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**| RESEARCH ARTICLE**

# Industry 5.0: Human-Centric Manufacturing for Sustainable and Intelligent Production Systems

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**| ABSTRACT**
Industry 5.0 has become a revolutionizing manufacturing paradigm which goes further from the automation-oriented strategy of Industry 4.0 by putting human welfare, sustainability, and resilience at the core of intelligent production systems. Instead of replacing humans with autonomous technologies, Industry 5.0 aims at collaboration between humans and intelligent digital technologies for better productivity, agility, and sustainable value creation. The present paper provides a comprehensive review of human-centric manufacturing and explores its importance in creating sustainable and intelligent production systems. The principles of Industry 5.0 are discussed, and the roles played by the major enabling technologies such as Artificial Intelligence (AI), cobots, Digital Twins, IIoT, Big Data Analytics, AR, VR, and Edge–Cloud Computing are analyzed. The applications of the mentioned technologies to the main manufacturing industries such as automotive, aerospace, electronics, additive manufacturing, medical devices, and food processing are thoroughly reviewed. In addition, the key implementation issues connected to cybersecurity, workforce competency, interoperability, ethical AI, and technology adoption, as well as promising research opportunities are identified. A conceptual framework based on the reviewed literature, combining the principles of human-centric manufacturing, enabling technologies, intelligent manufacturing processes, and sustainable production outcomes, is developed. It can be used to guide the implementation of the Industry 5.0.

**| KEYWORDS**

Industry 5.0; Human-Centric Manufacturing; Sustainable Manufacturing; Intelligent Production Systems; Artificial Intelligence; Collaborative Robots; Digital Twin; Industrial Internet of Things; Smart Manufacturing.

**| ARTICLE INFORMATION**

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## 1. Introduction

### *1.1 Background*

Manufacturing has witnessed an incredible evolution over the past three centuries through multiple industrial revolutions that have involved the introduction of different forms of technology in production. During the First Industrial Revolution, for instance, steam engines were used to increase productivity while minimizing the need for human effort. On the other hand, the use of electricity, assembly line productions, and mass manufacturing has been the defining characteristics of the Second Industrial Revolution. The Third Industrial Revolution, also known as the Digital Revolution, saw the integration of electronics, computers, and automation in manufacturing processes to increase accuracy, efficiency, and process control. Currently, the Fourth Revolution in industry is seen in the form of Industry 4.0 where the use of cyber-physical systems, IIoT, cloud computing, big data analysis, AI, and digital twins has been embraced [1].

While tremendous progress has been made through Industry 4.0, its main focus has still been on automation, productivity, and efficiency. Although these innovations have created intelligent factories that can make decisions on their own and optimize processes in real time, questions have arisen about job loss, system complexity, cybersecurity threats, and human wellbeing, which has been largely ignored in highly automated manufacturing facilities. Simultaneously, some global problems, including climate change, exhaustion of resources, interruptions in the supply chain, and growing demands for personalized products, have underscored the importance of having a manufacturing system that is not just advanced but resilient, sustainable, and value-based [2].

To address these new challenges, the concept of Industry 5.0 has been presented as the future stage of industrial development. However, Industry 5.0 is not meant to replace but rather to complement Industry 4.0 in that it places importance on collaboration of people and smart technologies. It acknowledges that while automation can be developed, human creativity, analytical skills, experience, and ethics are essential parts of manufacturing process which cannot be automated. Thus, Industry 5.0 focuses on creating a production environment in which advanced technologies will help rather than substitute people.

### *1.2 Motivation*

The appearance of Industry 5.0 is a result of a paradigm shift in the focus of manufacturing from being tech-oriented towards value-oriented manufacturing that harmonizes economic efficiency with people's well-being and environmental considerations. People-oriented manufacturing has become essential because it has been realized that competitiveness depends not only on innovative technologies but also on the health and knowledge of the employees [3].

Due to the development of artificial intelligence, cobots, digital twins, augmented reality, and intelligent decision support systems, there is a chance to use both human knowledge and machine capabilities together. In contrast to automation technologies that were developed to substitute people in repetitive activities, such tools are intended to help human operators to make their work safer, decrease physical efforts and improve productivity. The use of this approach makes it possible to increase process flexibility and improve it constantly without sacrificing the human mind peculiarities [4].

In addition to this, another important factor that drives the development of Industry 5.0 is sustainability in manufacturing. Manufacturing industries are increasingly being expected to conserve energy, use fewer materials, emit less carbon, and be circular in their approach to business operations. Human-centered manufacturing helps to realize this goal by allowing smart management of resources, efficient production processes, better product quality, and decision making that is environmentally sound. At the same time, manufacturing systems that are resilient and adaptable to disruptions like pandemics, wars, and uncertainties in the supply chain have become vital for ensuring operational efficiency [5].

Thus, Industry 5.0 can be seen as an all-encompassing concept of manufacturing based on intelligent technologies and human skills.

### *1.3 Objectives and Scope of the Review*

The main purpose of this study is to perform an extensive review on human-centric manufacturing as part of Industry 5.0, particularly focusing on how it facilitates the development of sustainable and intelligent manufacturing processes. The review focuses on the basic concepts of Industry 5.0 and the contribution of recent technologies in enabling human-intelligent manufacturing collaboration.

In other words, this paper intends to:

- Review the definition and basic principles of human-centric manufacturing in Industry 5.0.
- Consider the part played by enabling technologies such as artificial intelligence, collaborative robots, digital twins, IIoT, big data analytics, and augmented reality in helping achieve human-centric manufacturing.
- Study the impact of human-centric manufacturing on environment, economy, and society.
- Look into the current applications in industry at present in manufacturing industries.
- Identify existing problems and gaps in the literature which make it difficult to adopt the practice in industry at large scale.
- Formulate future research directions and framework.

