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Review article

Virtual manufacturing in Industry 4.0: A review

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ABSTRACT

Virtual manufacturing is one of the key components of Industry 4.0, the fourth industrial revolution, in improving manufacturing processes. Virtual manufacturing enables manufacturers to optimize their production processes using real-time data from sensors and other connected devices in Industry 4.0. Web-based virtual manufacturing platforms are a critical component of Industry 4.0, enabling manufacturers to design, test, and optimize their processes collaboratively and efficiently. In Industry 4.0, radio frequency identification (RFID) technology is used to provide real-time visibility and control of the supply chain as well as to enable the automation of various manufacturing processes. Big data analytics can be used in conjunction with virtual manufacturing to provide valuable insights and optimize production processes in Industry 4.0. Artificial intelligence (AI) and virtual manufacturing have the potential to enhance the effectiveness, consistency, and adaptability of manufacturing processes, resulting in faster production cycles, better-quality products, and lower prices. Recent developments in the application of virtual manufacturing systems to digital manufacturing platforms from different perspectives, such as the Internet of things, big data analytics, additive manufacturing, autonomous robots, cybersecurity, and RFID technology in Industry 4.0, are discussed in this study to analyze and develop the part manufacturing process in Industry 4.0. The limitations and advantages of virtual manufacturing systems in Industry 4.0 are discussed, and future research projects are also proposed. Thus, productivity in the part manufacturing process can be enhanced by reviewing and analyzing the applications of virtual manufacturing in Industry 4.0.

1. Introduction

The Fourth Industrial Revolution, or "Industry 4.0", is the term used to describe the present trend of automation and data sharing in manufacturing and other sectors of the economy. It involves the use of advanced technologies such as artificial intelligence (AI), the Internet of things (IoT), big data analytics, and robotics to create a more interconnected and efficient system of production. The concept of Industry 4.0 is based on the idea of interconnectedness, in which machines and devices can communicate with each other and with humans, creating a seamless and efficient manufacturing process (Xu et al., 2021). Industry 4.0 also includes the use of advanced analytics and predictive maintenance to optimize production processes and reduce downtime. The manufacturing process is anticipated to undergo substantial changes because of Industry 4.0, including improved product quality, enhanced productivity, and expanded production flexibility. It also has the potential to transform supply chains, logistics, and customer engagement to enhance the productivity of part manufacturing processes.

Cloud computing, the industrial Internet of things (IIoT), cyber-physical systems, and big data analysis are some of the key components of Industry 4.0, which aims to develop a completely automated and interconnected manufacturing system (Bai et al., 2020). This leads to increased efficiency, productivity, and quality as well as reduced costs and waste during the parts production process (Castelo-Branco et al., 2019). Industry 4.0 also allows for the real-time monitoring, analysis, and optimization of production processes, leading to increased

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productivity, lower costs, and improved quality (Zheng et al., 2021). Manufacturing and other areas such as healthcare, transportation, and energy are anticipated to be significantly impacted by Industry 4.0 (Benitez et al., 2020). Additionally, it is expected to create new opportunities for growth and creativity as businesses can produce new goods and services that utilize the capabilities of these technologies. However, this also raises concerns regarding job displacement and the need for new skills and worker training. In Industry 4.0, virtual manufacturing is often facilitated by technologies such as computer-aided design (CAD), simulation software, and digital twins (Ghobakhloo and Fathi, 2019).

Virtual manufacturing uses computer simulations and modeling to design and test products and manufacturing processes before they are physically created (Alexopoulos et al., 2020). Virtual manufacturing is a key component of Industry 4.0 that aims to create highly integrated and efficient manufacturing systems by leveraging advanced technologies such as big data analytics, AI, and the IoT (Roldán et al., 2019). As a result, producers can identify possible problems early and make adjustments without having to pay the high expenses involved with physical prototypes (Mourtzis, 2020). Virtual manufacturing also enables manufacturers to optimize production processes, reducing waste and improving efficiency (Jihong et al., 2021). Virtual manufacturing is a key concept in Industry 4.0 and refers to the use of digital technologies and data-driven processes to optimize and streamline manufacturing operations (Mantravadi and Møller, 2019). Virtual manufacturing can be defined as the creation of a virtual model of a production system that allows the analysis and optimization of various manufacturing processes before actual production occurs. Advanced digital technologies are used to create a virtual environment in which manufacturers can design, simulate, and optimize production processes before physically implementing the actual manufacturing process (Ullah, 2019). The following are some specific examples and case studies that highlight the application of virtual manufacturing in Industry 4.0.

(1) Digital twins for predictive maintenance in Siemens' gas turbine manufacturing: Siemens employs digital twin technology to create virtual replicas of its gas turbines. Real-time data from sensors on actual turbines are fed into the digital twin, which enables predictive maintenance. Engineers can monitor the health of turbines, identify potential issues, optimize maintenance schedules, reducing downtime and improving efficiency (van Dinter et al., 2022).
(2) Augmented reality (AR)-assisted assembly in Boeing aircraft assembly: Boeing utilizes AR glasses for assembly tasks. Technicians wear AR glasses that overlay digital instructions, diagrams, and annotations onto their view of the physical aircraft. This enhances accuracy, accelerates assembly, and reduces errors (Mei and Maropoulos, 2014).
(3) Simulation-driven design at Ford Motor Company: Ford uses simulation software to test and optimize new vehicle designs virtually before physical production begins. This approach helps identify potential design flaws, improves safety, and reduces the need for expensive physical prototypes (Park et al., 2022).
(4) Virtual reality (VR) training in Airbus A380 cabin crew training: Airbus employs virtual reality simulations to train cabin crews. Trainees wear VR headsets to experience various in-flight scenarios, emergencies, and procedures. Immersive training enhances crew preparedness and reduces training costs (Buttussi and Chittaro, 2020).
(5) Remote equipment monitoring and control in General Electric wind turbine maintenance: General Electric employs IoT sensors and data analytics to remotely monitor and control wind turbines. By analyzing real-time data from turbine sensors, they can predict maintenance needs, optimize turbine performance, and reduce the frequency of physical inspections (Yang et al., 2014).
(6) Quality control and defect detection in BMW's quality assurance: BMW uses computer vision and AI-powered systems for quality control. Cameras and sensors are used to inspect defective components during the manufacturing process. Any deviation from the standard was immediately flagged to ensure high-quality production (Azamfirei et al., 2023).

These examples demonstrate how virtual manufacturing technologies transform various aspects of the manufacturing process in the context of Industry 4.0. The integration of simulation, digital twins, AR, VR, and data analytics has led to improved efficiency, reduced costs, enhanced training, and improved decision-making in manufacturing operations.

One of the key benefits of virtual manufacturing is that it can help manufacturers identify potential problems or bottlenecks in the production process before they occur in the real world. This can lead to significant cost savings and improved efficiency, as manufacturers can adjust their processes and equipment to maximize productivity and minimize waste (Sjödin et al., 2018). CAD software allows manufacturers to design digital models of products and production systems, whereas simulation software enables them to test and optimize these designs in a virtual environment (Kuhn, 2006). Digital twins are virtual representations of real-world systems or products that can be used to track and improve part manufacturing performance in real time (Marmolejo-Saucedo, 2020). By leveraging these technologies, manufacturers can reduce the cost and time required to develop new products and production processes (Mohamed et al., 2019). They can also improve the efficiency and quality of their manufacturing operations by identifying and addressing potential issues before they occur in the physical world (Gunasegaram et al., 2021). In addition, virtual manufacturing can enable greater flexibility and customization in production, as manufacturers can rapidly reconfigure their production systems in response to changing market demands. Virtual manufacturing also enables manufacturers to perform what-if analysis to test different scenarios, evaluate the impact of changes in the production process, and identify opportunities for improvement. Manufacturers can develop a digital twin of their production system and use it to model various scenarios such as changes in product design, process parameters, or equipment configuration by employing sophisticated simulation and visualization tools. In addition to simulation and optimization, virtual manufacturing can promote cooperation and communication between various groups and those engaged in the production process. By providing a common digital platform for sharing data and information, virtual manufacturing can help ensure that all stakeholders have access to the same information, which can help reduce errors and improve decision-making. The applications of virtual manufacturing in Industry 4.0 are presented in Fig. 1.

To increase the effectiveness of Industry 4.0 in the part production process, a digital manufacturing foundation was presented for productivity enhancement from both commercial and public perspectives (Gerrikagoitia et al., 2019). To create improved assembly systems for Industry 4.0, procedures for digital production and assembly systems have been studied (Cohen et al., 2019). To improve product production in Industry 4.0, product development using smart simulation has been proposed (Ahmed et al., 2019). A virtual engineering factory was developed to enhance decision-making in Industry 4.0 (Shafiq et al., 2016). A versatile framework is offered to represent Industry 4.0 processes for virtual simulations of part production (Ottogalli et al., 2019). To transform agent technology into a manufacturing sturdy, an Industry 4.0 review and platform is suggested (Adeyeri et al., 2015). To reduce design and production costs in part manufacturing, a learning environment of virtual reality for Industry 4.0 is provided (Liagkou et al., 2019). To increase the efficiency of smart manufacturing, it has been suggested that product production can be improved through creative virtual product development (Ahmed et al., 2020). The incorporation of virtual reality in training for Industry 4.0 is proposed as a way to minimize costs and improve part production efficiency and safety (Paszkiewicz et al., 2021).

