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The Role of Precision Mechanics and Digital Fabrication in Sustainable and Green Manufacturing Practices

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Abstract: In this era of globalization, competitive manufacturing practices demand optimization of all critical design and manufacturing processes in order to guarantee profitability and sustainability of operations. This study presents the contributions of precision mechanics and digital fabrication in driving sustainable manufacturing. Precision technologies have contributed to material and energy efficiency goals in manufacturing by minimizing tolerances and reducing waste, while digital fabrication techniques such as 3D printing, digital twins, and so on support design flexibility, localized production, and lower environmental emissions. In a manufacturing era that is increasingly being redefined and reshaped by stiff competition, dwindling margins, environmental urgency, and rapid digital transformation, effective acquisition and efficient deployment of technology have become the critical pathways to competitive success. This study clearly highlighted the synergistic roles of precision mechanics and digital fabrication in advancing sustainable and green manufacturing practices. Furthermore, this research critically examined how ultra-precision technologies and digital manufacturing methods, such as additive manufacturing (AM), digital twins, and smart micro-factories, can reduce waste, optimize energy use, and enable localized, as well as on-demand production. Through a critical literature review, the study reveals that integrating digital technologies and mechanical precision in manufacturing not only enhances production efficiency but also supports circular economy principles, lifecycle optimization, and sustainable supply chain resilience. Key industry case studies were also reviewed, and comparative assessments revealed the tangible benefits of these technologies in reducing production cost, material wastage, and environmental impact, while also identifying factors such as high initial investment cost, weak legislation and regulatory inertia, and lack of workforce readiness as the major barriers to the widespread adoption of this manufacturing concept. This approach allowed us to critically explore the role of precision mechanics and digital fabrication in sustainable manufacturing, by helping to draw insights from scholarly publications, industry reports, and documented real-world applications. Comparative evaluations suggest that digital technologies outperform traditional methods in agility, resource management, and environmental impact, though challenges related to scalability, regulation, data security, and privacy, as well as workforce skills gap still persist. The paper concludes by proposing strategic pathways for technological adoption, policy support, and educational reforms necessary to accelerate sustainable innovation in manufacturing. Ultimately, this research underscores the strong belief that the convergence of precision mechanics and digital fabrication is not merely a technical evolution but a critical enabler of global sustainability goals in the fourth industrial era. The findings of this research will create the needed awareness and galvanize support towards overcoming the challenges in the promotion of precision and digital fabrication technologies as a viable model for sustainable and green manufacturing industrial transformation.

Keywords: Precision mechanics; Digital fabrication; Sustainable manufacturing; Green technologies; Additive manufacturing; Digital twins