Unlike several other current review papers which mainly concentrate on technology progress, the present review takes the multidisciplinary approach by considering the intersection of technological progress, human welfare, and sustainability. The suggested review will be helpful in becoming a useful reference tool for the creation of robust, sustainable, and intelligent manufacturing systems in line with the Industry 5.0 concept [6].

## 2. Human-Centric Manufacturing in Industry 5.0

### *2.1 Definition and Concept*

Industry 5.0 is a new paradigm for manufacturing in that human beings become the focus of the manufacturing process and advanced technologies can be used to complement humans and not replace them in their manufacturing processes. As opposed to industry 4.0, which focuses mainly on automation, connectivity, and decision-making through data, industry 5.0 aims at ensuring a collaboration between intelligent machines and humans in sustainable, resilient, and personalized manufacturing. This paradigm understands that even though artificial intelligence, robotics, and cyber-physical systems can be very efficient at repetitive and data-driven tasks, there is still no replacement for human intuition and imagination [7].

Therefore, the human-centric approach to manufacturing can be understood as a way of producing products by means of intelligent technologies that support people in enhancing their skills to provide a safe environment, better decision making, flexibility, and innovative capabilities. In such a way, instead of being machine operators, people become valuable partners working alongside the AI-powered technologies and optimizing production processes to produce more valuable goods. Such a trend can be regarded as one of evolution from technology-oriented to value-oriented manufacturing that meets the social requirements and improves human well-being [8][9].

### *2.2 Core Principles of Industry 5.0*

These three pillars are described by the European Commission as forming the foundation of Industry 5.0 and what makes it different from earlier industries. They are centered on human centricity, sustainability, and resilience.

- Human-Centricity

Human-centricity makes sure that workers play an important role in the manufacturing process by making sure that technology works in collaboration with humans rather than working against them. Smart manufacturing is introduced to ensure safety for operators, decrease the workload on physical and mental levels, optimize ergonomics, and allow decision making based on intelligence. Cobots, augmented reality, wearables, and AI-enabled decision-making tools make it possible for employees to complete their jobs more efficiently and effectively while providing safety and productivity [10] [11].

- Sustainability

Sustainability goes beyond environmental sustainability to include economic sustainability and social responsibility. The advent of Industry 5.0 ensures that manufacturers can effectively maximize the use of resources, conserve energy, generate less waste, and promote circular economy practices at all stages of production. With intelligent production systems, it becomes easy for companies to monitor resource use, predict maintenance requirements, and optimize processes with a view to mitigating any harm to the environment and increasing efficiency [12].

- Resilience

The recent developments in the global environment, such as outbreaks of diseases, geopolitical tensions, and disruptions in the supply chains, have proven the need for resilience of manufacturing operations. Industry 5.0 promotes production networks that can quickly adjust themselves to changes in the demand on the markets and sudden disruptions. With the help of AI, digital twins, cloud manufacturing, and predictive analytics, companies will be able to identify potential dangers and make better decisions. However, human knowledge is still required to deal with uncertainties [13].

### *2.3 Characteristics of Human-Centric Manufacturing*

Human-centered manufacturing integrates digital technology with human intellect to create cooperative, adaptive, and intelligent production processes. There are several features that set this style of manufacturing apart from others.
Man + AI Collaboration: The role of artificial intelligence in this context is to be a decision-making aid and not the automation of human jobs through automation. In other words, AI can help with production planning, quality testing, predictive maintenance, and process optimization, while humans will bring knowledge and ethics into play.

Collaborative Robots: New-age cobots are built with human safety and cooperation in mind. Therefore, cobots perform mundane and repetitive jobs, while people have time for other productive and important work.
Worker Wellness and Ergonomics: In Industry 5.0, occupational health is achieved through reducing repetitive strain injuries, ergonomic workplaces, and improved workplace safety. Wearable devices, monitoring tools, and ergonomically designed workplaces help increase worker well-being.

Personalized Manufacturing and Flexibility: The human-centered nature of production allows businesses to meet ever-increasing customer demands because human innovation is integrated into automation technology. With the aid of artificial intelligence and digital technologies, flexible manufacturing systems make it possible to quickly customize products without compromising productivity.

Continuous Learning and Workforce Development: As technologies become more intelligent, workers need to learn new skills continuously. This is why Industry 5.0 focuses on continuous learning, multidisciplinary cooperation, and development of digital skills to facilitate human-machine cooperation.

Ethical and Transparent Decision Making: The use of AI requires transparency, ethics, accountability, and privacy of workers. It is important to have people monitor the decisions made by AI technologies because only in this way it will be possible to comply with regulations.

In conclusion, human-centric manufacturing changes the relationship between people and technologies from the replacement of humans by machines to their cooperation with each other. In this way, Industry 5.0 creates productive, innovative, sustainable, and worker-satisfying production systems.

## 3. Enabling Technologies for Human-Centric Manufacturing

Industry 5.0 will be achieved through the smooth implementation of new-age technologies which enable human interaction with intelligent manufacturing processes. In contrast to Industry 4.0, where technology was mainly used for automation and autonomous manufacturing processes, Industry 5.0 implements technology to make humans stronger, safer at work, better at making decisions, and producing sustainably. Below are the technologies forming the basis of human-centered manufacturing.