Soori et al. (2013, 2014, 2016, 2017) suggested virtual machining techniques for evaluating and enhancing CNC machining in virtual

Fig. 1. The applications of virtual manufacturing in Industry 4.0.

environments. To investigate and enhance performance in the process of component production employing welding procedures, Soori et al. (2020) suggested an overview of current developments in friction stir welding techniques. Soori and Asmael (2021d) examined the implementation of virtual machining technology to minimize residual stress and displacement errors throughout the turbine blade five-axis milling procedures. Soori and Asmael (2021b) explored the applications of virtualized machining techniques to assess and reduce the cutting temperature during the milling operations of difficult-to-cut objects. Soori et al. (2021) proposed an advanced virtual machining approach to improve surface characteristics during five-axis milling procedures for turbine blades. Soori and Asmael (2021c) created virtual milling processes to reduce displacement errors throughout five-axis milling operation of impeller blades. Soori (2019) discussed virtual product development to examine and develop the component production process in virtual settings. Soori and Asmael (2022) proposed an overview of current advancements in published research to review and enhance the parameter technique for machining process optimization. To increase the effectiveness of energy usage, the reliability and precision of component manufacturing, and the quality and availability of data across the supply chain, Dastres et al. (2022) proposed a review of raido frequency identification (RFID)-based wireless manufacturing systems. Soori et al. (2023e) explored machine learning and AI in CNC machine tools to boost productivity and improve profitability in the production of components employing CNC machining operations. To improve the performance of machined components, Soori and Arezoo (2022c) reviewed the measurement and reduction of residual stress during machining operations. To improve the surface integrity and decrease the residual stress during Inconel 718 grinding operations, Soori and Arezoo (2022b) proposed optimum machining parameters using the Taguchi optimization method. To analyze and modify the CNC machine tool operations and structures, application of the finite element method is reviewed by Soori and Arezoo (2023f). To enhance accuracy in the five-axis CNC milling operation of turbine blades, a deformation error compensation methodology was presented by Soori (2023b).

To increase the life of cutting tools during machining operations, Soori and Arezoo (2022a) examined different tool wear prediction algorithms. Soori and Asmael (2021a) investigated computer-assisted process planning to boost productivity in part manufacturing procedures. Dastres and Soori (2021c) reviewed the applications of artificial neural networks in different sections, such as risk analysis systems, drone navigation, evaluation of welding, and evaluation of computer simulation quality, to explore the execution of artificial neural networks to improve the effectiveness of products. Dastres and Soori (2021e) proposed employing a communication system for environmental concerns to minimize the negative effects of technological advancement on natural catastrophes. To enhance network and online data security, Dastres and Soori (2020) suggested a secure socket layer. Dastres and Soori (2021b) studied web-based decision support systems to develop a methodology for decision support systems by evaluating and suggesting gaps between the proposed approaches. To strengthen network security measures, Dastres and Soori (2021d) analyzed recent advancements in network threats to enhance security in the web of data. To increase the potential of image processing systems in several applications, Dastres and Soori (2021a) evaluated image processing and analysis systems. Dimensional, geometrical, tool deflection, and thermal defects have been modified by Soori and Arezoo (2023b) to improve the accuracy of five-axis CNC milling processes. Recent developments in published articles were examined by Soori et al. (2023b) to assess and improve the impact of AI, machine learning, and deep learning in advanced robotics. Soori and Arezoo (2023c) developed a virtual machining system application to examine whether cutting parameters affect tool life and cutting temperature during milling operations. Soori and Arezoo (2023d) studied the impact of coolant on the cutting temperature, surface roughness, and tool wear during turning operations with Ti6Al4V alloy. Additional recent developments in published papers were reviewed by Soori (2023a) to examine and alter composite materials and structures. Soori et al. (2023d) examined the Internet of things application for smart factories in Industry 4.0 to increase quality control and optimize part manufacturing processes. To minimize cutting tool wear during drilling operations, Soori and Arezoo (2023a) designed a virtual machining system and Soori and Arezoo (2023e) decreased the residual stress and surface roughness to improve the quality of items produced utilizing abrasive water jet machining. Application of a virtual machining system for deformation error compensation was proposed by Soori (2023b) to enhance the accuracy of the five-axis milling operation of turbine blades. Application of digital twins in smart manufacturing was reviewed by Soori et al. (2023c) to analyze and enhance the performance of smart manufacturing in the part production process. Recent achievements in virtual manufacturing systems were reviewed and discussed by Soori et al. (2023a) to analyze and modify the processes of part production. Optimization of energy consumption in industrial robots was discussed by Soori et al. (2023f) with the aim of optimizing the energy consumption in industrial robots.

While the potential benefits of virtual manufacturing in the Industry 4.0 era have been widely studied in different studies, a noticeable gap exists in the comprehensive understanding of its practical implementation, challenges, and impact on traditional manufacturing paradigms. Despite the growing body of literature on this subject, there is a lack of synthesis and critical analysis consolidating diverse findings and insight into a coherent framework for the application of virtual manufacturing in Industry 4.0. Through an in-depth analysis of the literature, this review aims to contribute to the body of knowledge surrounding virtual manufacturing in Industry 4.0 by offering a comprehensive overview of its implications for manufacturing processes, resource allocation, cost effectiveness, innovation, and overall operational efficiency. The results of this study provide valuable insight for practitioners and researchers looking to harness the full potential of virtual manufacturing within the rapidly evolving landscape of Industry 4.0.

To evaluate and modify the part production processes in Industry 4.0, recent breakthroughs in the application of virtual manufacturing systems were investigated and addressed in this paper. This review aims to address this gap by systematically examining the role of virtual manufacturing in the context of Industry 4.0. By conducting a thorough review and synthesis of the existing research, this study seeks to provide a holistic understanding of the key concepts, technologies, and methodologies associated with virtual manufacturing. Furthermore, it intends to identify the major challenges, limitations, and barriers that organizations may encounter when transitioning to virtualized production environments. Future research topics are also suggested, and the limitations and benefits of Industry 4.0's virtual production systems are highlighted. Reviewing and assessing recently released publications in virtual manufacturing in Industry 4.0 has been found to advance the scientific field.

The advantages and limitations of virtual manufacturing in Industry 4.0 are presented in Sections 2 and 3, respectively. Virtual manufacturing and the Internet of things in Industry 4.0 are discussed in Section 4. Virtual manufacturing and big data analytics in Industry 4.0 are presented in Section 5. Section 6 presents virtual and additive manufacturing in Industry 4.0. Applications of autonomous robots and big data analysis in virtual manufacturing and Industry 4.0 are presented in Sections 7 and 8, respectively. AI and sustainability in virtual manufacturing and Industry 4.0 are discussed in Sections 9 and 10, respectively. Web-based virtual manufacturing platforms and cybersecurity in Industry 4.0 are presented in Sections 11 and 12, respectively. RFID technology for Industry 4.0, is discussed in Section 13. Simulation-based optimization of CNC machining using virtual machining systems is presented in Section 14. Finally, the results of the study and suggestions for future research are presented in Section 15.

2. Advantages of virtual manufacturing in Industry 4.0

Virtual manufacturing in Industry 4.0 offers numerous advantages that can help companies improve their manufacturing processes, reduce costs, and increase efficiency and productivity (Möller and Möller, 2016). The advantages of virtual manufacturing in Industry 4.0 are outlined below.

(1) Reducing costs: Virtual manufacturing allows companies to simulate production processes and test their designs, which can help them identify potential problems and make changes to the process before production begins. This reduces the cost of physical prototyping and can also reduce the number of physical prototypes required (Javaid et al., 2022b).
(2) Improved efficiency: By identifying obstacles, cutting waste, and increasing productivity, virtual manufacturing helps businesses optimize their production procedures. Consequently, the efficiency of the production process can be improved (Enrique et al., 2021).
(3) Faster time to market: By using virtual manufacturing, companies can decrease the time required to develop and promote a product. As the design and testing phases can be completed more quickly, companies can start producing their products sooner, leading to a faster time to market (Cardoso et al., 2017).
(4) Flexibility: Virtual manufacturing allows companies to quickly and easily modify their production processes to accommodate changes in product design and customer demand. This can lead to greater flexibility in the manufacturing process and improved responsiveness to market changes (Krauβ et al., 2021).
(5) Improved quality: Virtual manufacturing enables companies to identify and eliminate potential problems in the production procedure before production begins. This improves the quality of the final product and reduces the likelihood of defects and errors (Javaid et al., 2022b).
(6) Improved safety: By using virtual manufacturing, companies can simulate potentially hazardous manufacturing processes and identify potential safety hazards before production begins. This can improve worker safety and reduce the likelihood of accidents and injuries (Ammar et al., 2021).

3. Limitations of virtual manufacturing in Industry 4.0

Virtual manufacturing in Industry 4.0 has many advantages; however, it also has some limitations that should be carefully considered to ensure the successful implementation of Industry 4.0. By understanding these limitations, manufacturers can make informed decisions regarding how to integrate virtual manufacturing into their operations to optimize efficiency and performance (Skobelev and Borovik, 2017). Although virtual manufacturing has many advantages, it also has some limitations and challenges (da Silva et al., 2019). Some of the key limitations of virtual manufacturing in Industry 4.0 include the following.