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1 Introduction

Different governments and organizations across the globe have declared a climate emergency arising from concerns due to the urgent need to minimize the environmental impacts of human activities, especially manufacturing processes. Manufacturing activities are very crucial in both developed and developing economies of the world. Since it has been established that the development and growth of any economy depends mainly on the extent of manufacturing activities taking place in such an economy. Though globally acknowledged that the manufacturing industry plays a vital role in global economic growth and development, with the manufacturing industry standing as a cornerstone of global economic progress, driving innovation, employment, and infrastructure development across nations. However, available evidence has shown that this sector also significantly contributes to environmental degradation through excessive energy consumption, resource depletion, and pollution [1, 2]. As rightly noted by the study [2], although industrialization is essential for economic and societal growth, it is responsible for damaging the environment to a large extent. The manufacturing sector has been identified as being responsible for a significant portion of global waste and energy consumption, thereby making it imperative to explore and implement more sustainable practices [3]. As rapid industrialization has exacerbated environmental degradation, with carbon dioxide emissions reported to have risen from 95.43 million tons in 2020 to 113.43 million tons in 2023 [3]. It is also reported in the study [4] that about 17% of the world's total CO_2 emission comes from the industrial sector. Today, organizations are under huge pressure to implement sustainable production techniques to address issues related to environmental change and sustainability [2]. As the traditional manufacturing systems are often linear and resource-intensive [5], this has resulted in escalating greenhouse gas emissions, toxic waste generation, and over-reliance on non-renewable materials [1]. This has given rise to the global clamour for sustainable manufacturing, with many businesses turning it to their pivotal focus, by seeking to minimize their environmental footprint, so as not only to remain profitable but at the same time to be in the good books of environmental protection campaigners. Since it has become clear that the age-long linear concept of extraction-production-consumption-disposal is no longer sustainable [5, 6]. This has made minimizing and eliminating the environmental impacts of manufacturing not only a socially vital concept, but also a critical competitive strategy. In light of these pressing environmental concerns, the concept of sustainable and green manufacturing has gained global prominence. In response to the adverse effects of manufacturing, the United Nations came up with the concept of sustainable and green manufacturing, with the aim of aligning industrial activities with environmental stewardship, social equity and responsibility, and enduring economic viability. According to the UN Commission on Environment and Development, Sustainable Development entails meeting the needs of today without compromising the ability of future generations to meet their own needs [6, 7]. According to the study [8], sustainable manufacturing is the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources as well as enhancing employee, community, and product safety [4, 8]. According to the study [6], this ultimately gave rise to what is known today as the concept of eco-efficiency: environmental impact per unit output. However, in spite of the recorded improvements in eco-efficiency of products and services over the years, the total global environmental impact of manufacturing processes has continued to increase due to the rise in consumption, driven by industrial effluence and population [6]. Sustainable manufacturing is about producing goods in a way that minimizes waste, reduces energy consumption, and lessens carbon footprint [9]. The US Department of Commerce has defined Sustainable manufacturing as processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound [6, 10]. Sustainable manufacturing is critical to achieving sustainable development [10]. Sustainable manufacturing aims to satisfy the needs of present and future generations, and emphasizes the development of processes that minimize environmental impacts, conserve natural resources, and enhance safety for workers and surrounding communities. The ultimate goal of sustainable manufacturing is to achieve zero-waste, complete recyclability, and reduced energy consumption. Green manufacturing is a core subset of this broader agenda which focuses on cleaner production methods, eco-conscious product design, and the integration of energy-efficient technologies [11]. Driven by global policy frameworks such as the United Nations Sustainable Development Goals (SDGs) and the Paris Climate Agreement, there is a growing consensus among governments, researchers, and industry leaders to achieve net-zero emissions and transition toward a circular economy [12]. As a result of this awakened consciousness of the impact of manufacturing on the environment, governments, consumers, and stakeholders alike are placing pressure on manufacturers to adopt greener practices, with regulations tightening and consumer expectations rising [9]. The various circular economy strategies and their potential utilization to increase material efficiency and reduce environmental impacts have been documented in [6]. By integrating sustainability into the design phase of a product, manufacturers can significantly reduce the environmental impact of their products. For instance, through the use of digital twins, engineers can test and refine product designs in a virtual environment, ensuring that new products are optimized for sustainability from the outset. This includes selecting eco-friendly materials, designing for energy efficiency, and ensuring that products are easy to recycle at the end of their lifecycle [13].