### *3.1 Artificial Intelligence (AI)*

Artificial intelligence (AI) can be seen as one of the key technologies which are leading industry 5.0. It helps manufacturing systems to analyze huge amounts of production data, find any patterns, predict failures of equipment, optimize production processes, and make real-time decisions. Instead of completely taking control over the decision making, AI serves as an assistant which gives recommendations but leaves all the control for the operators [14] [15].

Applications of artificial intelligence (AI) in the form of predictive maintenance, quality assurance, demand forecasting, process optimization, and production planning increase efficiency while reducing downtime and use of resources. In addition to this, explainable artificial intelligence (XAI) gets more and more popular since it allows giving transparent recommendations, which improves the trust of workers.

### *3.2 Collaborative Robots (Cobots)*

The cobots have significantly improved upon the traditional industrial robots by facilitating safe interactions with human workers. While the traditional industrial robots operate in separate work cells from human workers, the collaborative robots have sensors, vision, and force limiting technologies that enable them to interact with the presence of human workers [16].

In human-centric manufacturing, the cobots do the physically difficult, repetitive, and dangerous activities in production while the human workers bring their cognitive abilities into play. Some of these abilities include problem solving and creativity.

### *3.3 Digital Twins*

Digital twins use real-time data synchronization in order to create a virtual copy of physical manufacturing assets, production lines, or even whole factories. It is possible for engineers and factory workers to analyze the performance of such systems, make different simulations regarding the manufacturing process, perform tests on process changes and predict potential equipment breakdowns thanks to this virtual twin [17].

The use of digital twins within Industry 5.0 becomes a very useful tool for making decisions since humans are able to analyze multiple options of production without interrupting the ongoing process itself. Moreover, the combination of digital twins and AI allows for optimized maintenance, better quality of products and effective resource management.

### *3.4 Industrial Internet of Things (IIoT)*

Through the use of high-speed networking technologies, the Industrial Internet of Things (IIoT) interconnects machines, sensors, equipment, and production lines to facilitate the ongoing flow of manufacturing information. IIoT ensures that real-time information on the state of machines, their energy usage, the quality of products being produced, and performance is always available [18].

In the case of human-centric manufacturing, IIoT ensures that operators have access to accurate information to enable them to make decisions. This is achieved through monitoring systems and dashboard provision of relevant information. Consequently, IIoT improves the efficiency of both manufacturing and productivity of workers while facilitating sustainable resource management.

### *3.5 Big Data Analytics*

The manufacturing environment today produces huge volumes of data in the form of structured and unstructured information from sensors, machines, enterprise applications, and customer engagement. Big Data Analytics leverages such data to derive insights that can be used for making effective decisions [19].

Through the use of advanced analytics, manufacturers are able to uncover production bottlenecks, optimize energy usage, ensure high-quality products, reduce defects, and plan maintenance activities. Industry 5.0 uses data analytics to complement human skills and provide evidence-driven advice that enhances the quality of decision-making while retaining the opportunity to leverage human experience [20].

### *3.6 Augmented Reality (AR) and Virtual Reality (VR)*

Through the use of AR and VR, human interaction with manufacturing processes is greatly improved because of the ability to visualize and provide digital assistance. AR helps in visualizing how to do things by overlaying the digital assistance over the actual equipment, helping workers get assembly instructions, maintenance instructions, inspection instructions, and alerts on the process right where they can see it [21].

This will help eliminate human errors, cut down training times, and increase maintenance effectiveness. VR offers immersive virtual environments which help in the training of the workforce, production planning, ergonomics assessment, and simulation of safety measures without interfering with the manufacturing processes.

### *3.7 Edge and Cloud Computing*

The growing amount of manufacturing data demands an efficient computing architecture that can handle real-time analytics and make intelligent decisions. In this regard, cloud computing is an effective solution providing scalable storage and computing capabilities for big data analysis and manufacturing optimization on the company level. At the same time, cloud-based computing can cause some communication delays in time-sensitive manufacturing operations [22].

To eliminate the problem, edge computing is used, which enables handling manufacturing data closer to manufacturing devices and thus allows responding quickly to any events in production. The use of edge and cloud computing in conjunction with each other provides a balanced computing approach that enables real-time machine control, predictive maintenance, AI implementation, and decision-making, keeping in mind the enterprise-wide approach. It becomes especially important when speaking about the implementation of the concept of Industry 5.0.

- Integration of Enabling Technologies

While the individual contribution of each technology to the intelligent manufacturing process should not be disregarded, their full potential will only be unlocked through an integration process. AI interprets the information gathered on the production process through the IIoT sensors; digital twins model the manufacturing process through live information; cobots perform collaborative activities alongside human employees; AR/VR tools make the operator interaction more effective; while edge and cloud computing create the computational framework required by intelligent systems [23].

## 4. Human-Centric Manufacturing for Sustainability

Being sustainable has now become an important goal for current manufacturing operations where there is a growing need to reduce their negative impact on the environment and maintain competitiveness at the same time. Industry 5.0 goes further to incorporate sustainability by including the aspect of human well-being into the intelligent production system framework. In contrast to traditional manufacturing processes that concentrate mainly on productivity, human-centered manufacturing aims to have an equilibrium in improvements concerning economic performance, environment protection, and social development.

### *4.1 Environmental Sustainability*

The need for environmental sustainability is one of the main factors that drive the emergence of Industry 5.0 since companies tend to lower their energy use, emission of greenhouse gases, generation of waste and pollution of the environment at all stages of production. With the help of intelligent technologies like Artificial Intelligence (AI), Digital Twins, IIoT, and Big Data Analytics, companies have the opportunity to monitor their production processes and enhance efficiency [24].