(1) Accuracy: Virtual manufacturing relies heavily on computer simulations to predict the behavior of manufacturing systems. Although these simulations can be highly accurate, they are not always perfect. Real-world manufacturing systems are complex and exhibit unexpected behavior that cannot be fully captured in a simulation (Verma et al., 2022).
(2) Scope: Virtual manufacturing is typically used to simulate discrete manufacturing processes and components. It is often difficult to simulate entire manufacturing systems that include many interconnected processes and components (Leng et al., 2021).
(3) Complex and customized products: Virtual manufacturing may struggle with highly complex or customized products that have intricate geometries, materials, or functionalities. Simulating every possible configuration can be computationally intensive and time consuming. Therefore, advanced simulation algorithms and models that can handle complex geometries and materials must be developed. In addition, high-performance computing to expedite simulations should be utilized to integrate AI and machine learning to predict and optimize the outcomes for different configurations.
(4) Materials and physical properties: Virtual manufacturing often relies on accurate material data for simulations. In certain sectors, particularly those involving novel materials, precise data may not be readily available. To address this issue, it is essential to invest in material characterization and testing to gather accurate data and develop material databases that can be integrated into simulation tools. Material suppliers and researchers can help solve this problem by ensuring accurate material representation.
(5) Data availability: Virtual manufacturing relies on accurate data to simulate manufacturing processes. However, data collection can

be challenging, particularly in legacy systems that were not designed with data collection in mind.

(6) Customization: Virtual manufacturing systems are often designed for specific manufacturing processes or components. It can be challenging to customize these systems to fulfil the specific needs of certain industrial operations (Perez et al., 2022).

(7) Human involvement: Virtual manufacturing systems are highly automated, which limits the role of human workers in the manufacturing process. This can be disadvantageous in situations in which human expertise is required to resolve unexpected problems or make decisions (Peruzzini et al., 2021).

(8) Skill and knowledge gap: Lack of expertise and training in virtual manufacturing tools can hinder their adoption in certain sectors. Therefore, training and educational programs should be provided to upskill the workforce. Collaboration between academia and industry can be fostered to develop specialized training programs for virtual manufacturing.

Overcoming these limitations requires a combination of technological advancements, interdisciplinary collaboration, and a proactive approach to addressing sector-specific challenges. By continuously refining virtual manufacturing tools and methodologies, industries can unlock their full potential and reap the benefits of enhanced efficiency, reduced costs, and accelerated innovation. Applications of virtual manufacturing in Industry 4.0 is shown in Fig. 2.

4. Virtual manufacturing and IoT in Industry 4.0

Virtual manufacturing and the IoT are two related concepts in Industry 4.0 and are applied to developing manufacturing processes for optimization (Gerrikagoitia et al., 2019). These concepts have rapidly transformed the manufacturing industry. IoT is a global network of real-world objects that can collect and exchange data through software, sensors, and connections. These objects include machinery, automobiles, and buildings (Branger and Pang, 2015). IoT devices can be employed in manufacturing to manage inventories and data in the supply chain, operate production equipment, and optimize energy consumption. The combination of these two concepts can provide significant benefits for manufacturers. For example, the IoT can present real-time data on the performance of machines, which can be used to optimize virtual manufacturing models (Kurfess et al., 2020a,b). This can help manufacturers identify areas for improvement, make changes to improve productivity, reduce costs, and increase quality. Virtual manufacturing and the IoT can create a highly optimized and efficient manufacturing process in Industry 4.0 (Bi et al., 2021). The development of new manufacturing technologies, such as additive manufacturing (3D printing), which can be utilized to create complex and personalized components on demand, is also being facilitated by the modification of virtual manufacturing and the IoT (Ashima et al., 2021). These technologies are transforming the manufacturing industry by enabling faster prototyping, greater flexibility, and more efficient resource use. IoT devices can be used to collect real-time data on the performance of manufacturing equipment and feed these data into a virtual model of the production line. This allows engineers to identify potential bottlenecks, optimize machine settings, and improve overall efficiency (Riley et al., 2021). Additionally, virtual manufacturing can be used to emulate various scenarios and evaluate the impact of modifications before implementing them. This reduces the risk of errors and downtime and allows for continuous improvement of the manufacturing process (Jeschke et al., 2017). Overall, virtual manufacturing and the IoT are transforming the manufacturing industry, making it more efficient, cost-effective, and flexible. Future manufacturing methods are expected to become considerably more sophisticated and creative as these technologies improve. The combination of virtual manufacturing and the IoT enables manufacturers to create

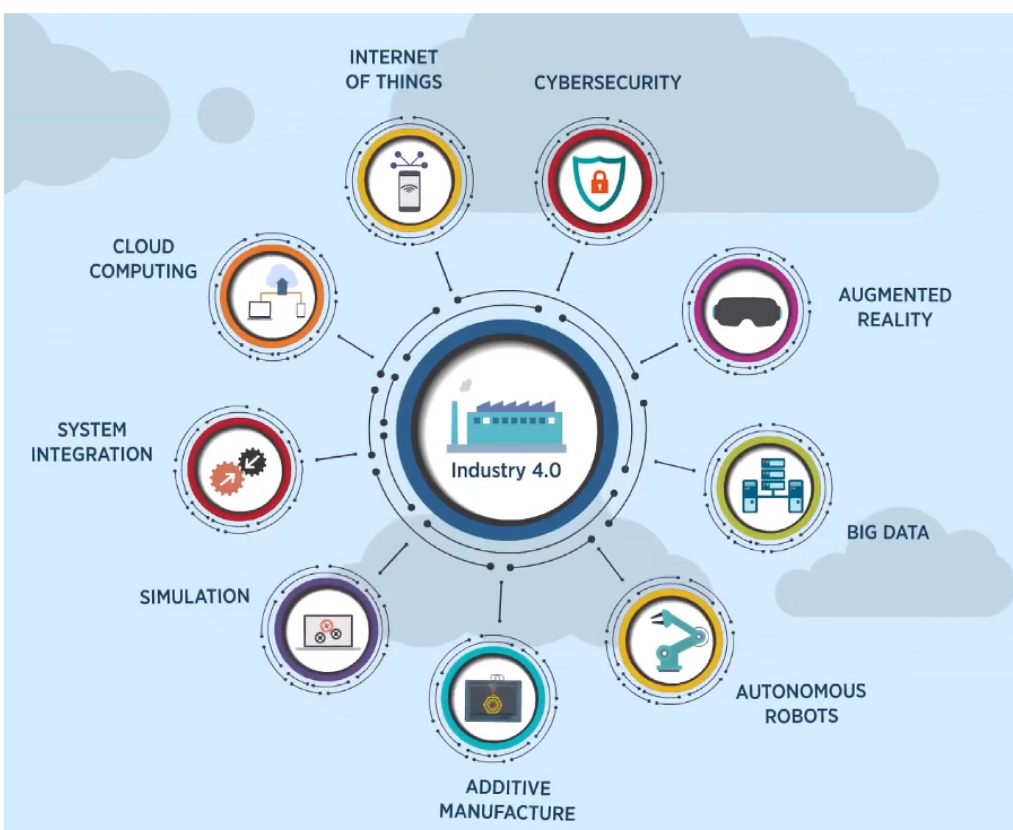

Fig. 2. Applications of virtual manufacturing in Industry 4.0.

smarter, more efficient, and more responsive production systems (Zemrane et al., 2021). Although virtual manufacturing and the IoT offer numerous benefits in Industry 4.0, these limitations must be carefully considered and managed to ensure successful implementation and operation.

(1) Security and privacy concerns: Connecting numerous devices and sensors to the Internet increases the potential attack surface for cybercriminals, leading to security and privacy vulnerabilities.
(2) Data overload: The IoT generates vast amounts of data that can overwhelm systems and make it challenging to extract meaningful insight. This can lead to difficulties in data processing, storage, and analysis (Liu et al., 2020).
(3) Interoperability: IoT devices from different manufacturers often use different communication protocols and standards, which makes it difficult for them to communicate and work together seamlessly.
(4) Reliability and maintenance: IoT devices can experience technical glitches, software bugs, or hardware failures leading to potential downtime and maintenance challenges (Jeschke et al., 2017).
(5) Costs: The deployment and maintenance of IoT devices, sensors, and networks can incur significant costs, especially for small and medium-sized enterprises (SMEs).
(6) Skill gap: Implementing and managing IoT systems require specialized knowledge and skills that may not be readily available in the workforce.
(7) Environmental impact: The production and disposal of IoT devices can contribute to electronic waste and environmental concerns if not managed properly (Lopes de Sousa Jabbour et al., 2018).
(8) Dependency on connectivity: IoT systems rely heavily on network connectivity. Poor or unstable network connections can disrupt the functionality of the IoT devices and systems.
(9) Ethical and legal issues: The collection and use of data through IoT devices raise ethical and legal questions regarding data ownership, consent, and potential misuse (Soldatos et al., 2016).
(10) Cultural shift: Adopting IoT technologies often requires a cultural shift within organizations, including changes in processes, workflows, and decision-making practices (Manavalan and Jayakrishna, 2019).

Addressing these limitations requires careful planning, investment, and continuous improvement strategies. It is essential for industries to weigh the benefits against the challenges and strategically adopt these technologies to fully leverage their potential in the context of Industry 4.0.