Amid the shift toward manufacturing sustainability, precision mechanics and digital fabrication technologies have emerged as transformative tools. Precision machining and digital fabrication technologies are the fundamental manufacturing processes for producing precision mechanical parts and other products used across different industries and homes. Precision mechanics involves the deployment of high-accuracy machining and control systems such as micro-manufacturing, ultra-precision computer numerical control (CNC) machining, and mechatronic assemblies to fabricate intricate components with minimal energy and material waste [14]. These methods enhance product quality, reduce the need for rework, and contribute to extended product lifespans. In the same vein, digital fabrication technologies which include 3D printing, often referred to as additive manufacturing (AM), computer-aided design (CAD)/computer-aided manufacturing (CAM) systems, and integrated CNC workflows, enable manufacturers to produce customized goods through localized and on-demand processes. At the core of the successful implementation of precision machining and digital fabrication in achieving sustainability in manufacturing through these technologies is data. In the era of data-driven Industry 4.0, intelligent and sustainable manufacturing relies on accurate and complete data for real-time monitoring, predictive maintenance, and process optimization, which leads to minimized waste, enhanced efficiency, and reduced environmental impact. According to the study [15], data can act as a driver for improvement of sustainability, productivity or resilience. Hence, it is expected that manufacturers will leverage data and analytics applications to catalyze productivity, cultivate new customer experiences, and make a significant impact on society and the environment in a sustainable manner. With precision mechanics and digital fabrication technologies, manufacturing companies can drive sustainability in their processes by harnessing the avalanche of data acquired through digitalization, big data, and advanced analytics, and deploy the same to support process optimization, which reduces waste, energy and environmental footprint. By reducing supply chain complexity, minimizing scrap, and facilitating real-time design iterations, these systems support more agile and resource-efficient production models [16]. It has been reported that the global machine tools market size exceeded USD 82.9 billion in 2022 and is expected to rise to USD 139.69 billion by 2032, poised to grow at a compound annual growth rate (CAGR) of 5.9% from 2023 to 2042 [17], and supported by an estimated $73 billion cutting tools market [17, 18]. Moreover, it is reported that the Fourth Industrial Revolution will continue to unlock an unprecedented amount of data for the manufacturing industry to manage, which will also need to be safeguarded. Through the deployment of data analytics which is a key feature of intelligent factories, data will add an additional layer of intelligence to sustainable manufacturing operations, by making it possible to quickly identify and fix process snags or gaps while improving existing processes [15]. When precision mechanics and digital fabrication are strategically combined, they offer a compelling pathway to achieve low environmental impact and high-performance manufacturing. Their potential to decouple production from the traditional centralized systems while at the same time enhancing innovation, flexibility, and environmental performance which is cardinal to the next-generation manufacturing models [19]. Nevertheless, despite these technological advancements, their adoption remains uneven, as many industries face systemic barriers, including high implementation costs, shortage of skilled personnel, data cyberattacks, insufficient policy support, and limited awareness of long-term sustainability gains. This study will investigate the role of precision mechanics and digital fabrication in advancing sustainable and green manufacturing practices. Specifically, it seeks to reveal how these technologies contribute towards reducing the impacts of manufacturing processes on the environmental ecosystem. This paper will focus primarily on precision mechanics and digital fabrication technologies, their applications and contributions towards sustainability in manufacturing. In writing this paper, information was drawn primarily from published articles, conference papers, technical reports, and other published case studies related to this topic. It is expected that the findings of this work will create the needed awareness and galvanize support for the establishment of a conceptual and theoretical framework and basis that could inform future empirical research and guide industrial strategies toward greener and more resilient manufacturing ecosystems through the utilization of precision and digital fabrication technologies.

2 The Evolution of Precision Mechanics and Digital Technologies in Manufacturing

Precision mechanics has been integral to the advancement of manufacturing since the onset of the Industrial Revolution. Precision mechanics, which was initially rooted in the development of simple measuring instruments, lathes, mills, and Cam-driven machines, has advanced significantly with the invention of machine tools and gauges that allowed for the mass production of interchangeable parts. However, the introduction of the punched-tape numerically controlled machine tools in 1952 by Massachusetts Institute of Technology (MIT), ushered in the control of machines with coded instructions instead of hand-wheels, marking the beginning of integration of precision mechanics with digital technology in manufacturing MIT Press [20]. This breakthrough heralded a departure from pure mechanics-driven mechanization of manufacturing, whereby products' accuracy was limited by human skill and mechanical tolerances of the order of 0.01 mm [21]. In the 20th century, further integration of electromechanical systems in manufacturing led to the replacement of punched tapes with computers in the 1970s, giving rise to what is known today as CNC machines, which has revolutionized component accuracy, repeatability, and efficiency in manufacturing processes [22, 23]. These developments enabled improved precision and tighter tolerances ($<$0.001 mm) [24], automation, and miniaturization, which are critical factors for sectors such as aerospace, automotive, and electronics [23]. Further development in the 1980s led to the process of linking design to the manufacturing tool paths with automated control logic (programmable logic control), giving rise to what is known as CAD/CAM [25]. Further advancement in technology in the 1990s brought about Ultra-precision machines such as diamond turning, which achieved nanometer tolerances, thanks to precision engineering and adaptive control of manufacturing processes, which compensated for wear, temperature, vibration during manufacturing operations [26]. With the year 2000, came what is referred to as Digital Twins, which enabled virtual mirroring for predictive maintenance and enhanced monitoring as well as real-time control of manufacturing processes, through virtual factory replication [27]. According to the study [28], 2010 marked the advent of a lot of technologies, such as AI, industrial internet of things (IIoT) and AM, with AI and machine learning promoting product and process optimization, as well as quality control, and IIoT enabling real-time data acquisition and analysis, while AM facilitates fast, and efficient production of geometrically complex parts with high precision [28]. Over time, precision engineering and digital technology has evolved from a purely mechanical discipline into an interdisciplinary field, encompassing mechatronics, robotics, and control systems, thereby supporting high-precision manufacturing while reducing energy consumption and material waste [29]. The IIoT, which refers to the interconnection of sensors, instruments, and other devices networked together with computers in industrial applications, for efficient manufacturing operations and energy management, is one of the most recent technologies utilized in sustainable and green manufacturing.

