from Industry 4.0 to the emerging paradigm of Industry 5.0. This transition is characterized by a significant shift towards human-centricity, where humans and intelligent machines collaborate to enhance productivity, efficiency, and sustainability. Industry 5.0 embodies the vision of a more just and sustainable society, focusing on the harmonious relationship between humans and machines, with a primary emphasis on human well-being. Key themes in this body of research include the integration of technologies such as AI, IoT, and automation, as well as the importance of collaborative decision-making involving humans in the face of contemporary challenges like climate change and pandemics. Industry 5.0 is a concept that is in line with the need to embrace lean principles, eliminate waste, and put workers back at the center of decision-making.

Furthermore, Industry 5.0 is viewed as an enhancement of Industry 4.0 rather than a replacement, fusing the sustainability and resilience of a more human-centric approach with the efficiency of digitalization and automation. Its ultimate goal is to create intelligent systems that enhance the welfare of both individuals and society at large. It envisions the coexistence of digital and human realms. The study also emphasizes the importance of addressing societal and organisational issues surrounding the co-working of humans and robots as well as the incorporation of cutting-edge technologies into manufacturing and production processes.

Industry 5.0 offers a chance to generate more jobs than it eliminates, which will help the manufacturing sector and the overall economy. In summary, Industry 5.0 emphasises the cooperative relationship between humans and machines for the greater good of society, marking a fundamental shift in the industrial sector. The study work that is being presented here emphasises how important it is to address the opportunities and problems that come with this new phase of industrial development, as well as the necessity of continuing conversations, cooperation, and investigation of this changing paradigm. Industry 5.0 offers exciting new possibilities for the future of production and manufacturing, with a focus on innovation, sustainability, and human prosperity.

Data availability No data available.

Declarations

Conflict of interest No conflict of interest among all authors.

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