5. Virtual manufacturing and big data analytics in Industry 4.0

Virtual manufacturing and big data analytics are two interconnected concepts that are transforming manufacturing processes to develop the manufacturing process in Industry 4.0. Big data analytics can be used in conjunction with virtual manufacturing to provide valuable insight and optimize production processes (Möller and Möller, 2016). Big data analytics provide tools and techniques for processing, analyzing, and extracting insight from this massive amount of data. By analyzing the vast amounts of data generated by sensors and other sources, manufacturers can identify patterns and trends that may not be immediately apparent (Kurfess et al., 2020a,b). This information can be used to enhance manufacturing procedures, reduce waste, and improve product quality. Big data and analytics can be used to monitor production line performance in real time and identify potential bottlenecks and other issues before they impact production (Tao et al., 2019). This can assist organizations in making prudent decisions regarding personnel, equipment servicing, and production schedules. Big data and analytics can be used in conjunction with virtual manufacturing in Industry 4.0 to provide valuable insight and further optimize production processes. By analyzing the vast amounts of data generated by different sensors and other devices, manufacturers can identify patterns and trends that may not be immediately apparent. Utilizing data helps enhance product quality, decrease waste, and optimize production operations (Aceto et al., 2020). In addition, big data and analytics can be used to analyze customer feedback and other data sources to inform product design and development. This can help manufacturers create products that better meet customer needs and preferences, leading to improved customer satisfaction and increased sales. Overall, Industry 4.0 applications can offer companies a potent collection of tools to optimize their production processes, cut costs, and increase product quality and customer satisfaction. Fig. 3 demonstrates the applications of virtual manufacturing and big data analytics in prodcutivity enhancement of part manufacturing.

Some of the key applications of big data analytics in Industry 4.0 include the following:

(1) Predictive maintenance: By analyzing sensor data, big data analytics can proactively predict equipment failures and schedule maintenance, which reduces downtime and improves overall equipment effectiveness (Sahal et al., 2020).
(2) Quality control: Big data analytics can identify patterns and anomalies in production data, which can help detect and prevent defects in products, reduce waste, and improve product quality (ur Rehman et al., 2019).
(3) Supply chain optimization: Big data analytics can provide insight into supply chain performance, including inventory levels, delivery times, and supplier performance. This can help improve supply chain efficiency and reduce costs (Lu and Xu, 2019).
(4) Product design and development: Big data analytics can be used to analyze customer feedback, product usage data, and other sources to identify opportunities for product improvement and new product development (Bag et al., 2021a,b).
(5) Energy management: Big data analytics can help optimize energy usage in manufacturing processes, thereby reducing energy costs and environmental impact.

Overall, big data analytics is a crucial component of Industry 4.0 as it offers the tools and methods needed to properly utilize cutting-edge technology, promote innovation, and expand the economies of manufacturing and other sectors.

6. Virtual manufacturing and additive manufacturing in Industry 4.0

Three-dimensional objects are constructed using an additive manufacturing technique, which involves stacking layers of material on top of one another. This process, also known as 3D printing, involves the use of a computer-controlled machine to create a physical object from a digital model. Complex forms and structures that can be challenging or impossible to produce using conventional production techniques can be produced using additive manufacturing (Hernandez Korner et al., 2020). It is often used to produce prototypes, custom parts, and small batches of products. Although virtual and additive manufacturing are distinct concepts, they are often used together in modern manufacturing processes (Butt, 2020). The integration of virtual and additive manufacturing can provide significant benefits to manufacturers. Virtual manufacturing can be applied to designing and optimizing the additive manufacturing process, while additive manufacturing can be applied to produce parts and components for the virtual manufacturing process. These technologies can help manufacturers create more efficient and effective manufacturing processes, reduce costs, and improve product quality (Mehrpouya et al., 2019). This allows manufacturers to use virtual tools to design and simulate their products and processes and then use additive manufacturing to physically produce those products in Industry 4.0 (Sepasgozar et al., 2020). This procedure results in faster product development, improved product quality, and lower costs. Virtual

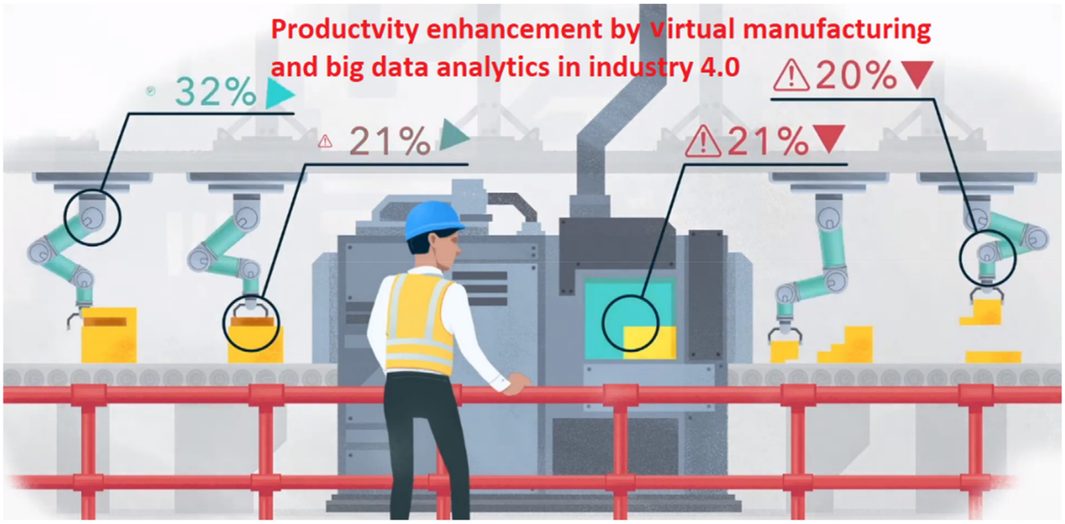

Fig. 3. The applications of virtual manufacturing and big data analytics in prodcutivity enhancement of part manufacturing.

manufacturing can be used to optimize the production design and process before physically producing a part, and additive manufacturing can be used to create that part in a more efficient and cost-effective manner (Ceruti et al., 2019). Together, they enable manufacturers to create high-quality, customized products at a lower cost and with a shorter lead time. The finite element analysis of produced part by the additive manufacturing is presented in Fig. 4.

Additive manufacturing can be used in Industry 4.0 to completely alter the method of part production in different industries. The ability to produce complicated parts that are difficult or impossible to fabricate using conventional methods is one of the main advantages of additive manufacturing (Nazir and Jeng, 2020). This methodology enables companies to create new products and improve existing ones, leading to greater innovation and competitiveness. Additionally, additive manufacturing is a highly adaptable technique that can be utilized to efficiently produce a small number of parts (Rai et al., 2021). This is especially crucial in Industry 4.0, as businesses place greater emphasis on creating individualized and unique goods that cater to each customer's unique desires. The ability to build parts on demand via additive manufacturing eliminates the need for businesses to have significant reserves of parts (Lemu, 2019), which can help reduce waste and optimize supply chain management. Overall, additive manufacturing is a key technology in Industry 4.0, enabling companies to create more complex and customized products, reduce waste and inventory, and improve supply chain management (Mahamood et al., 2021).

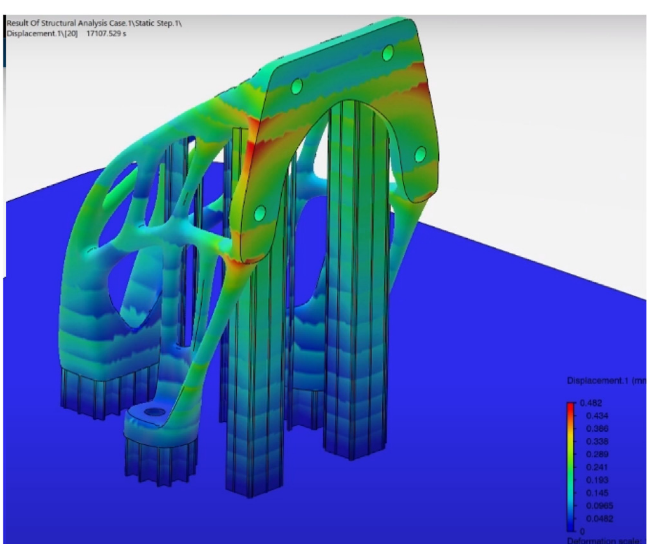

Fig. 4. The finite element analysis of produced part by the additive manufacturing.

7. Virtual manufacturing and autonomous robots in Industry 4.0

Two technologies are revolutionizing manufacturing in Industry 4.0: virtual manufacturing and autonomous robots. Robots that can work independently of human direction or control are considered autonomous. These robots are programmed with algorithms that enable them to sense, perceive, and act on their environment (Goel and Gupta, 2020). Manufacturing facilities are increasingly using autonomous robots to perform repetitive and dangerous tasks such as welding, painting, and assembly, enabling human employees to concentrate on more difficult and sophisticated activities. Virtual manufacturing and autonomous robots are interconnected concepts that have changed the face of the manufacturing industry (Gonzalez et al., 2017). In Industry 4.0, when virtual manufacturing and autonomous robots are coupled, producers can build highly effective and adaptable production lines that can change swiftly to meet changing customer demands and market conditions (Fragapane et al., 2022). Virtual manufacturing systems can also be utilized to simulate and optimize a production line, while autonomous robots can be deployed to perform tasks on said production line with little to no human intervention (Tosello et al., 2019). The combination of virtual manufacturing and autonomous robots is particularly effective. Virtual manufacturing allows manufacturers to design and optimize production processes that are specifically tailored to the capabilities of autonomous robots (Inkulu et al., 2022). This, in turn, can lead to more efficient and cost-effective manufacturing operations (Ustundag et al., 2018a,b). Moreover, as autonomous robots become more advanced, they will be able to work collaboratively with humans, taking on dangerous tasks or reducing the physical demands of labor and allowing people to concentrate on more complicated and creative activities. The use of autonomous robots in Industry 4.0 has several advantages, including the following:

(1) Increased productivity: Autonomous robots can work around the clock without resting, leading to increased production rates and efficiency (Rüßmann et al., 2015).
(2) Improved safety: Autonomous robots can perform tasks in hazardous environments, thereby reducing the risk of injury to human workers.