2.1 Digital Fabrication: Concepts, Tools, and Techniques

Digital fabrication refers to computer-controlled processes that transform digital designs into physical products. Key technologies include 3D printing, laser cutting, CNC milling, and automated assembly systems. These technologies allow for rapid prototyping, customized production, and tool-less manufacturing, which drastically reduces time-to-market and enables more flexible production strategies [30]. 3D printing, in particular, has gained global traction due to its ability to fabricate complex geometries with minimal waste. It has been used across sectors such as medical device manufacturing, automotive tooling, and architectural modeling. The rise of digital transformation has ushered in disruptive trends into the manufacturing sector, such as internet of things (IoT), machine learning, data and analytics and hyper-personalization [15]. Moreover, the emergence of Industry 4.0 has further enhanced digital fabrication by integrating IoT sensors, material passports, blockchains, cloud computing, and AI-based design tools, which allows for real-time quality control and predictive maintenance [31]. These advancements offer promising avenues for resource-efficient production, decentralized manufacturing, and on-demand supply chains, which are the key pillars of sustainable development [32]. It is reported in the study [15] that Industry 4.0 will spur enterprises to join forces in interconnected value networks to leverage data and analytics applications to facilitate productivity, cultivate new customer experiences, and make a significant impact on society and the environment. Industry 4.0 is expected to unlock an unprecedented amount of data for the manufacturing companies to manage, which will also need to be safeguarded [15]. This makes data security and management pivotal for sustainability in the manufacturing industries.

2.2 Sustainability and Green Manufacturing: Goals and Metrics

Sustainable manufacturing aims to balance economic productivity with environmental responsibility and social equity. Its core objectives include minimizing energy use, reducing greenhouse gas emissions, enhancing product recyclability, and maximizing resource efficiency [33]. Metrics such as carbon footprint, energy intensity, material utilization rate, and water usage per unit output are commonly used to evaluate the sustainability performance of manufacturing systems [34]. The most commonly used indicator is energy intensity or productivity, which measures the ratio of energy consumption per unit of GDP, while reflecting the relationship between energy consumption and economic output or its inverse [35, 36]. Green manufacturing specifically refers to the integration of these sustainability goals into product and process design. This requires manufacturers to commit to global environmental, social, and governance initiatives, leaving manufacturers who do not comply to be at the risk of loss of reputational standing, falling behind competitors, or becoming obsolete in the industry [15]. It focuses on reducing environmental impact across the product life cycle, from raw material extraction and production to end-of-life disposal or reuse. Regulatory frameworks like ISO 14001 and strategic roadmaps like the UN SDG 9 and SDG 12 have become reference points for industries adopting greener manufacturing practices [12].

