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Advancing sustainable development goals in aerospace industry through Industry 5.0

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Abstract
The aerospace manufacturing industry is facing increasing pressure to align with the United Nations' Sustainable Development Goals, such as responsible production, climate action, and industry innovation. Industry 4.0 notwithstanding, most of these technologies are concerned with efficiency and automation while paying little heed to human-centric, sustainable goals that can be achieved in line with the SDGs. This would present a possibility to bridge this gap with Industry 5.0, which is on the way to collaborating with human-machine interaction and sustainability practices. This paper discusses the possibility of how this new paradigm, focused on collaborative work between advanced automation and human-centric, sustainable production, can help aerospace manufacturers achieve those key Sustainable Development Goals. Industry 5.0 will provide an opportunity for a symbiotic partnership between humans and machines with avenues that open opportunities to reduce environmental impacts, optimize the use of resources, and enhance innovation in aerospace manufacturing processes. The research illustrates the implementation strategy of Industry 5.0, smart factory, robotics, digital twin, and artificial intelligence towards the achievement of SDG 8, SDG 9, SDG 12, and SDG 13.

Keywords: Industry 5.0, Sustainable development goals, Aerospace, Human and Machine

1. Introduction

1.1 Overview of sustainable development goals in manufacturing

The United Nations' Sustainable Development Goals (Fig. 1) have defined the framework for global sustainable development, articulated environmental protection, social equity, and economic growth. SDGs adopted by manufacturing industries mean a transformation toward responsible production practices in order to reduce the consumption of resources and their resultant negative impact on the environment. The holistic evaluation of corporate sustainability calls for a set of performance metrics based on SDGs within the sustainable manufacturing system [1]. Because companies increasingly integrate SDG principles within their models of operations, manufacturing systems become more resilient and agile, hence balanced growth of the economy and environmental sustainability. Manufacturing firms leverage sustainable business models to implement SDGs, thus reducing waste and enhancing resource efficiency [2]. This shift towards sustainability meets the needs of the regulatory bodies and stakeholders alike, while it also provides industries with long-term economic sustainability and resilience. In particular, this is particularly true for environmentally intensive industries, such as aerospace manufacturing. Even in the aerospace industry, they are looking for sustainable propellants and technology through Industry 5.0. Later, scientists and researchers are looking for sustainable rocket propulsion such as a hybrid rocket, which is an intermediate between a solid and liquid rocket engine [3-5]. It will add the new scope to reach a low Earth orbit and replace the expensive space mission with an affordable price.

Fig. 1 Sustainable Development Goals

1.2 Evolution of Industry 4.0 to 5.0 in aerospace

The industry 4.0 shift towards Industry 5.0 has significantly impacted the aerospace industry, marking an industrially dynamic change in industrial practices. Industry 4.0 thrusts digitalization and connectivity to the fore, thereby converging IoT, big data, and automation in every function of manufacturing. The current step is that aerospace manufacturers have achieved high productivity and efficiency due to interconnected systems and data-driven decision-making [6]. Accordingly, the aerospace industry saved processes such as predictive maintenance and higher-quality products. Industry 5.0, on the other hand, introduces a system emphasizing human-centricity and sustainable development, reframing the role of technology within industrial frameworks.

Unlike the fully automated approach taken by Industry 4.0, Industry 5.0 advocates for cooperative interactions between humans and machines, where the benefits of human creativity and intuition are merged with the machine's precision. Such shifts are important in pursuing sustainability and adaptability in these complex manufacturing environments, as found in aerospace [7]. For example, in Industry 5.0, humans and machines come together to solve problems and thus provide a more inclusive means of production, with environmental factors considered and worker satisfaction increased.

With the help of technological inventions such as digital twins, AI, and robotics, for example, which can accommodate collaborations with humans in real-time environments, Industry 5.0 is able to make sustainable manufacturing possible in the Aerospace industry. These technologies ensure better resource utilization, waste reduction, and greater safety standards, making this industry meet the sustainability goals [8]. Furthermore, the focus on digital transformation provided in Industry 5.0 allows an automobile manufacturer to build robust and agile systems that can respond dynamically to rapidly changing demands and operational needs. Solutions for the production of aircraft, as well as MRO, suggest the impact of Industry 5.0 on aerospace.