(3) Higher quality: Autonomous robots can perform tasks with extreme accuracy and consistency, thereby creating products of better quality (Silvestri et al., 2020).
(4) Cost savings: Companies can save money by using autonomous robots to boost productivity and decrease labor expenses (Erboz, 2017).
(5) Flexibility: Autonomous robots can be scheduled to perform a wide range of tasks, making them adaptable to changing production needs. Application of virtual manufacturing and autonomus robots in Industry 4.0 is shown in Fig. 5.

Although virtual manufacturing and autonomous robots offer significant benefits in Industry 4.0, they also have certain limitations and challenges. Some key limitations associated with these technologies are as follows:

(1) Complex environments: While autonomous robots excel in controlled environments, they may struggle in complex, unstructured, or unpredictable settings. Handling variability and adapting to unforeseen circumstances can be challenging (Javaid et al., 2021).
(2) Safety concerns: Autonomous robots operating alongside humans raise safety concerns. Ensuring the safety of human workers and preventing accidents in dynamic environments require advanced sensing, collision avoidance, and fail-safe mechanisms (Cheng et al., 2016).
(3) Limited dexterity: Many autonomous robots have limitations in terms of their dexterity and fine motor skills. This can restrict their ability to perform intricate tasks that require human-like precision.
(4) High initial costs: Developing and deploying autonomous robots can be costly, particularly for customized solutions. The integration of robotics into existing production processes may require substantial investments in training, infrastructure, and software.
(5) Maintenance and repairs: Maintaining and repairing autonomous robots can be complex and require specialized skills and resources. Downtime due to maintenance can affect the overall productivity.
(6) Ethical and social implications: The rise of autonomous robots raises ethical questions related to job displacement, the loss of a human touch in certain industries, and the potential impact on society. Balancing automation with human welfare is a key consideration (Jamwal et al., 2021a,b).
(7) Legal and regulatory challenges: Regulations and standards for autonomous robots are still evolving. Navigating the legal and regulatory frameworks for safety, liability, and compliance can be complex.
(8) Limited adaptability: Some autonomous robots are designed for specific tasks or environments, which makes them less adaptable to changes or new tasks without significant reprogramming or modifications (Vachálek et al., 2017).

It is important to note that advancements in technology continue to address many of these limitations, but they remain important factors to consider when implementing virtual manufacturing and the use of autonomous robots in the context of Industry 4.0. Overall, virtual manufacturing and autonomous robots are driving innovation in manufacturing in Industry 4.0. Their potential benefits are substantial, including increased efficiency, reduced costs, and improved safety for workers. They are revolutionizing the manufacturing industry, making it more efficient, productive, and cost-effective. Autonomous robots are a crucial part of Industry 4.0 to boost production, efficiency, and quality while lowering costs and enhancing safety.

8. Virtual manufacturing and cloud computing in Industry 4.0

Industry 4.0 is placing increasing emphasis on two related ideas: cloud computing and virtual manufacturing. The principles of virtual manufacturing and cloud computing can be applied to improving the efficacy and efficiency of manufacturing operations (Aceto et al., 2020). Cloud computing employs distant servers to store, manage, and process data rather than using local servers or personal PCs for these purposes. This allows manufacturers to access and share data more easily, collaborate with partners and suppliers in real time, and scale their operations up or down as needed (Velásquez et al., 2018). Virtual manufacturing and cloud computing can revolutionize the manufacturing industry by enabling greater flexibility, efficiency, and agility. By leveraging these technologies, manufacturers can rapidly prototype and iterate new products, optimize production processes, and respond quickly to changing customer demands. Virtual manufacturing and cloud computing offer a powerful combination of tools for Industry 4.0 to improve productivity throughout the part production process (Dogo et al., 2019). Manufacturers can optimize their operations and reduce costs by creating virtual models of their manufacturing processes and products. By using cloud computing in Industry 4.0 to store and share

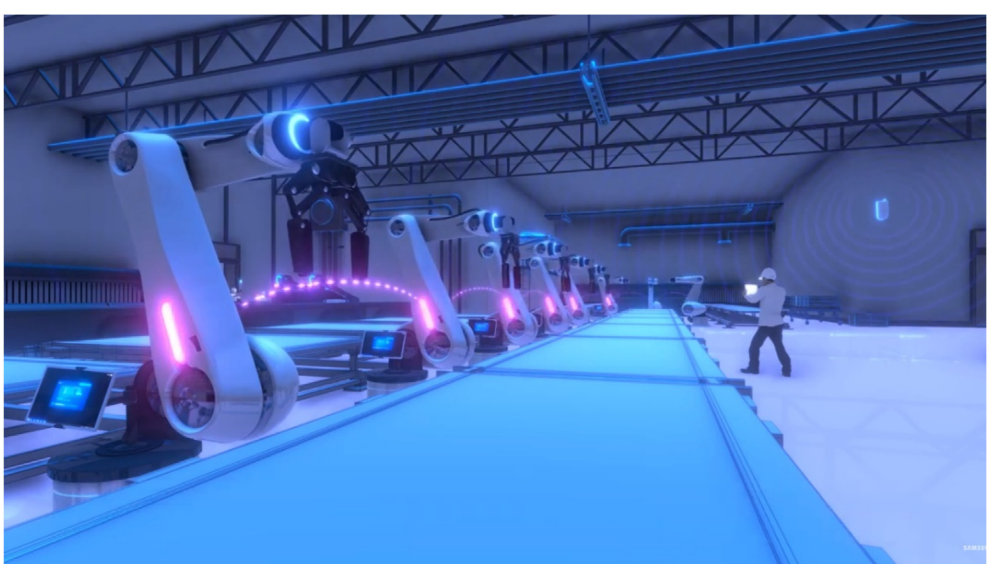

Fig. 5. Application of virtual manufacturing and autonomus robots in Industry 4.0.

data, manufacturers can improve communication, collaboration, and efficiency across their supply chains. Manufacturers can create a virtual manufacturing environment hosted on the cloud by combining virtual manufacturing and the cloud (O'Donovan et al., 2019). This environment can be accessed by manufacturers and their partners from anywhere in the world, enabling collaboration and real-time monitoring of manufacturing processes (Matt, 2018). Cloud-based virtual manufacturing can also help manufacturers reduce their environmental footprint by minimizing the need for physical prototyping and testing. This process can result in significant cost reductions and increased sustainability. Cloud computing provides the infrastructure necessary for Industry 4.0. It enables the storage, processing, and sharing of data and applications across multiple devices and platforms, facilitating manufacturers in accessing and analyzing data in real time (Sanchez et al., 2020). Cloud computing also provides a scalable and flexible computing environment that can adapt to the changing demands of manufacturing processes. One of the main advantages of cloud computing in Industry 4.0 is the development of digital twins. The virtual reproduction of tangible assets such as machinery, goods, and even complete industries is known as a digital twin (Moraes et al., 2022). Digital twins enable producers to model and test various situations before making changes in the real world to save costs and increase efficiency (Hussain et al., 2020). Cloud computing also enables manufacturers to leverage the power of AI and machine learning to optimize their processes. For example, real-time sensor data analysis using machine-learning algorithms can be employed to identify abnormalities and predict equipment problems (Liu and Xu, 2017). This can help manufacturers increase productivity and reduce downtime. The applications of cloud computing in Industry 4.0 is shown in Fig. 6.

Overall, Industry 4.0 is greatly facilitated by cloud computing in terms of increasing part manufacturing productivity. It provides businesses with the infrastructure and resources needed to take advantage of cutting-edge technology to build flexible, productive, and efficient smart factories.

9. Virtual manufacturing and AI in Industry 4.0

In Industry 4.0, the design, production, and evaluation of products are being revolutionized by two closely connected technologies: virtual manufacturing and AI. AI can be used in virtual manufacturing to analyze data from simulations and make recommendations for improvements (Lee et al., 2018). For example, AI algorithms can analyze data from virtual simulations to identify areas in which production can be optimized by adjusting machine settings or streamlining workflows (Jan et al., 2022). AI can also be used to proactively predict equipment failure, schedule maintenance, reduce downtime, and minimize the risk of unexpected delays (Bécue et al., 2021). Virtual manufacturing and AI can enable manufacturers in Industry 4.0 to accomplish the following.

(1) Optimize production processes: Virtual manufacturing can be used to simulate many situations and determine the most effective production methods. AI can then be used to analyze data from the manufacturing process in real time and make adjustments to optimize production (Bécue et al., 2021).
(2) Reduce costs: Virtual manufacturing can help reduce production costs by simulating different manufacturing scenarios and optimizing production processes. Moreover, AI can be used to detect inefficiencies and waste in the manufacturing process, further reducing costs (Massaro et al., 2020).
(3) Improve quality: Virtual manufacturing can be applied to simulate various quality control situations and identify potential manufacturing process imperfections. AI can then be used to detect defects in real time and make adjustments to improve quality (Javaid et al., 2022a).
(4) Increased flexibility: Virtual manufacturing can be used to simulate different production scenarios and identify potential bottlenecks or production constraints. AI can then be used to adjust production in real time to maximize output (Fragapane et al., 2022).
(5) Predict maintenance needs: By analyzing data from the manufacturing process, AI can identify potential equipment failures and predict the need for maintenance before these issues occur. This can help reduce downtime and maintenance costs (Lee et al., 2019).