2.3 Integration of Precision and Digital Technologies in Green Practices

The intersection of precision mechanics and digital fabrication with sustainability is shaping the future of eco-efficient manufacturing. Precision machining reduces material waste by enabling near-net-shape production, while digital fabrication tools like 3D printers support layer-by-layer manufacturing, which consumes only the necessary amount of material [11]. Moreover, digital workflows reduce dependency on tooling and minimize inventory by facilitating just-in-time production, thus decreasing storage energy and material surplus. Hybrid manufacturing systems, which combine additive and subtractive methods, further enhance the adaptability and energy efficiency of production processes [14]. Studies have shown that implementing precision-based digital fabrication can lead to 20–40% reductions in material waste and 15–30% improvements in energy efficiency, depending on the industry and application [37]. This convergence is also driving innovation in closed-loop recycling systems, where digitally fabricated parts are designed for disassembly and material recovery. Machining industries have a social responsibility to ensure that they do not inadvertently support human exploitation [38] in their value chain. Digital technologies such as material passports, blockchains, etc., can be implemented to ensure traceability and transparency of tools and materials used in machining.

2.4 Relevance of Data in Precision Mechanics and Digital Fabrication Deployment in Sustainable Manufacturing

One of the major features of Industry 4.0 is that manufacturing plants' activities are increasingly becoming interconnected and automated. This interconnection of machines is driven by data. According to the study [9], as businesses currently face growing pressure to meet sustainability targets, data has become the key to unlocking more efficient, eco-friendly operations. Data has now become the new oil upon which Industry 4.0 technologies run [15]. These days, manufacturing organizations maintain a lot of data which includes everything from proprietary designs to production algorithms, to supply chain logistics and customer information. The amount of data required for effective manufacturing operations in most industries is burgeoning and spreading fast, due to the increasing level of advancement in manufacturing technologies made possible by the deployment of precision mechanics and digital fabrication for sustainability and green manufacturing. In this era of digital technology, sustainable manufacturing starts with data [9]. According to the study [15], manufacturers nowadays are sitting on a goldmine of information which they can utilize to make critical decisions. Sustainable manufacturing requires transformative and innovative technologies, which generate a large amount of data to be analyzed, and acted upon real-time. This helps manufacturers to optimize resource usage, reduce waste, and lower their environmental impact [9]. Reliable data makes for effective manufacturing decisions to be made in order to ensure efficient resource utilization in manufacturing. It was reported by the study [8] that committing to sustainable manufacturing will enable manufacturers to monitor and evaluate environmental performance, set realistic sustainable goals, optimize processes and reduce waste. Moreover, the utilization of data-driven insights will enable manufacturers to reduce resource and production costs by optimizing energy use, shrinking waste, and augmenting process efficiency [15]. According to the study [8], sustainable manufacturing involves creating products in a way that minimizes environmental impact, conserves resources and promotes economic growth [8]. This development is not only pushing the manufacturing industry to become increasingly dependent on data, but also creating greater demand for sophisticated analytical tools and robust data security measures [15]. The various potential benefits of using data for sustainable manufacturing have been listed in the study [15] to include improved efficiency, cost reduction, enhanced product and service quality, and optimized value chains. Manufacturers who fail to embrace and commit to the use of intelligent data stemming from digital transformation, risk losing reputational standing, falling behind competitors, or becoming obsolete in the industry. Manufacturing companies can now drive sustainability in their processes by harnessing the avalanche of data acquired through digitalization, big data, and advanced analytics, and deploying same to support process optimization, which in turn, reduces waste, energy and environmental footprint. The acquisition and storage of a large amount of data by manufacturing companies for their effective and efficient operations, make them attractive targets for cybercriminals and competitors seeking to gain a competitive edge or disrupt operations. Hence the need for proper data management, as any breach in data privacy of these organizations not only compromises the confidentiality of their sensitive information but also undermines the integrity and availability of critical systems and processes.

2.4.1 Challenges facing the use of data in sustainable manufacturing

Despite the general acknowledgement of the relevance of data in sustainable manufacturing, there are still some challenges facing the widespread utilization of data in the transformative technologies that promote sustainability and green manufacturing. The challenges facing Industry 4.0 technologies which are concentrated on the deployment of big data and analytics to reshape manufacturing to as listed in the study [15] include:

(i) Data integration: Data integration is one of the major obstacles facing data application in most transformative manufacturing processes. In integrating different datasets, ranging from structured to unstructured data forms from various sources, into machine logs, enterprise systems, and sensors can be very tasking. Turning the diverse data generated from different sources in manufacturing operations into an organized usable form can be very challenging.