Using AI-based optimization algorithms, companies can detect inefficient production processes and suggest optimal production parameters to lower energy consumption and preserve quality of the output product. Predictive maintenance allows companies not only to save from the replacement of equipment but to avoid its breakdown and prevent industrial waste. Moreover, digital twins help with sustainability because companies can simulate their production processes and select the best scenario without using any resources [25].

Circular economy is another aspect of Industry 5.0 where there is a push towards the reusing, remanufacturing, recycling, and proper management of resources. Humans are still critical in the design of sustainable manufacturing processes, use of sustainable materials, and making the right decisions that promote efficiency alongside sustainability. Human-focused manufacturing plays an important role in attaining global sustainability objectives [26].

### *4.2 Social Sustainability*

The distinctive feature of Industry 5.0 is its focus on social sustainability due to increased attention to employee welfare, occupational health and safety, and ongoing education. Contrary to Industry 4.0, in which automation meant unemployment of workers, in Industry 5.0 workers are treated as essential partners, and their innovative ideas, experience, and decision-making capabilities are supplemented with intelligent machines.

Cobots ensure that the workers do not have to engage in repetitive and heavy jobs, thus preventing work-related injuries. AR and VR systems create an interactive learning environment for developing skills of the workforce while keeping risks to a minimum. In addition, intelligent decision-support systems help operators perform complicated production activities [27].

In addition to this, Industry 5.0 encourages life-long learning and ongoing training of the workforce so that employees are capable of working alongside new digital technologies. This is done through investments in digital capabilities, cross-disciplinary education, and human-centered workspaces. This, in turn, improves employee engagement, job satisfaction, and innovation in the organization. The issue of ethics becomes more important here in this context since it further enhances social sustainability through trust in workers [28].

### *4.3 Economic Sustainability*

Economic sustainability is crucial to ensuring competitiveness in the manufacturing industry in a dynamic global market environment. Human-centered manufacturing increases the performance of organizations through the use of intelligent automation together with human expertise, allowing manufacturers to become more productive while retaining production flexibility and quality of products.

Through advanced analytics, process optimization using AI, and predictive maintenance, production costs are reduced by eliminating equipment downtime, cutting down on material waste, and improving the efficient utilization of resources. Through digital twins, manufacturers can assess production changes before implementation, which lowers development costs and accelerates the product development process [29].

Industry 5.0 also helps achieve mass customization through flexible manufacturing systems that allow the creation of customized products without compromising on production efficiency. Creativity from humans is essential when it comes to innovating the product, engaging customers, and making decisions. Intelligent technologies help analyze the data and assist in operations within a short time, thus allowing companies to make necessary adjustments in order to keep pace with changes in customer demands and gain competitive advantages and profit [7] [30].

Additionally, resilient manufacturing systems minimize the financial threats posed by disruptions in the supply chain, machine failures, and other unforeseen factors related to market conditions. The cooperation of intelligent technologies and skilled human workers allows companies to adjust their manufacturing strategy.

### *4.4 Integration of the Triple Bottom Line*

What makes Industry 5.0 unique is the ability of this approach to combine all three aspects of sustainability, namely environmental, social, and economic aspects into one manufacturing process. Instead of focusing only on efficiency, human-centric manufacturing focuses on creating value for both the organization and human beings through the use of advanced technologies.

Thus, for instance, artificial intelligence-based production optimization will not only reduce costs but also decrease the use of energy and emissions of carbon dioxide. At the same time, the application of collaborative robots will increase the safety of workers and production efficiency at the same time. The use of digital twins will help minimize waste of materials during the virtual simulation of products' creation [31].

Therefore, Industry 5.0 constitutes a holistic manufacturing framework wherein smart technology, talented people, and sustainable business work together seamlessly to produce robust manufacturing systems that can deliver sustained economic development, environmental sustainability, and social welfare.

## 5. Applications of Human-Centric Manufacturing in Industrial Sectors

The concepts of Industry 5.0 have become widely implemented by many industries in order to enhance their productivity, product quality, employee wellbeing, and sustainability. In particular, through the use of intelligent technologies such as artificial intelligence (AI), cobots, digital twins, and IIoT alongside human knowledge, industries have been able to establish flexible, resilient, and consumer-focused production systems. Despite the fact that there is a disparity in the degree of application of these concepts in different industries, it is clear that human-centered manufacturing holds great promise.

### *5.1 Automotive Manufacturing*

This sector has embraced the applications of Industry 5.0 technology from the onset because of the level of automation of the production process in this sector as well as the need to customize their products. Collaborative robots are being used more often in manufacturing processes working hand-in-hand with the workers in the assembly lines carrying out heavy tasks.

AI facilitates predictive maintenance, production scheduling, and quality control through analysis of large amounts of manufacturing data in order to detect defects and to optimize production parameters. The digital twin helps to perform validation of manufacturing process virtually prior to its actual execution, which saves the time of development and decreases the number of production errors. Human-centered manufacturing improves ergonomic working conditions.

### *5.2 Aerospace Manufacturing*

The manufacturing of aerospace products requires an elaborate manufacturing process, which needs to be precise and of high quality, alongside having skilled workers. Human-centric manufacturing is achieved through integrating automation and human experts' knowledge in the design, manufacturing, and inspection process.

Digital twins have been extensively applied for the simulation of the manufacturing processes, assessing machine performance, and analyzing different manufacturing options before their implementation. The AI-powered inspection process helps detect defects while enabling the engineers to validate the inspection findings. Augmented Reality (AR) is utilized in assisting technicians with the assembling and maintenance tasks using live digital guidance instructions.