There are limitations and challenges associated with the implementation of virtual manufacturing and AI in Industry 4.0.

(1) Data dependence: Virtual manufacturing and AI rely heavily on accurate and abundant data to make informed decisions and predictions. Poor data quality, a lack of data integration, and data privacy concerns can hinder the effectiveness of these technologies.
(2) Initial investment and implementation costs: Adopting virtual manufacturing and AI technologies requires significant upfront investment in terms of hardware, software, training, and infrastructure. Smaller and resource-constrained companies may find it

Fig. 6. The applications of cloud computing in industry 4.0.

challenging to afford and implement these technologies (Jamwal et al., 2021a,b).

(3) Complex integration: Integrating virtual manufacturing and AI into existing manufacturing processes can be complex and time consuming. Compatibility issues between different systems and the need for reengineering processes can slow the adoption process.
(4) Skill gap: The successful implementation and operation of virtual manufacturing and AI require a skilled workforce with expertise in areas such as data analysis, machine learning, and automation. The shortage of skilled professionals in these domains may be an obstacle.
(5) Limited generalization: AI models often perform well in specific scenarios or tasks on which they have been trained but may struggle when faced with new or unfamiliar situations. However, achieving true generalizations across various manufacturing processes can be challenging.
(6) Ethical and social concerns: AI and automation can lead to job displacement and ethical concerns related to decision-making algorithms. Decisions made by AI systems may lack transparency, accountability, and the ability to understand the ethical implications of the choices made (Yao et al., 2017).
(7) Uncertainty and variability: Manufacturing processes can be subject to various sources of uncertainty, such as material variability, machine wear and tear, and unexpected events. AI models may struggle to effectively handle these uncertainties (Peres et al., 2020).
(8) Maintenance and reliability: AI-driven systems can become less reliable or even fail if not properly maintained or if the underlying algorithms degrade over time. Ensuring the ongoing reliability and robustness of these systems presents a challenge (Leng et al., 2021).
(9) Cultural resistance and change management: Implementing new technologies often requires changes in the organizational culture and employee mindsets. Resistance to change difficulties in managing the transition can hinder successful adoption (Bécue et al., 2021).
(10) Security and cybersecurity risks: As manufacturing becomes more digitally connected, the risk of cyberattacks and data breaches increases. Protecting sensitive information and ensuring the cybersecurity of AI-driven systems is crucial.

It is important to note that while these limitations exist, ongoing research, development, and improvements in technology can help mitigate many of these challenges over time. The successful integration of virtual manufacturing and AI in Industry 4.0 requires careful planning, investment, and a proactive approach to addressing these limitations. Overall, AI and virtual manufacturing have the potential to enhance the effectiveness, consistency, and adaptability of manufacturing processes, resulting in quicker production cycles, better-quality products, and lower prices. As these technologies develop, they may become more significant in the industrial sector. AI and virtual manufacturing can help businesses increase productivity, reduce costs, and produce better products. Increased use of these technologies in manufacturing is likely in the future as they continue to evolve and improve.

10. Virtual manufacturing and sustainability in Industry 4.0

Sustainability is an increasingly important consideration in manufacturing as companies strive to reduce their environmental impact while maintaining profitability. Virtual manufacturing can help companies achieve sustainability goals by reducing the waste, energy consumption, and emissions associated with physical prototyping and testing in Industry 4.0 (Tseng et al., 2021). It can also help companies optimize their supply chain, reduce transportation-related emissions, and minimize the use of resources such as water and materials (Sharma et al., 2021). Additionally, virtual manufacturing can facilitate the design of more sustainable products by allowing manufacturers to test and optimize their designs for recyclability, energy efficiency, and durability. Virtual manufacturing in Industry 4.0, which can also enable the use of alternative sustainable materials, may be more difficult or costly to test using physical prototypes (Bag et al., 2021a,b). In summary, virtual manufacturing and sustainability are closely linked concepts that can work together to create a more efficient and environmentally friendly Industry 4.0 (Kamble et al., 2020a,b). By using computer simulation to design and optimize manufacturing processes, companies can decrease waste, energy usage, and CO_2 emissions while also creating more sustainable products. Sustainability in digital manufacturing is shown in Fig. 7.

The following are several examples of how Industry 4.0 can promote sustainability:

(1) Energy efficiency: Using IoT sensors and big data analytics, manufacturers can monitor energy consumption, identify opportunities to reduce waste, and optimize energy usage (Koh et al., 2019).
(2) Waste reduction: AI and robotics can be used to improve the product design and reduce material waste during production. In addition, IoT sensors can help monitor waste levels in real time, enabling companies to make adjustments and reduce waste (Jamwal et al., 2021a,b).
(3) Supply chain transparency: To identify and mitigate environmental and social risks in the supply chain, blockchain technology can be used to build a transparent and traceable supply chain (Kamble et al., 2020a,b).
(4) Circular economy: Technology from Industry 4.0 can be used to move toward a circular economy, in which resources are used as long as feasible with the least amount of waste and environmental effect possible (Kumar et al., 2020).
(5) Social responsibility: By using AI and other advanced technologies, companies can monitor and improve working conditions, safety, and labor practices, promoting social responsibility and ethical business practices (Leng et al., 2020).

In summary, sustainability in Industry 4.0 involves using advanced technologies to optimize industrial processes while minimizing environmental impact and promoting social responsibility.

11. Web-based virtual manufacturing platforms In industry 4.0

Web-based virtual manufacturing platforms play a crucial role in Industry 4.0 by providing a collaborative environment for designing, testing, and optimizing the manufacturing process. Modern technologies, such as cloud computing, IoT, and AI, are being incorporated into manufacturing processes as part of Industry 4.0 (Liu et al., 2022). Web-based virtual manufacturing platforms are a key component of this movement. These platforms enable manufacturers to create virtual replicas of their factories, which can be used to simulate and optimize manufacturing processes (Elbestawi et al., 2018). One of the key benefits of web-based virtual manufacturing platforms is that they allow for virtual prototyping, which can significantly reduce the time and cost of developing new products. By creating a digital model of a product and simulating its behavior in a virtual environment, manufacturers can identify and correct design flaws before physical prototypes are produced, saving time and money (Wu et al., 2015). Furthermore, web-based virtual manufacturing platforms facilitate remote collaboration and communication among team members, even when they are located in different parts of the world (Kurfess et al., 2020a,b). This enables faster decision-making and problem-solving, which can lead to increased productivity and efficiency (Kabasakal et al., 2023). Furthermore, these platforms can assist manufacturers in optimizing their production processes by evaluating data from numerous sources, including

Fig. 7. Sustainability in digital manufacturing.

sensors and machines. They can accomplish this by looking for trends and insights that can be utilized to increase efficiency and decrease waste. Some of the key features of web-based virtual manufacturing platforms in Industry 4.0 include the following:

(1) Simulation and modeling: These platforms allow manufacturers to create 3D models of their factories and simulate manufacturing processes, including material flow, assembly lines, and logistics. This helps identify bottlenecks, optimize workflows, and reduce production costs (Kerin and Pham, 2019).
(2) Real-time monitoring: Web-based virtual manufacturing platforms enable manufacturers to monitor their production processes in real time. This provides valuable insight into production efficiency, equipment utilization, and quality control (Shamsuzzoha et al., 2021).
(3) Predictive maintenance: Web-based virtual manufacturing systems can determine when the equipment is likely to break by collecting data from sensors and other sources, allowing manufacturers to proactively undertake maintenance and save expensive downtime (Georgakopoulos and Bamunuarachchi, 2021).
(4) Collaborative design: These platforms facilitate collaboration among designers, engineers, and other stakeholders, enabling them to work together on product design and development.
(5) Cloud-based deployment: Most web-based virtual manufacturing systems are cloud-based, making it possible to use them from any location with an Internet connection. This makes them highly flexible and scalable, enabling manufacturers to easily add new features and capabilities as required (Wu et al., 2015).

Overall, web-based virtual manufacturing platforms are an essential tool for manufacturers in the Industry 4.0 era, helping them increase efficiency, reduce costs, and improve product quality.

12. Cybersecurity in Industry 4.0

Although connections among different devices and technologies can bring significant benefits to organizations in Industry 4.0, they also create new security challenges that should be evaluated to ensure the safety and security of sensitive data and systems. Cybersecurity in Industry 4.0 involves the protection of critical assets and infrastructure from cyber threats, including cyber-attacks, data breaches, and other malicious activities (Mullet et al., 2021), and requires a comprehensive approach that addresses both the technical and non-technical aspects of security, including policies, procedures, and employee training. One of the key challenges in Industry 4.0 cybersecurity is the increased attack surface created by the use of IoT devices and other connected technologies (Fernández-Caramés and Fraga-Lamas, 2020). These devices often lack the security features necessary to protect themselves from sophisticated attacks, making them vulnerable to compromise. To mitigate this risk, organizations must implement robust security controls and regularly monitor their networks for suspicious activity. Another critical aspect of Industry 4.0 cybersecurity is the protection of data privacy (Mahesh et al., 2020). Organizations must create efficient data governance policies and ensure that data are securely protected and stored in consideration of the growing volume of data generated by IoT devices and other technologies. Industry 4.0 presents both opportunities and challenges for cybersecurity (Thach et al., 2021). To protect against the evolving threat landscape, organizations must adopt a proactive and holistic approach to cybersecurity with a focus on risk management, threat intelligence, and continuous monitoring and improvement. The following are key considerations for cybersecurity in Industry 4.0.