The integration of human-machine collaboration in these processes enhances flexibility and supports innovations in sustainable practices [9]. Furthermore, the use of AI-driven frameworks to optimize repair and production timelines aligns well with Industry 5.0's focus on productivity and resource efficiency. This change will be sure to herald tremendous changes in both operational sustainability and the quality of human engagement in an industrial setting with the introduction of Industry 5.0 technologies in the aerospace sector [10-11].

1.3 Role of Industry 5.0 in aerospace manufacturing

Industry 5.0 (Fig. 2) was the birth of a new era in sustainable manufacturing by bringing human creativity, AI, and smart technologies together to produce systems that focus on efficiency and environmental responsibility. As opposed to Industry 4.0, which was mainly about automation and efficiency, Industry 5.0 seeks to introduce much more balance and sustainability. The human-centered approach lies at the heart of Industry 5.0; this allows for environments designed for collaboration between humans and machines. Such a design not only results in increased productivity but also reduces environmental impact in terms of efficient resource usage and better management of waste [12].

One of the core objectives in sustainable manufacturing for Industry 5.0 is to develop a framework that aligns manufacturing processes with global sustainability standards. Industry 5.0 offers an outline for moving toward a more sustainable production model as it uses data-driven insight to improve energy efficiency and reduce emissions [13]. Industry 5.0 embraces the well-being of its workers and the greatest performance of its operation for this culture of manufacturing. The environmentally concerning impact of Industry 5.0 sustainable manufacturing raises concern over the ethical and healthier ways to work [14]. AI and robots in coordination and design with humans avoid redundancies and hazardous exposure within work for human safety purposes and develop an even friendly atmosphere of work.

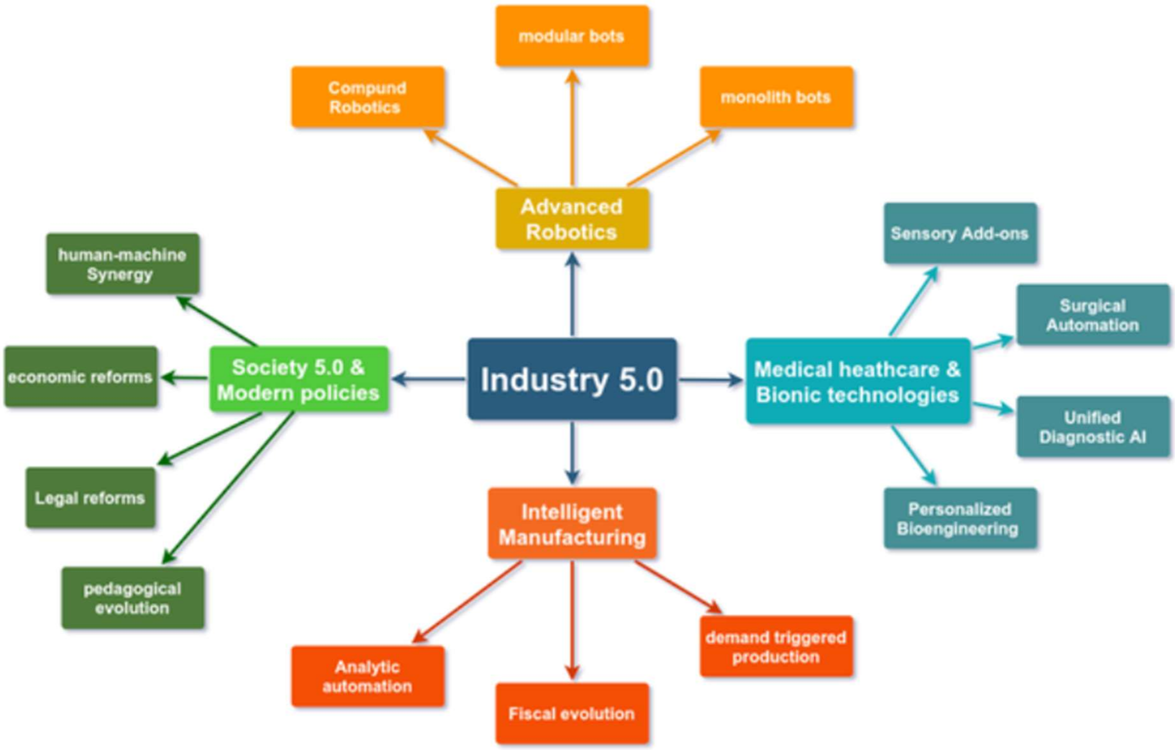

Fig. 2 A generic block diagram for Industry 5.0 [15]