### *5.3 Electronics Manufacturing*

The electronics manufacturing industry features small components, short product lifecycles, and constantly changing customer requirements. With human-centric manufacturing, manufacturers can accomplish high efficiency in manufacturing and product customization through intelligent automation in combination with human workers.

Computer vision and artificial intelligence technology used in quality inspection detects manufacturing flaws quickly, but it is up to human workers to confirm the results that are complex or not clear to the computer system. Robotic assistance for assembling, packaging, and testing of components relieves the burden on the human worker and makes production more efficient [32].

### *5.4 Additive Manufacturing*

Additive manufacturing has emerged as an essential application area for Industry 5.0 because of its flexibility, freedom of design, and mass customization ability. Expertise from humans plays a vital role in planning the process, selecting materials, optimizing process parameters, and conducting quality assessments, whereas intelligent systems enable continuous process monitoring and decision-making support.

Algorithms for AI optimize process parameters, detect process errors, and increase precision. Digital twins simulate manufacturing conditions before the manufacturing process, which helps in minimizing the material wastage and unnecessary experimentation. In more sophisticated manufacturing processes, like WAAM (Wire Arc Additive Manufacturing), IIoT-powered sensors monitor process variables constantly, helping in making wise decisions.

### *5.5 Medical Device Manufacturing*
High precision, regulation adherence, and customization of products are some of the features that characterize the manufacture of medical devices. Human-centered manufacturing enhances these characteristics by leveraging intelligent technology along with skilled human intervention to enhance safety and quality.

The use of collaborative robots helps in performing precise assembly and handling of fragile parts while inspection systems that rely on AI identify defects in the process of manufacture with high accuracy. Digital documentation, traceability systems, and intelligent quality management systems help adhere to regulations and increase quality of the products. Human expertise is required to validate the results of production, understand the quality data, and adhere to health care regulations.

### *5.6 Food and Consumer Goods Manufacturing*
The human-centric approach is revolutionizing the food processing industry and the consumer goods industry as well by enhancing the quality of products, increasing production flexibility, and ensuring the safety of working environments. AI-driven monitoring system maximizes the efficiency of production scheduling, predicts failures of machinery, and minimizes food wastage using intelligent process control.

Collaborative robots undertake routine tasks of packaging, sorting, and palletizing while humans monitor the production quality and process improvement. Intelligent sensors monitor the temperature and humidity of the production environment, guaranteeing the safety of the product. Moreover, intelligent manufacturing systems provide an opportunity for manufacturers to respond to changing consumer demands fast enough.

- Summary of Industrial Applications

Within all areas of manufacturing, Industry 5.0 shows that intelligent systems work best when they supplement humans' abilities, but do not substitute for them. AI helps in analysis and decision-making, cobots make manufacturing processes safer and more productive for humans, digital twins help to optimize processes, and IIoT makes it possible to monitor the manufacturing process in real time. The knowledge and skills of a human being are vital for innovation, creativity, ethics, and strategic problem solving.

## 6. Challenges and Research Gaps
Though there are huge possibilities offered by Industry 5.0 with regard to the revolutionizing of the manufacturing sector through sustainable and human-centric production processes, there are some technological, organizational, and socio-cultural issues that keep on posing barriers to the adoption of Industry 5.0 at an industrial scale. While the technological enablers of Industry 5.0 including AI, cobots, Digital Twins, and IIoT have advanced immensely, the integration of these technological advancements into the manufacturing sectors poses some problems.

### *6.1 Implementation Challenges*
- High Initial Investment

The integration of technologies associated with Industry 5.0 requires considerable expenditure on state-of-the-art equipment, intelligent sensors, networking systems, cloud computing, software, and training. While major manufacturing corporations have enough financial means to undergo digital transformation, SMEs may experience budget constraints in the process of adopting such technologies. The unavailability of cost-effective solutions is a key challenge to the adoption of technology in industry.

- Workforce Skills and Training

Manufactory systems based on humans need tight cooperation between employees and smart systems, which results in ever-growing requirements for specialists who are proficient in many fields like manufacturing, automation, artificial intelligence, data analytics, robotics, etc. Nowadays, there is a shortage of professionals who can work with innovative manufactory systems in numerous companies. Thus, education and reeducation play key roles in realizing Industry 5.0.

- Cybersecurity and Data Privacy

The high level of connectivity of IIoT devices, cloud services, and cyber-physical systems is a major reason for increased vulnerability to cyberattacks for manufacturing companies. The risks include unauthorized access, ransomware, manipulation of data, and stealing of confidential industrial information that may affect operations of manufacturing businesses. Also, wearables and AI-based surveillance systems gather considerable amount of data about employees, which creates a privacy issue and makes strong cybersecurity frameworks essential.

- Interoperability and Standardization

The implementation of Industry 5.0 involves many different types of technologies made by various vendors who use a variety of communication protocols and software architectures. However, due to the lack of universally recognized standards, interoperability among devices for manufacturing, enterprise applications, artificial intelligence solutions, and digital twin systems can be problematic.

- Human Trust and Technology Acceptance

The successful cooperation between humans and AI is not possible without the presence not only of technical skills but also of the trust of workers toward the intelligent system. The lack of transparency or explainability of the decisions of artificial intelligence may lead to distrust and may become a barrier to the implementation of technologies. The same problem exists in relation to fears of replacing human workers by machines.