(1) Risk assessment: The first step in developing a cybersecurity strategy is to assess the risks faced by an organization. This includes the identification of potential threats, vulnerabilities, and consequences.
(2) Cybersecurity frameworks: Organizations should adopt cybersecurity frameworks such as National Institute of Standards and Technology (NIST), International Organization for Standardization (ISO), and International Electrotechnical Commission (IEC), to establish a baseline for their security posture and ensure that all relevant security controls are in place.
(3) Network segmentation: Industry 4.0 systems often involve complex networks with multiple entry points. Segmentation of networks and systems can reduce the impact of a breach and limit an attacker's ability to move laterally (Abdullahi et al., 2022).
(4) Secure communication: All communication channels among IoT devices, machines, and other systems must be secured. This includes implementing encryption, strong authentication, and access-control measures.
(5) Endpoint security: Endpoint security measures such as antivirus software, intrusion detection/prevention systems, and routine

software upgrades should be used to protect Industry 4.0 equipment such as sensors and machines.

(6) Data protection: As more data are generated and transmitted across Industry 4.0 systems, ensuring confidentiality, integrity, and availability becomes more critical. Encryption, backup, and disaster recovery measures must be implemented to protect data from loss and theft (Pang et al., 2021).

(7) Employee taining: Employee awareness and training are essential for effective cybersecurity. Employees must be trained in security policies, procedures, and best practices to prevent common cyberattacks such as phishing and social engineering (Ustundag et al., 2018a,b). Cyber-physical System in digital manufacturing is shown in Fig. 8.

In summary, cybersecurity is critical to the success and sustainability of Industry 4.0. Organizations must take a proactive approach to identify and mitigate risks, implement effective security controls, and continually monitor and improve their security posture.

13. RFID technology for Industry 4.0

RFID technology employs radio waves to transmit data between a reader and an electronic tag affixed to an item such as a product or container. RFID is a wireless communication technology. It has been around for several decades but has become more popular in recent years due to its potential applications in Industry 4.0 (Elbasani et al., 2020). Throughout the supply chain, Industry 4.0 uses RFID technology to track and monitor products, resources, and equipment. RFID technology is an essential component of Industry 4.0 and is transforming the manufacturing industry by providing real-time visibility, optimizing processes, reducing costs, and improving productivity (Chiarini, 2021). The ability to allow real-time data collection is a major advantage of RFID technology in Industry 4.0. These data can then be used to monitor and optimize the manufacturing process as well as to provide valuable insight into customer behavior and preferences (Neal et al., 2021). Additionally, RFID technology can enable predictive maintenance, which involves the use of data analytics to identify potential equipment failures before they occur (Anbalagan and Moreno-Garcia, 2021). Companies can monitor the flow of goods from their point of origin to the point of consumption by adding RFID tags to items or containers, thereby ensuring visibility and transparency across the supply chain (Raut et al., 2020). This can help companies optimize their inventory management, reduce waste, and improve their overall efficiency. RFID technology can also be used to improve supply chain safety and security. By tracking the movement of products and materials, companies can identify potential security threats or safety issues and take appropriate action to prevent them. In addition, RFID technology can be used to enable automated and autonomous systems in Industry 4.0 (Beliatis et al., 2021). For example, RFID tags can be used to identify products or materials as they move through a production line, triggering automated processes or machine-learning algorithms that optimize production and reduce downtime (D'Avella et al., 2022). In addition, products, raw materials, and equipment can all be assigned RFID tags so that they can be traced throughout the manufacturing process (Ghoreishi et al., 2020). As a result, manufacturing processes are optimized, waste decreases, and quality control is enhanced. The following are ways in which RFID technology is transforming Industry 4.0.

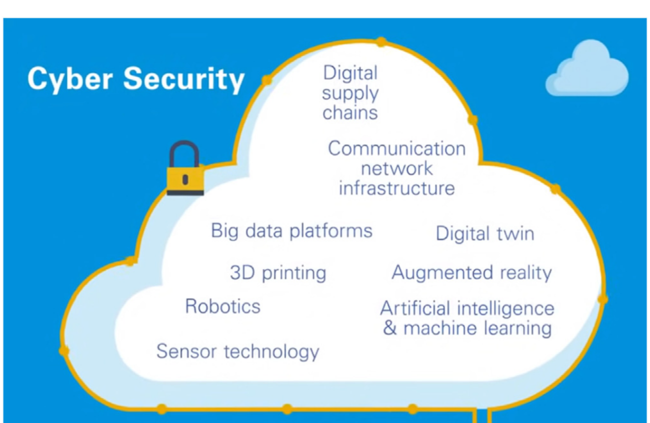

Fig. 8. Cyber-physical system in digital manufacturing.

(1) Asset tracking: RFID technology is used to track assets in manufacturing plants, warehouses, and supply chain operations. Assets can be assigned RFID tags so that their whereabouts can be tracked in real time, giving managers a real-time view of their inventory and asset usage (Židek et al., 2020).

(2) Production monitoring: RFID technology is used to monitor the production processes in real time. RFID tags can be attached to components, and the production line can be monitored for bottlenecks or issues. This can help optimize production processes and improve productivity (Neal et al., 2021).

(3) Quality control: RFID technology is also being used for quality control purposes. RFID tags can be attached to products, and their quality can be monitored at each stage of the production process. This can ensure that the product meets the required quality standards (Rafiquea et al., 2022).

(4) Supply chain management: Additionally, RFID technology is used in supply chain management. Products can be supplied with RFID tags to monitor their movement throughout the supply chain. This can accelerate deliveries, reduce costs, and increase supply chain efficiency (Dastres et al., 2022).

(5) Maintenance and repair: Finally, RFID technology is employed for maintenance and repair. The maintenance and repair history of machinery and equipment can be identified using RFID tags. This can enhance machine performance, save downtime, and optimize maintenance schedules (Karabegović et al., 2020). The applications of the RFID system in Industry 4.0 are shown in Fig. 9.

RFID technology is an important component of Industry 4.0, providing a reliable and efficient method to track and monitor products, materials, and equipment throughout the supply chain. As technology continues to evolve, it will likely play an even greater role in manufacturing and logistics.

14. Simulation-based optimization of CNC machining using virtual machining systems

A virtual model of the CNC machining process was developed using physics-based simulation software incorporating real-world material properties, tool characteristics, and machine dynamics. As a result, the surface quality of the machined turbine blades was increased using the virtual machining system developed in this study (Soori et al., 2021). The effects of the optimized machining parameters on the surface quality enhancement of machined turbine blades are shown in Table 1 (Soori et al., 2021).

Thus, the ability to model, simulate, and optimize manufacturing processes leads to substantial improvements in machining time, tool wear, surface finish, energy consumption, and resource utilization. These findings emphasize the potential of virtual fabrication to revolutionize manufacturing practices and contribute to the goals of efficiency, sustainability, and cost effectiveness in Industry 4.0.

15. Conclusion and future research directions

Industry 4.0, also known as the fourth industrial revolution, is defined as the incorporation of cutting-edge technology into manufacturing and

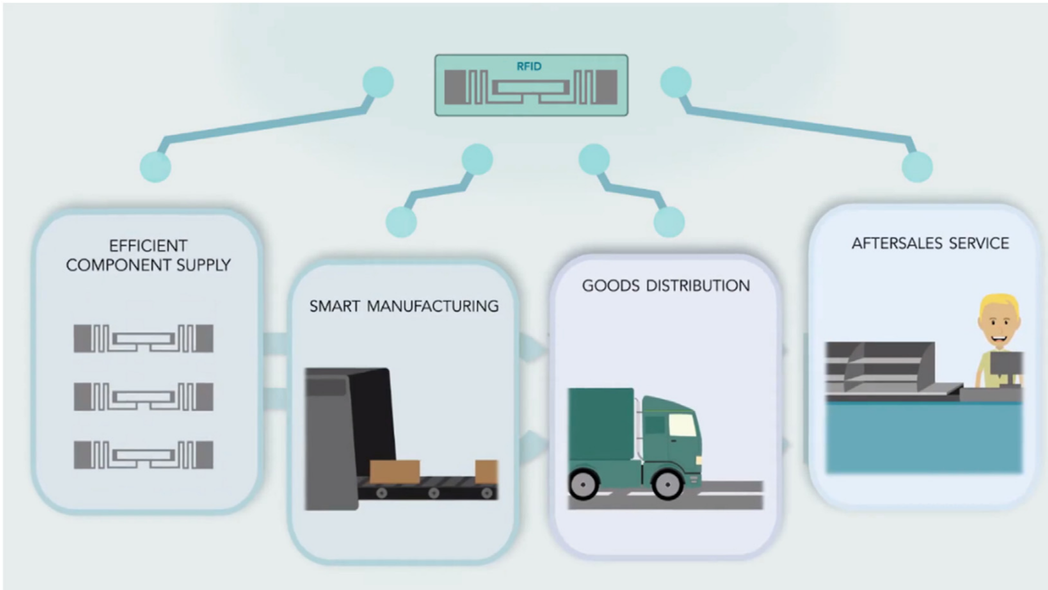

Fig. 9. The applications of the radio-frequency identification (RFID) system in Industry 4.0.

Table 1
The effects of optimized machining parameters in surface quality enhancement of machined turbine blades (Soori et al., 2021).