2. Key Principles of Industry 5.0 in Aerospace Manufacturing

2.1 Human-Centric Approach

A human-centric approach (Fig. 3) is a core component of Industry 5.0, which involves harmonized advanced technology with human values, experiences, and needs. Human-centric AI in Industry 5.0 is designed not only for automation but also for enhancing human skills and decision-making within the manufacturing environment [16]. This approach facilitates a more interactive workspace with AI systems working as collaborators and not replacements, allowing the human aspect to maintain control and apply their creativity for high-stakes aerospace projects. Such a framework of balancing human-centric innovations with sustainable and inclusive solutions is very important since it promotes a balanced industrial ecosystem that values both social and environmental well-being alongside technological progress [17].

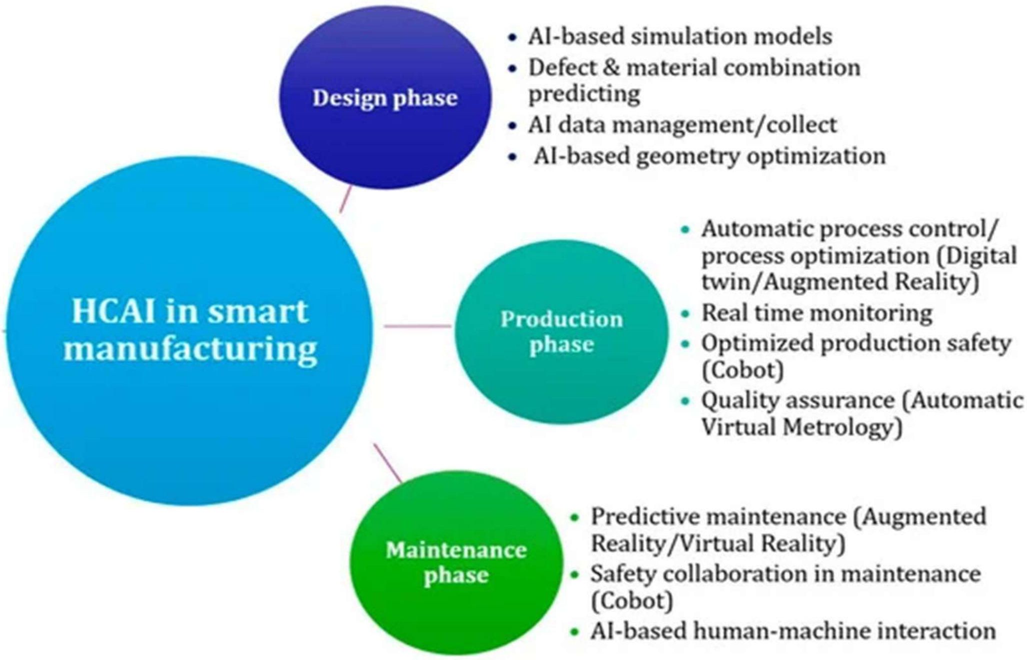

Fig. 3 Human-centered AI in smart manufacturing [18]

2.2 Personalization and Customization in Manufacturing

Industry 5.0 focuses on high customization of aerospace components with a particular operational requirement using intelligent systems and data-driven designs. There are numerous challenges and opportunities concerning the development of highly customized personalized product-service systems that are able to meet the varied demands of customers without compromising resiliency and sustainability. A level of customization is critical in aerospace manufacturing, wherein components often have to meet multiple standards for many applications [19]. This principle helps in the standardization of MRO operations, making the process as flexible and accurate as possible with enhanced aircraft life and safety.