### *6.2 Research Gaps*

Although Industry 5.0 has attracted considerable academic interest, several important research gaps remain that require further investigation.

- Explainable and Trustworthy AI

AI technologies used for manufacturing today are concerned mainly about prediction accuracy and optimization, but not about model transparency and explainability. In future, it is necessary to introduce explainable AI models that will allow manufacturing people to understand, verify, and trust AI suggestions.

- Human–Digital Twin Interaction

The majority of the existing research efforts are dedicated to monitoring and maintenance of equipment as well as process optimization. On the other hand, there is limited research on the way to facilitate interaction between humans and digital twins. Human interaction with digital twins is an area worth exploring in the future.

- Ethical AI and Responsible Manufacturing

There is a growing number of ethical issues that arise from the use of AI technology in manufacturing due to the issue of algorithm bias, accountability, transparency, workforce surveillance, and ownership of data. Therefore, there is a need for strong governance to ensure that intelligent manufacturing remains ethical and transparent.

- Human–Robot Collaboration

Despite the immense promise shown by cobots thus far, more research still needs to be conducted to further enhance adaptive interaction, collective decision making, ergonomic evaluation, and dynamic task assignment between human beings and cobots. Cobots of the future must be able to understand the intent of the operator and adapt accordingly.

- Sustainability Assessment Frameworks

The majority of current sustainability studies assess the environmental or economic performance individually. There is a lack of assessment methods, which take into account all three dimensions of sustainability (environmental, economic, and social), in the manufacturing process of Industry 5.0. The need for the indicators of sustainability is evident.

- Industry 5.0 Adoption in SMEs

Most literature studies revolve around big manufacturing firms that have abundant technical capabilities. Implementation models that would be applicable to SMEs are limited. The next wave of literature in the field should revolve around cost-effective strategies, scalable systems, and easy-to-implement models that would work in SMEs.

- Workforce Competency Development

While there are many works dedicated to the issue of technologies associated with digital transformation, there is not much discussion about effective education models that would help to prepare the future manufacturing workers. More effort has to be made in this direction.

### *6.3 Future Outlook*

Meeting the above challenges would involve multi-disciplinary collaborations from researchers, industry players, technologists and policymakers. In future, Industry 5.0 research should focus on developing transparent AI applications, interoperable digital platforms, resilient cyber-physical infrastructure and implementation frameworks that consider both technology innovations and human welfare.

Additionally, there is need for manufacturing firms to adopt an approach where intelligent technologies enhance human capabilities without replacing them. It is the adoption of such an approach that will ensure the success of Industry 5.0 by making sure that it is able to effectively integrate digital technologies, human labor, sustainable manufacturing processes and proper governance mechanisms.

## 7. Future Research Directions

Industry 5.0 is a revolutionary concept in manufacturing where intelligent systems work together alongside human expertise to create sustainable, resilient, and customized production processes. Despite great advancements having been made toward the creation of such technologies, there still remains much more research that needs to be conducted in order for human-centered manufacturing to be fully realized. This research should focus not just on technological advancement, but on how to create an ecosystem in manufacturing that improves human and industry performance.

One interesting research area is the development of human-centric AI. The AI tools that have been developed so far concentrate on the optimization and prediction aspects. However, AI tools of the future should give transparent, explainable and trustworthy advice for human beings. XAI would play an important role in gaining the trust of operators and allowing engineers to understand why such a recommendation was generated by AI.

The evolution of future collaborative robots is also a critical area of research to focus on. The future generation of collaborative robots must have the capability of being able to adapt to learn from situations and environments, be aware of their surroundings, and use a highly developed perception system to allow them to interact effectively with humans in dynamic production environments.

Another field that is developing in the context of research includes the convergence of Digital Twins, IIoT, Edge Computing, and AI in a comprehensive manufacturing ecosystem. Future digital twins must transcend their current status of being mere surveillance technologies to become decision-making systems that can carry out simulations in real time and make autonomous recommendations for processes. The fusion of edge computing and cloud analytics would improve this aspect even further.

Assessment of sustainability is still another important research topic. Presently, most researchers conduct independent assessments for either the environment, economics, or social dimensions. The need is therefore to develop frameworks that are capable of measuring the impacts on the environment, economics, worker wellness, and sustainability of Industry 5.0 factories. This will help organizations objectively measure their human-centric manufacturing strategy success.

The embrace of Industry 5.0 by small and medium-sized enterprises is another aspect that deserves more focus. The existing models of implementation are geared towards big organizations, which have ample amounts of technology and money. Future studies need to create flexible models of digital transformation that would allow small firms to implement the technology of Industry 5.0 at an affordable price and without investing large sums of money.

Lastly, the future success of Industry 5.0 will be determined by the creation of a very flexible and competent labor force. Academic research needs to explore new ways of educating and training people, incorporating manufacturing engineering with artificial intelligence, robots, big data, and digital technology. Continuing education, immersive learning through AR/VR training, and interdisciplinary education will be crucial for preparing engineers and technicians for work in intelligent manufacturing systems.

In all, future research needs to focus on the design of manufacturing systems that take into account both technological progress and human values, sustainability, and resilience. With the use of intelligent technology and the capabilities of humans for creation, ethics, and constant learning, Industry 5.0 can shape the future of manufacturing and create systems of production that are highly efficient and socially responsible.

## 8. Proposed Conceptual Framework for Human-Centric Manufacturing

Whereas many studies have analyzed the role of AI, Digital Twin, Cobots, IIoT, and data analytics independently in smart manufacturing, there have been very few studies which have suggested a model to explain how all these technologies come together to support human-centric, sustainable, and intelligent manufacturing systems. This paper has, therefore, developed a framework based on the results of the research carried out in previous sections, where human beings are central to Industry 5.0 and intelligent technologies are leveraged for productivity, sustainability, and resilience.