(ii) Data security and privacy: The increase in data generation and collection required for effective operations of the transformative technologies utilized in sustainable manufacturing has also brought with it an increase in risk of data breaches. These exposure to different attacks such as ransomware attacks, cyberattacks from sources, and distributed denial of service attacks are all in the increase [15]. This makes it imperative for manufacturers to put robust security measures in place in order to safeguard sensitive data utilized in manufacturing.

(iii) Data quality and accuracy: Every product is only as good as the data utilized in its production. It is important to mention that any manufacturing process is as good as the data utilized in controlling its operations. As it has been generally accepted that for manufacturing data to be relevant and meaningful, the data must be accurate and reliable. According to the study [15], it is often difficult to guarantee the quality of data obtained in manufacturing processes as a result of certain compromises such as sensor errors, missing data and other irregularities often encountered due data collection methods.

(iv) Shortage of skilled labour: The increased reliance on data by different organizations for their manufacturing operations has led to a spike in need for labour with data analysis skills, which is currently insufficient. As is usually the case, whenever technology advances, a "skills gap" emerges, which leaves some workers without the requisite qualifications to operate the new systems [39]. McKinsey Global Institute reported that there are needs for new experts in this digital transformation era [40]. According to the study [15], a report by the United States Bureau of Labor Statistics forecasted a growth of 36% in employment in data skills by 2031, while in a State of Data Science report, 63% of the respondents indicated they were moderately worried about the talent deficiency in the field. As a result of this lack of qualified data analysts, not every manufacturer will have the benefit of having their big data properly analyzed into useful and actionable manufacturing insights [15].

3 Transformative Impacts of Precision Mechanics and Digital Fabrication in Sustainable Manufacturing

Sustainable manufacturing entails designing and producing products that are consistently of acceptable standards of quality, while maintaining economy of materials, energy and other production resources, and without compromising the environment. The introduction of precision mechanics and digital fabrication has brought a lot of positive impacts both in the way products are conceived, designed and eventually produced. Thereby giving organizations that embraced them competitive edge through efficient product design and production process optimization, shorter manufacturing lead time, and to the users excellent customer experience via product personalization, timely demand satisfaction, while also delivering less environmental footprint.

3.1 Impact of Successful Implementation of Precision Mechanics and Digital Fabrication in Sustainable Manufacturing

Sustainable manufacturing relies on accurate, complete and reliable data for real-time monitoring, predictive maintenance, and process optimization, which leads to minimized waste, enhanced efficiency, and reduced environmental impact. Manufacturing companies can drive sustainability in their processes by harnessing the avalanche of data acquired through digitalization, big data, and advanced analytics, and deploying the same to support process optimization, which reduces waste, energy, and environmental footprints [15]. Many authors have reported that several industry leaders have now embraced precision and digital technologies to enhance sustainability. Some firms have implemented CNC-controlled hybrid manufacturing cells for turbine blade production, and achieved significant reductions in material usage and rework ratess [41]. Furthermore, General Electric has used AM for jet engine components, resulting in 30% weight reduction and improved fuel efficiency [42]. A similar report by the study [43] indicated that Local Motors, an automotive company, utilized 3D printing for the production of vehicle chassis and interiors, and obtained drastically shortened production cycles, with reduction in waste. Additionally, in the construction sector, it has been reported that modular prefabrication supported by robotic precision tools has lowered on-site energy consumption and material inefficiencies [44]. These studies demonstrate how integrating digital and precision technologies into conventional workflows can significantly reduce carbon footprints and promote circular economy practices.

3.2 Precision Mechanics and Digital Fabrication Technologies Supporting Sustainable and Green Manufacturing

Precision mechanics and digital fabrication technologies have revolutionized the pursuit of sustainability in manufacturing by enabling tighter tolerances, higher efficiency, and less material waste. These technologies, when integrated into sustainable frameworks will facilitate the shift from traditional, resource-intensive production to smarter, greener practices.