2.3 Integration of Advanced Technologies (AI, Robotics, IoT, Cyber-Physical Systems)

To make Industry 5.0 effectively work in aerospace manufacturing, advanced technologies such as Artificial Intelligence (AI), Robotics, Internet of Things (IoT), and Cyber-Physical Systems (CPS) must be well integrated (Fig. 4). Such technologies provide for more significant automation, precision, and adaptability in manufacturing processes, thereby making them intelligent and responsive. Explainable AI in Industry 5.0 is an essential aspect since it enhances decision-making for aerospace applications, but also helps engineers and operators understand and interpret better the behavior of the machine. The implementation of this kind of explainable AI enhances the transparency of the decisions made by the machines, thereby building trust between humans and machines [20]. The assembly and inspection of composite fuselage panels with precision and flexibility requires high accuracy and flexibility. Robotics can be used for an integrated architecture that combines sensing and feedback systems to let robotic arms work in concert with human operators in precise tasks of assembly and quality inspection in real time. This will allow for improved aerospace manufacturing output while increasing robotic accuracy without decreasing human oversight [21]. Besides this, IoT and sensor networks also significantly contribute to the development of intelligent factories for Industry 5.0.

The establishment of IoT enables the connection of equipment and sensors with control systems with real-time data collection and analysis in aerospace manufacturing facilities. This connectivity supports predictive maintenance, reduces downtime, and optimizes operational efficiency since it gives a holistic view of the manufacturing environment [22]. In addition, these architectures of smart cyber-physical systems are integrating physical manufacturing processes with virtual systems of control, thereby yielding more robust autonomous frameworks in production. In the field of aerospace manufacturing, for instance, this system would ensure that machinery communication has been integrated with proper controls in corresponding software, so therefore dynamic adjustments take place automatically, and all sorts of production processes are optimized. The integration of CPS not only increases production efficiency but also concurs with sustainability targets by wasting fewer materials and less energy consumption [23].