Number	Before optimization		After optimization		Percentage of change	
	Measured surface roughness (μm)	Predicted surface roughness (μm)	Measured surface roughness (μm)	Predicted surface roughness (μm)	Measured surface roughness	Predicted surface roughness
Point 1	0.50	0.45	0.4	0.35	20.00000	22.22222
Point 2	0.54	0.49	0.39	0.4	27.77778	18.36735
Point 3	0.58	0.51	0.41	0.33	29.31034	35.29412
Point 4	0.53	0.48	0.39	0.37	26.41509	22.91667
Point 5	0.52	0.49	0.37	0.35	28.84615	28.57143
Point 6	0.59	0.45	0.39	0.3	33.89831	33.33333
Point 7	0.51	0.43	0.39	0.34	23.52941	20.93023
Point 8	0.52	0.46	0.41	0.33	21.15385	28.26087
Point 9	0.47	0.45	0.36	0.30	23.40426	33.33333
Point 10	0.53	0.47	0.38	0.33	28.30189	29.78723
Average	0.529	0.468	0.389	0.34	26.26371	27.30168

other sectors, including the IoT, big data analytics, AI, machine learning, and automation. This revolution focuses on the development of smart factories that can operate autonomously and communicate with each other, thereby enabling a higher degree of efficiency, productivity, and quality in the manufacturing process. The way commodities are created and produced is being revolutionized, which has a significant impact on the world economy, improving production procedures and decreasing downtime. Industry 4.0 also uses sophisticated analytics and predictive maintenance. The phrase "Industry 4.0" is used to refer to the present automation and data-sharing trend in industrial technology. This enables companies to produce specialized goods and services on demand and react rapidly to shifting consumer needs. Industry 4.0, a paradigm shift in manufacturing that uses cutting-edge technologies such as AI, the IoT, big data analytics, and cloud computing, is centered on virtual manufacturing. In virtual manufacturing, computer simulations and models are used to design and optimize the manufacturing processes and products. Virtual manufacturing helps businesses build products faster and more affordably by enabling them to test and improve their ideas in a virtual setting before spending money on prototypes. By providing real-time data on inventory levels, production schedules, and delivery time-frames, virtual manufacturing may help businesses better manage their supply chains. Virtual manufacturing in the context of Industry 4.0 also refers to the integration of digital technologies such as simulation, modeling, and virtual reality into manufacturing processes to enhance efficiency, productivity, and decision-making. Consequently, businesses can better coordinate their efforts and react to shifts in market dynamics. This may have resulted in a shorter time to market and better product quality. Virtual manufacturing will be a key element in Industry 4.0, allowing firms to enhance their processes, cut costs, and commercialize cutting-edge goods more quickly and effectively than ever before. Manufacturers will be able to work more efficiently with their suppliers, clients, and other partners owing to virtual manufacturing. Manufacturers can collaborate to create and improve goods and processes as well as improve supply chain operations by exchanging virtual models and data. The utilization of big data analytics and virtual manufacturing, which helps businesses simplify their processes, save money, improve quality, and enhance production, is revolutionizing the manufacturing sector. RFID technology is an important tool for manufacturers seeking to adopt Industry 4.0 principles and stay competitive in today's fast-paced business environment. RFID technology enables real-time supply chain monitoring and control and offers insightful data that may help businesses enhance productivity, cut costs, and satisfy customers. As technology advances, its significance in enabling the smart factories of the future will as well. Generally, virtual manufacturing is a crucial element of Industry 4.0, allowing manufacturers to optimize their processes, increase productivity, reduce costs, and improve cooperation and communication across numerous teams and stakeholders. It is a key enabler of Industry 4.0 vision and is likely to play an increasingly important role in the future of manufacturing. In the era of Industry 4.0 (IoT), there will surely be an increase in the utilization of big data analytics, cloud computing, and the IoT. Large volumes of data from equipment, goods, and consumers will be collected, stored, and analyzed by manufacturers owing to these technologies. These data can then be used to improve production processes, predict maintenance needs, and personalize products and services for customers.

The following are some potential areas of future research in Industry 4.0 using virtual manufacturing.

(1) Smart factories: Future studies should look at the best ways to plan, execute, and scale smart factories to increase manufacturing productivity, quality, and agility while lowering costs and environmental impact. This could include topics such as the development of smart sensors, automation, and optimization algorithms to improve the production process.
(2) Smart machines: One key trend in Industry 4.0 is the increasing use of smart machines that can communicate with each other and with humans. These machines can gather and analyze data in real time, allowing for more efficient production processes and better decision-making. In addition, Industry 4.0 is likely to see increased use of robotics and automation, which will allow for greater precision and accuracy in manufacturing.
(3) Augmented reality (AR): AR technology is used to train workers in Industry 4.0 and is expected to become more prevalent in the future. This enables workers to see virtual images and information overlaid on the real world, which can help them perform their jobs more effectively.
(4) Increased automation: The use of robotics, AI, and machine learning is expected to become more widespread, thereby reducing the need for human intervention in manufacturing processes.
(5) Digital twins: Digital twins are virtual representations of genuine resources that enable real-time monitoring and preventive maintenance. Future studies may examine how digital twins and Industry 4.0 technology can be used to streamline production, reduce downtime, and boost product quality.
(6) Internet of things (IoT): The IoT will continue to play a significant role in Industry 4.0, as it enables the connection of machines and devices to the Internet, enabling them to communicate with each other and exchange data.
(7) Supply chain optimization: Virtual manufacturing can extend beyond the factory floor to the entire supply chain. Researchers can investigate how digital technologies can optimize logistics, demand forecasting, and inventory management, leading to more responsive and efficient supply chains.
(8) Blockchain: Blockchain technology can help secure and authenticate data in Industry 4.0. Future research could explore how blockchain can be used to secure the supply chain, improve traceability, and reduce the risk of fraud.
(9) AI and machine learning: These technologies are already being used in Industry 4.0; however, many remain to be learned regarding how to optimize their use and improve their accuracy and efficiency. AI and machine learning can be used to assess data from machines and sensors, identify patterns, and forecast the future. By doing this, firms can cut costs, enhance product quality, and optimize manufacturing processes.
(10) Adoption of the IoT: For machines, sensors, and other devices to share data and interact with one another, the IoT includes connecting them to the Internet. This can assist producers in real-time production monitoring, rapid problem detection and resolution, and data-driven decision making.
(11) Greater connectivity: Industry 4.0, which is anticipated to rely extensively on the IoT, will make it possible for machines and gadgets to connect with one another and with centralized systems, increasing production and efficiency.
(12) Cybersecurity: As more devices are connected in Industry 4.0, the risk of cyberattacks increases. Future research could explore how to develop and implement effective cybersecurity measures to protect critical manufacturing infrastructure. Cybersecurity is becoming increasingly important in Industry 4.0. Therefore, companies must invest in cybersecurity measures to protect their data and intellectual property.
(13) Data analytics: Considering the growing volume of data produced by linked devices, sophisticated analytics tools are needed to make sense of these data and derive insight that can drive business decisions. Industry 4.0 generates vast amounts of data, and the ability to analyze and make sense of them is critical for optimizing processes and making informed decisions. Researchers are exploring new ways to collect, store, and analyze data to improve efficiency and productivity.
(14) Adaptive manufacturing systems: The ability of manufacturing systems to adapt quickly to changes in product design, production volume, and market demand is crucial. Research can also explore how virtual manufacturing technologies can enable versatile and responsive adaptive manufacturing systems.
(15) Human-machine interaction: As Industry 4.0 systems become more automated, there is a need to understand how humans interact with these systems. Future research could explore how to design human-machine interfaces that are intuitive, safe, and effective.
(16) Sustainability: Industry 4.0 has the potential to reduce waste and increase efficiency, but it also has the potential to increase energy consumption and carbon emissions. Future research could explore how to optimize Industry 4.0 systems for sustainability, including topics such as energy-efficient manufacturing processes and the recycling of electronic waste.
(17) Additive manufacturing: 3D printing is already being used in Industry 4.0; however, it is expected to become more widespread in the future. It allows for the creation of complex parts and products with less waste and at a lower cost than traditional manufacturing methods. With 3D printing, manufacturers can quickly and easily produce complex parts and components without expensive tooling and molds.
(18) Ethical and social implications: As with any new technology, ethical and social implications must be considered. Researchers are exploring the potential impact of Industry 4.0 on jobs, privacy, and society as a whole and developing frameworks for responsible implementation.
(19) Economic and business models: Beyond technical aspects, research can explore the economic implications of virtual manufacturing in Industry 4.0. This may involve studying new business models, calculating returns on investment, and assessing the long-term economic benefits of adopting these technologies.
(20) Standardization and interoperability: Industry 4.0 envisions a connected ecosystem of devices and systems. Future research should focus on developing standardized communication protocols and data formats to ensure seamless interoperability among different manufacturing components and technologies.
(21) Multidisciplinary collaboration: Virtual manufacturing involves expertise in various fields including engineering, computer science, and materials science. Future research should emphasize multidisciplinary collaboration to ensure a holistic approach to developing and implementing virtual manufacturing solutions.

Overall, the future of Industry 4.0 is exciting and full of opportunities for innovation and growth. As technology advances, manufacturers can produce products in a faster and more efficient way with greater precision. This has resulted in increased productivity, greater competitiveness, and better products for customers.

CRediT authorship contribution statement

Mohsen Soori: Writing – review & editing, Writing – original draft, Resources, Methodology. **Behrooz Arezoo:** Validation, Supervision, Resources, Methodology. **Roza Dastres:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Data curation.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

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