The framework presented includes four layers that are interrelated and include: Human Centric Principles, Enabling Technology, Intelligent Manufacturing Processes and Sustainable Production Results. This approach illustrates the shift from technology-based automation to value-based manufacturing where intelligent solutions augment human capabilities and do not replace them.

### *8.1 Layer 1: Human-Centric Principles*

The basis of the framework is laid by the following three core values of Industry 5.0:

- Human Centricity: Focusing on the welfare of the worker, his creativity, decision making abilities, and lifelong learning process.
- Sustainability: Encouraging sustainable manufacturing processes through the efficient use of resources, minimizing waste and using the circular economy approach.
- Resilience: Allowing for quick adaptation to disruptions and evolving consumer needs in manufacturing processes.

This framework directs the application and implementation of all technologies in manufacturing.

### *8.2 Layer 2: Enabling Technologies*

The next layer includes the digital technologies forming the technical base for Industry 5.0-based manufacturing:

- Artificial intelligence (AI)
- Collaborative robots (Cobots)
- Digital twin technology
- Industrial internet of things (IIoT)
- Big data analytics
- Augmented reality (AR) and virtual reality (VR)
- Edge computing and cloud computing

In contrast to working individually, these technologies constantly share information to enable monitoring, smart decisions, predictive maintenance, optimization of production processes, and human-machine cooperation. The combination of all of these technologies forms a digital ecosystem that is capable of enabling adaptive manufacturing.

### *8.3 Layer 3: Intelligent Manufacturing Functions*

The data produced by the enabling technologies becomes intelligent manufacturing capabilities that directly contribute to production operations, including the following:

- Real-time production monitoring
- Predictive maintenance
- Intelligent quality checking
- Adaptive production scheduling
- Collaborative decision-making between humans and AI
- Flexible manufacturing and mass customization
- Resource optimization
- Process improvement

The involvement of human operators is crucial for these operations since they confirm recommendations made by AI technologies, control autonomous systems, solve difficult tasks, and make informed decisions.

### *8.4 Layer 4: Sustainable Production Outcomes*

The final stage comprises the results obtained due to successful integration of human intelligence and intelligent machines. Such results are aligned with the triple bottom line of sustainability and include the following:

1. Economic Results

- Higher productivity
- Reduced operating costs
- High quality of products
- Manufacturing flexibility
- Competitiveness

2. Environmental Results
- Lower energy use
- Less waste materials
- Low CO2 emissions
- Efficient resource use
- Circular manufacturing

3. Social Results
- Increased safety at work
- Ergonomic design
- Human capital improvement
- Employee satisfaction
- Collaboration between human and machine

All in all, these results lead to the creation of sustainable, resilient and intelligent manufacturing systems.