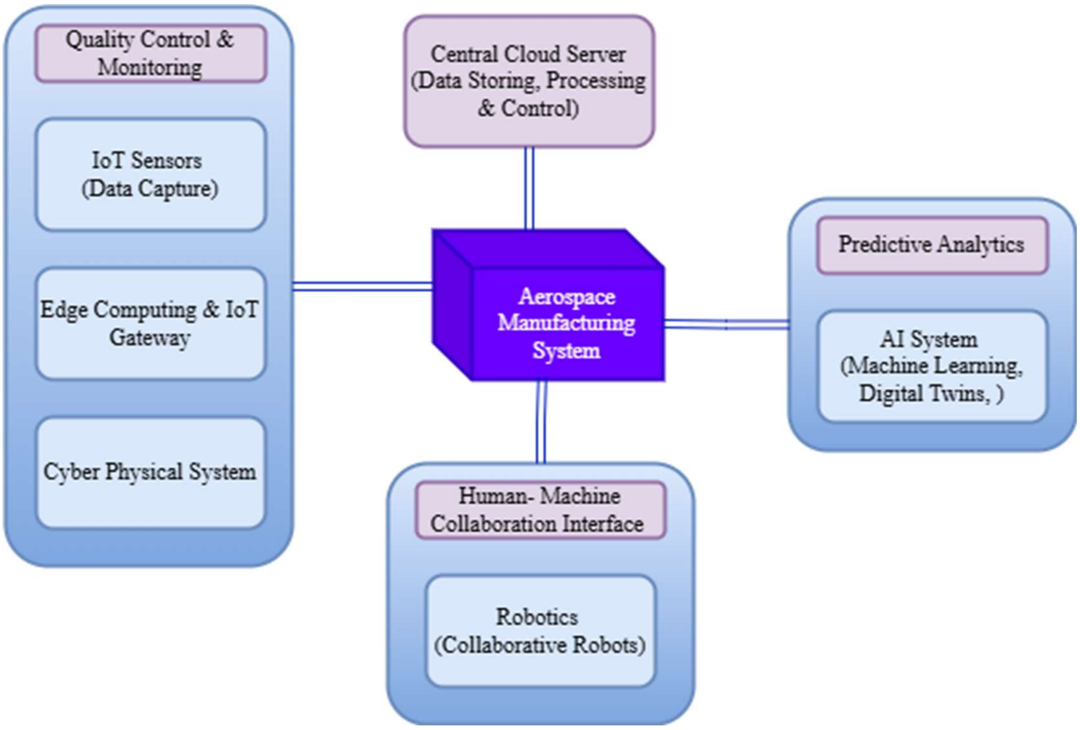

Fig. 4 Industry 5.0 integration framework for aerospace manufacturing

2.4 Collaboration Between Humans and Machines

Industry 5.0 is founded on the notion of human-machine collaboration, maximizing the synergy of human creativity and machine precision. It is a framework that is intended to boost productivity and innovation by ensuring that the machine supports rather than displaces human workers. Human-machine collaboration in Industry 5.0 has transformed manufacturing processes. Here, machines can absorb repetitive or complex calculations in such a way that a human concentrates on the creative, analytical, or decision-making task [24].

Additive manufacturing is yet another form of human-machine collaboration where a human designer and a machine collaborate to produce complicated and accurate aerospace components. Here, machines take care of the technical precision of the manufacturing process while human expertise guides design and innovation. Advanced sensors, combined with AI, are embedded into these machines that can function in tandem with human input; hence, the flexibility in collaboration is displayed as they respond dynamically to the changing requirements in the process. Such collaboration leads to the error reduction of the process and maximum adaptability, resulting in quicker efficient cycles of production in aerospace manufacturing [25].

3. Implementation of Industry 5.0 in Aerospace Manufacturing

3.1 Smart Factories and Digital Twins in Aerospace

Smart factories and digital twins introduce features of more efficient, precise, and adaptable production processes in aerospace manufacturing. Well advanced with data analytics, IoT, and AI-driven systems, a smart factory is an environment well covered to create highly automated and connected places where machinery, sensors, and control systems are all integrated (Fig. 5). Real-time monitoring and predictive maintenance mean that aerospace and equipment downtime can be lessened to the best productivity points. A key element, hence in the space industry, can be identified as a digital twin that presents a means of monitoring and optimization of physical assets like aircraft parts throughout their entire life span [26]. Digital twins enable one to simulate, analyze, and provide insight into performance problems before they happen, thus enabling proactive maintenance and reducing the risk of in-service failures. Digital twins really take this idea of smart factories beyond these concepts by providing an ideal virtual model that could mirror the environment of the physical factory, enabling manufacturers to test, optimize, and refine without interrupting production processes [27]. Digital twins play a significant role in this regard as they enable companies to test various production strategies and assess their environmental impact. For aerospace manufacturers, this means digital twin technology will now enable easy testing of the effects on the cost and sustainability of a certain process or material and production methods.