3.2.1 Computer numerical control machining

CNC machining is a manufacturing process that uses computerized controls to operate and manipulate machine tools. CNC machining automates the control of machine tools via software. The programmed software translates digital designs from CAD files into the precise physical components. This automation ensures high levels of accuracy, repeatability, and efficiency [3, 4]. In this era of stiff competition and rising quest for global sustainability in manufacturing, one innovative approach that has been widely acknowledged as a perfect match is CNC machining. CNC machining allows for highly accurate material removal with minimal waste. Because of their precision and efficiency, CNC machining is playing a crucial role in the transformation of industries towards more sustainable and green manufacturing practices [4]. Unlike the traditional machining methods, which usually generate significant amounts of scrap material due to inaccuracies and trial-and-error adjustments, CNC machines follow exact specifications programmed into their control systems. This precision ensures that only the necessary amount of material is used, thereby reducing waste, and making the most of available resources [4]. It is reported in the study [3] that CNC machining is indispensable in modern manufacturing as a result of its ability to produce complex parts with tight tolerances across various industries, including aerospace, automotive, medical, and electronics. The precision and efficiency of CNC machining make it a cornerstone of advanced manufacturing processes, while driving innovation and sustainability at the same time. This subtractive manufacturing method is vital in precision engineering, as it supports sustainable goals through efficient tool paths, reduced defects, and recyclable metal chips [1]. According to the study [3], CNC machining is renowned for its precision and efficiency, which makes it a veritable sustainable solution in manufacturing, as it offers significant reduction in material waste and energy consumption. The numerous environmental benefits of sustainable CNC machining as listed in the study [3] include helping to conserve natural resources and lower carbon emissions, thereby contributing to a healthier planet through reduction in material waste and energy consumption. Moreover, adopting sustainable CNC machining practices leads to significant cost savings and efficiency improvements. As energy-efficient machines and optimized resource utilization have been identified as ways of reducing operational costs and, ultimately increasing productivity. Furthermore, it has been reported that a commitment to sustainability positively impacts the brand reputation and customer relations of business organizations. As consumers and businesses are increasingly giving preference to environmentally responsible companies. The adoption and deployment of eco-friendly practices have enabled many businesses to enhance their brand's image, build customer loyalty, and attract new clients who value sustainability. Additionally, the current trend of integration of AI and machine learning, with CNC machining which optimize machining processes by predicting tool wear, enhancing precision, and reducing material waste, will enable real-time machine adjustments, resulting in further improvements in efficiency and sustainability [3, 45]. Besides, advancements in sustainable tooling materials and coatings have enabled the extension of machine tool life, thereby reducing the environmental impact of frequent tool replacements. These innovations are collectively paving the way for a more sustainable and efficient manufacturing landscape. Unlike traditional machining methods, which can generate significant amounts of scrap material due to inaccuracies and trial-and-error adjustments, CNC machines follow exact specifications programmed into their control systems. This precision ensures that only the necessary amount of material is used, reducing waste and making the most of available resources. According to the study [4, 45], the continuous advancement in CNC technology is driving further improvements in sustainability through innovations in the following Areas:

(i) Advanced materials: The development of new, more sustainable materials that can be efficiently machined by CNC tools.

(ii) Smart manufacturing: The integration of IoT and AI with CNC machines to monitor and optimize energy use and resource efficiency.

(iii) AM: Combining CNC with 3D printing techniques to reduce waste and create complex, lightweight structures.

These innovations are enhancing the ability of CNC machine tools to contribute to sustainable manufacturing practices and support green manufacturing initiatives [4, 45].