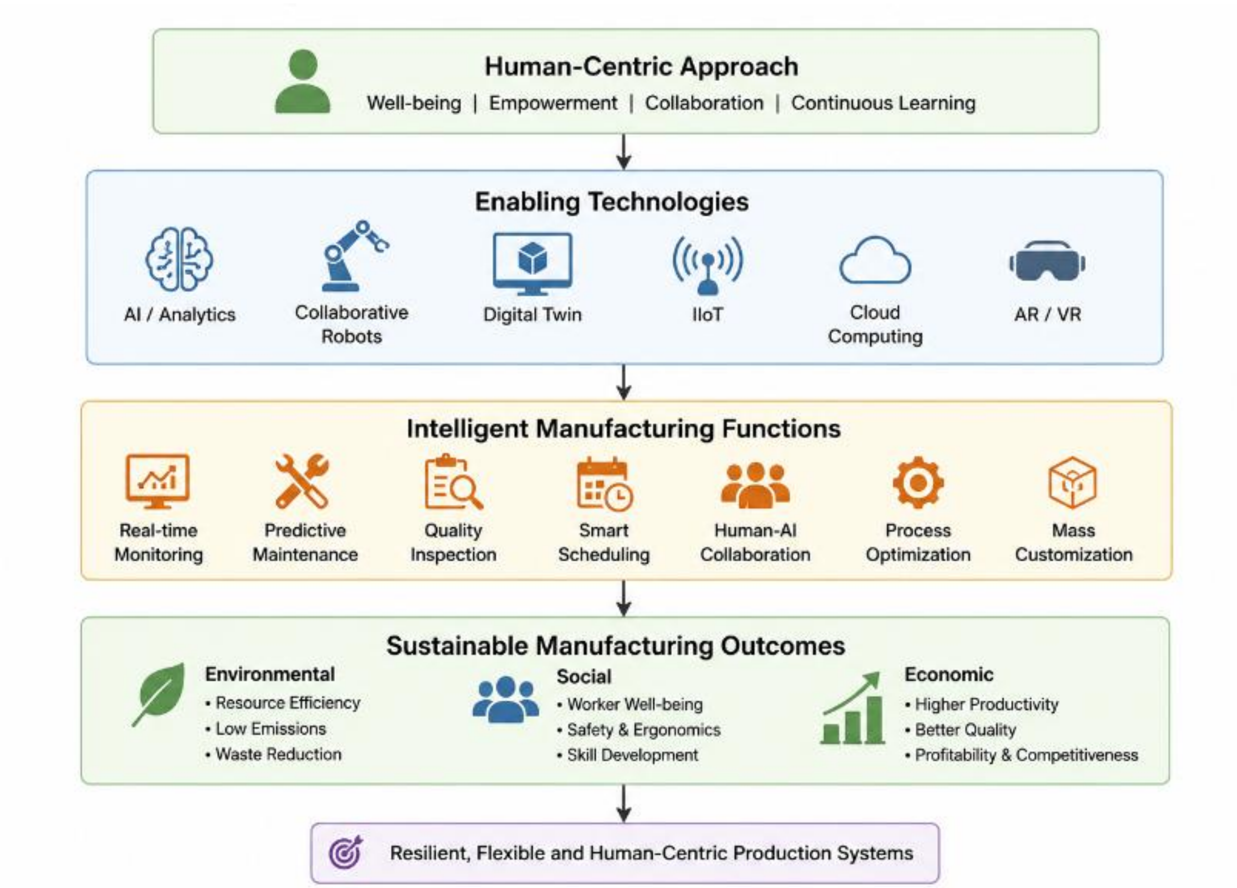

Fig 1. Framework for Human-Centric Manufacturing

Figure 1 shows the suggested conceptual architecture of Industry 5.0 human-centric manufacturing. The conceptual architecture is based on the human-centric approach, which implies worker health, empowerment, cooperation, and continuous learning. Such approaches are based on enabling technologies, such as Artificial Intelligence (AI), cobots, Digital Twins, IIoT, cloud computing, and AR/VR, which create the digital backbone of intelligent manufacturing. Using this technological approach allows carrying out the following manufacturing operations: real-time monitoring, predictive maintenance, quality inspection, intelligent production planning, human-AI interaction, process optimization, and mass customization. As a result of using this technology, there are possible sustainable manufacturing results, which can be achieved because of improved environmental sustainability due to efficient use of resources, low emissions, and waste reduction; improved social sustainability due to worker safety, well-being, ergonomics, and learning; and improved economic sustainability due to increased efficiency, product quality, profitability, and competitiveness. In general, the combination of the human experience and enabling technologies leads to the creation of resilient and flexible manufacturing systems.

### *8.5 Managerial and Research Implications*

The suggested framework can provide practical insights to organizations which would like to implement industry 5.0 technologies into their operations. Instead of adopting technologies individually, companies must opt for an integrated approach that will take into consideration the technological capability, personnel development, sustainability, and resilience of the organization.

From the point of view of research, the framework demonstrates the necessity of cooperation between such areas as manufacturing engineering, artificial intelligence, robotics, human factors, and sustainability. Moreover, the research agenda can be developed in such fields as explainable artificial intelligence, adaptive human-robot interaction, sustainability metrics standardization, and intelligent decision support systems.

## 9. Conclusions

Industry 5.0 is a new era in the manufacturing industry, as it involves a change in emphasis from technology-oriented automation to intelligent manufacturing systems oriented towards humans. As compared to Industry 4.0, where the major focus was on digitization and automated manufacturing processes, the key concept of Industry 5.0 is cooperation between people and highly sophisticated technologies for sustainable, resilient, and adaptable manufacturing processes. It is worth noting that even with the rapid advancement of AI, cobotics, Digital Twin, and IIoT technologies, human skills and abilities cannot be overlooked.

In this review, the basics of manufacturing with a focus on human-oriented aspects were reviewed and the role of some important enabling technologies that enable such systems to be intelligent was analyzed. AI helps improve decision-making, predictive maintenance, and optimization; cobots make workplaces safer and more productive; Digital Twins offer simulation and monitoring abilities; and the IIoT, big data analytics, and AR/VR help perform data-driven operations and empower employees. Thus, these technologies create manufacturing environments where the intelligent system acts as an assistant to humans.

Moreover, the review has pointed out that the role of Industry 5.0 in sustainable manufacturing was the integration of the three aspects of the Triple Bottom Line. First, environmentally, intelligent manufacturing decreases the use of energy and materials and also decreases carbon footprints owing to efficient utilization of resources. Second, socially, intelligent manufacturing makes manufacturing more human-centered by improving safety, ergonomics, continuous learning, and well-being through effective human-machine interaction. Third, economically, intelligent manufacturing contributes to increased efficiency, quality, flexibility, competitiveness, mass customization, and resilience of supply chains.

Even with all these benefits, however, there are some issues that keep the adoption of Industry 5.0 from being more extensive. Some of these include high implementation costs, cybersecurity threats, issues with integration, lack of skills among workers, and lack of trust in artificial intelligence. Besides this, research gaps still exist in topics like explainable AI, adaptable human-robot cooperation, human-centric Digital Twins, sustainability assessments, and implementation strategies for SMEs.

In order to overcome these challenges, the paper has presented an industry 5.0 framework which incorporates human centric approach, technological capabilities, intelligent manufacturing capabilities, and sustainable manufacturing outcomes into one comprehensive architecture. The framework suggests that any kind of technological innovation must have its focus on human welfare, environmental sustainability, and organizational resiliency other than productivity. Moreover, the paper has also given the structure of research which can help understand how AI, digital twins, industrial internet of things, collaborative robots, and advanced analytics can help in human-centric manufacturing.

To conclude, Industry 5.0 provides an all-inclusive blueprint for the future of manufacturing in which intelligent systems and human knowledge work in synergy to achieve sustainable and resilient manufacturing processes. The future of manufacturing would be successful not only in the sense of technological progress, but also through designing manufacturing processes that place the emphasis on human values, ethics, and sustainability. This can only be achieved by carrying out interdisciplinary research and developing cooperation between academic and industrial circles.

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