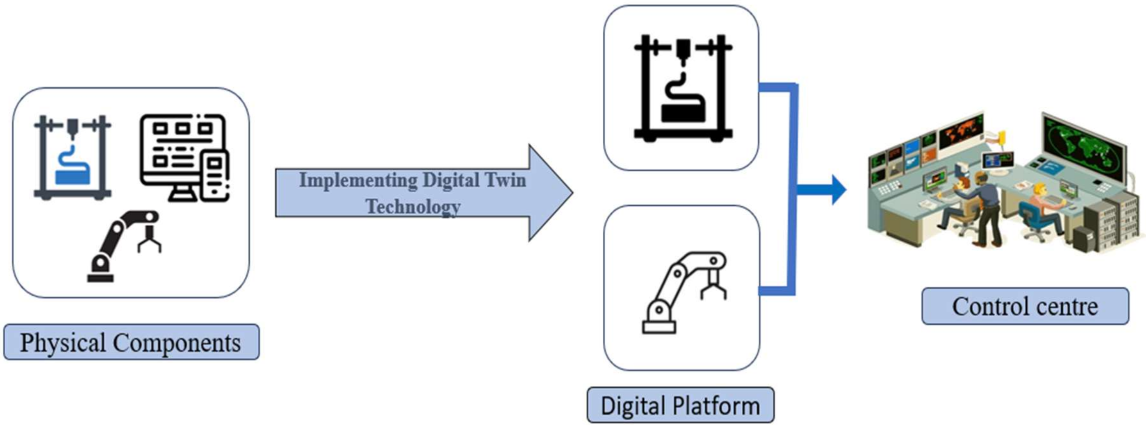

Fig. 5 Application of digital twin technology in aerospace manufacturing

3.2 Use of robotics and cobots for efficiency and safety

In Industry 5.0, cobots are a collaborative system; hence, they work along with human workers. Cobots are flexible, and they easily accept complex tasks along with dynamic variation. Unlike the traditional robots separated from human workers, the sensors and safety features of the cobots make them work safely in coordination with humans in a task where the oversight or intervention by humans is beneficial. Cobots in aerospace manufacturing can support delicate assembly processes and inspections by helping human workers handle intricate components in a safe manner while they are productive. Cobots in Industry 5.0 are designed to be efficient and have AI capabilities and to be able to learn from human interaction while performing operations according to the optimized results [28]. Cobots are generally used to support complex decision-making and to perform tasks requiring cognitive skills. Technology in aerospace manufacturing and maintenance: Cobots may be used to inspect aeronautical components for wear and tear, assist technicians in inspections, and even perform repairs at locations that are hard to reach or difficult to access. These result in reduced human exposure to hazardous conditions while improving process reliability as a whole [29].

3.3 Artificial intelligence for optimized resource utilization

The integration of AI in aerospace manufacturing enables producers to optimize their manufacturing not only materially but also energetically and in time. The system based on AI is capable of real-time analysis of humongous amounts of data, combined with predictive insights that help optimize the resource usage in the production process. In aerospace, precision, quality, and cost control are especially critical, and AI-based solutions go a long way in increasing productivity hand-in-hand with waste reduction. The contribution of AI in Aerospace engineering encompasses a number of applications, including the prediction of the wear and tear of the equipment and the maintenance requirements to avoid sudden stoppages and extend the life of the equipment. This will allow aerospace manufacturers to alter the mechanical maintenance approach from reactive to predictive and make use of available resources without any compromises on production schedules. Furthermore, AI algorithms could optimize supply chains by better forecasting demand, managing inventory, and reducing material waste within the supply chain. Since aerospace-grade materials are so extremely expensive, this is particularly important [30]. Moreover, thrust manufacturing is affected by AI, which ascertains its role in quality improvement and resource consumption reduction. Applying AI for real-time monitoring of production parameters will help the manufacturer to adjust conditions in an immediate manner, so that utmost efficiency can be achieved in resource usage. For instance, with the application of temperature, pressure, and machining parameters dynamically by AI-enabled systems, the materials would be sure to be processed without excess use, thus making manufacturing processes more sustainable [31].

3.4 Advanced data analytics and predictive maintenance

Advanced data analytics and predictive maintenance help aerospace manufacturing turn the corner from reactionary management of equipment. Big data and machine learning underpin predictive maintenance, which identifies the likelihood of failure and reduces downtime while maintaining longer periods on critical machinery and components. Predictive maintenance provides the foundation for aerospace, allowing manufacturers to ensure that certain levels of precision and reliability are achieved while achieving safety, efficiency, and costeffectiveness in the process of manufacturing. Using data analytics, problems involving imbalanced data; failure events are rare events in the aerospace industry, where equipment has a high quality, it can be efficiently used [32]. Advanced methods of data analytics can enable manufacturers to detect subtle patterns of wear or impending failure, even in sparse data sets with just a few examples of failures. This provision ensures timely notification, which helps prevent or minimize stoppages to equipment, therefore allowing smooth production without any unexpected costs from breakdowns of the equipment.

Big data analysis also supports predictive maintenance through constant monitoring of equipment health and performance. Within aerospace manufacturing, this means collecting data from sensors installed on the machine and analyzing real-time metrics using algorithms. Predictive maintenance systems can alert operators before minor issues escalate into more significant safety and efficiency concerns by examining trends and anomalies. This capability also permits strategic scheduling of maintenance, thus allowing more reduction in the disruption of operations and optimal resource utilization [33]. Predictive maintenance is of great importance in aerospace as it assists manufacturers in strategically managing the maintenance cycle without resorting to reactive repair of equipment. Predictive maintenance systems use data sources from various points, such as vibration, temperature, and operational metrics, to develop an all-around view of the health of the equipment in use [34]. The integrated approach leads to informed decision-making and makes the manufacturing process more resilient by removing waste incurred through unnecessary maintenance and minimizing resources used.

4. Alignment with Sustainable Development Goals

Industry 5.0 would support several of the United Nations' Sustainable Development Goals by being both technologically advanced and human-centric. Major areas of impact are improving decent work, supporting innovative infrastructure, resource efficiency, as well as climate change management. The above encompasses contributions to sustainable global development because of the relevance to most of the SDGs by Industry 5.0 [35].

4.1 SDG 8: Decent Work and Economic Growth – Impact of Industry 5.0 on Workforce

Industry 5.0 approaches are very human-centered since they center the workforce on innovations of advanced manufacturing. Emphasis on such aspects would be useful for promoting SDG 8, as it promotes a safer and friendlier workplace along with skill evolution parallel to technology evolution. The combination of cobots and AI at Industry 5.0, therefore, eliminates boredom at work and enhances productivity as job satisfaction increases since tasks that are drab or dangerous are left to the machines. Changing the paradigm of economic growth, this shift will therefore aim at favoring decent work conditions as found in the world's "endeavor to promote sustained, inclusive economic growth, productive employment, and decent work for all.".

4.2 SDG 9: Industry, Innovation, and Infrastructure – Advancements in Sustainable Production

Industry 5.0 establishes a resilient infrastructure and promotes inclusive, sustainable industrialization to support SDG 9. It is through such developments with digital twins, predictive maintenance, and smart factories that it delivers more efficient and more agile manufacturing systems. Such innovations reduce production downtime, enhance quality control, and lead to better use of resources, and lead towards a more sustainable and resilient industrial landscape. Tied to this is connectivity and real-time data sharing, leading to intelligent, agile infrastructure for Industry 5.0 in constant improvement and innovation.

4.3 SDG 12: Responsible Consumption and Production – Resource Efficiency and Waste Reduction

Some of the key objectives of Industry 5.0 involve better resource efficiency, less waste, and circular approaches in manufacturing, thus directly related to SDG 12. Technologies like AI-based predictive analytics will optimize the usage of materials, improve the management of inventories, and cut down energy consumption. Furthermore, additive manufacturing would allow for precise, on-demand production, decreasing overproduction and waste. It promotes responsible consumption and production, encouraging efficient use of resources, which reduces the environmental impacts by meeting the demands of modern society.

4.4 SDG 13: Climate Action – Emission Reduction and Sustainable Energy Use

Industry 5.0 supports climate action through energy-efficient technologies and the use of sustainable energy sources, in line with SDG 13. For instance, AI in energy management will optimize the power consumption of manufacturing facilities, while renewable energy will reduce dependence on fossil fuels. Smart factories rely on IoT and data analytics to monitor and reduce their emissions, thereby supporting low-carbon manufacturing ecosystems. All these initiatives mean that industry will have a strategic direction on the reduction of industrial carbon footprint to ensure that impacts of climate change are mitigated for the contribution to global goals.

5. Conclusions

Industry 5.0 is the era of manufacturing revolution, where human-centered innovation, advanced digital integration, and sustainability are central. This paper discusses some of the foundational principles of Industry 5.0 toward sustainable manufacturing, with its specific application in the aerospace sector. Collaborative technology integration in the form of artificial intelligence, the Internet of Things, cyber-physical systems, and robotics culminates in a highly productive, safe, and more efficient smart manufacturing ecosystem. Industry 5.0 focuses on close human-machine collaboration in order to ensure that the workers are involved in meaningful tasks for effective operational benefits and job satisfaction. In aerospace manufacturing, its implementation through the deployment of smart factories and digital twins contributes to advanced data analytics, predictive maintenance, optimized use of resources, and an increase in the reliability of the product. That leads to a paradigm shift with close alignment to the fundamental Sustainable Development Goals, enabling responsible consumption, inclusive growth, and environmental stewardship. Industry 5.0 redefines manufacturing processes and also provides a broader need by society through its commitment towards sustainable growth.

Industry 5.0 holds the great promise of achieving resilient, sustainable, and inclusive manufacturing ecosystems with a prospect of long-term industrial and economic growth. This paradigm asserts that innovation should be balanced by social and environmental responsibility based on technological prowess.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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