3.2.2 Computer-aided design/Computer-aided manufacturing

CAD/CAM technology is a manufacturing method which enables the integration of CAD for product design, and CAM for production of products. The CAD/CAM software is used to design and manufacture prototypes, finished products, and production runs of products using a single development tool [46–48]. Whereas CAD ensures efficient resource use by minimizing waste through precise drafting and fabrication drawings, CAM promotes efficient resource utilization during production, minimizing material usage and energy consumption in production. It has been reported that, CAD supports circular manufacturing through the incorporation of recycled materials and sustainable practices, such as designing components that are easy to disassemble, recycle or repurpose, which engenders sustainable production. This approach is very beneficial for industries that focus on sustainable manufacturing practices [46–48]. CAD creates modular designs that simplify repairs and upgrades. This results in the extension of the lifespan of products and reduces the need for new material extraction, thereby aligning with global sustainability goals. With the incorporation of recycled materials and sustainable practices. In design, CAD tries to reduce environmental consequences of manufacturing. CAD enables the creation of detailed drawings that optimize material specifications of components before production. Additionally, CAD fabrication drawings ensure that manufacturers follow clear, standardized guidelines, promoting consistency and reducing errors during production, which ensures a smoother workflow, eco-friendly designs, and a more sustainable overall process as well as a greener future. Moreover, the use of assembly drawing made easily made possible by CAD deployment contributes to better planning and production of products. Furthermore, CAD enables the outsourcing of drafting services, which enhances collaboration among teams, thereby improving project timelines and reducing waste. With CAD, digital CAD files are easily shareable, facilitating seamless communication between stakeholders. In addition, the CAD technology facilitates the preparation of product data submittals, which ensures transparency and compliance with industry standards [46, 47]. CAM enables design engineers with a proper understanding of manufacturing to create more manufacturable parts, within a short time, and at minimal cost, both in terms of material and energy consumed. The CAM software helps multidisciplinary engineers take digital designs to physical products while also addressing environmental sustainability. Through the advanced toolpath optimization and smart material utilization, CAM programming can help reduce waste and boost precision, as a result of dynamically optimized machining processes, leading to less scrap, fewer manufacturing errors and a more efficient use of resources such as coolant, material removal and energy, all of which tends to drive down operational costs, as well as environmental impact of manufacturing operations, while yielding savings [45–48]. Many authors have indicated that though the ongoing advancements in automation, AI and machine learning could be the future of CAM technology, since the current AI capabilities in manufacturing, which focus mainly on automating routine processes are yet to reach the level of sophistication needed to replace the highly essential human judgment required for complex design tasks [46, 49, 50]. However, according to the study [50], AI technologies such as machine learning and natural language processing have permeated all walks of life via the Internet, including the manufacturing industry. In China, there is a concerted effort towards the development of a new generation AI, which will focus on the major needs of the strong manufacturing countries and promotes full life-cycle manufacturing [50]. The application of AI in manufacturing will promote high-quality economic development, reduce labor costs, improve product quality, and promote the transformation of manufacturing to intelligence, which is a necessary step toward adapting to future economic needs and achieving sustainable development [50]. Besides, it has been reported that the synergy between CAD and CAM bridges the gap between creative design and precise, efficient production of products [50]. CAD/CAM, enables manufacturers working on new products to simulate the designed new product before actual manufacture [47]. This seamless assessment of proposed design before manufacture offered by CAD/CAM generally leads to better design outcomes, which is ultimately reshaping the future of sustainable manufacturing [47]. Some of the common CAD/CAM software packages include MasterCAM, HyperMILL, EDGECAM, Esprit EDGE, Vericut and NCSIMUL. The integration of CAD and CAM technologies in design and manufacturing respectively has revolutionized the traditional product manufacturing processes, enabling the incorporation of other advanced technologies such as artificial intelligence to optimize every production stage, which helps to minimize material waste and enhance design flexibility, even during the production of complex parts. The integration of CAM with CAD software promotes a streamlined workflow from conception to production for mechanical and design engineers. Through the use of direct data transfer and revisions of proposed new products, between design and manufacturing teams, engineers can reduce manufacturing lead times [46, 47]. Besides, the emergence of digital fabrication technologies streamlines production processes, reducing both time and resource consumption [45, 47]. By integrating energy-efficient designs and sustainable manufacturing practices, CAD/CAM can achieve optimal results while at the same time reducing the environmental footprint of manufacturing. Conclusively CAD/CAM supports sustainable manufacturing through optimized material usage, energy efficiency, design for disassembly, sustainable material selection and lifecycle analysis processes [45–47].

3.2.3 3D printing

The 3D printing manufacturing technology has revolutionized various manufacturing industries by enabling rapid prototyping, customized production and efficient production of parts having complex geometries with improved precision. 3D printing (or AM) continues to gain momentum as a key enabler of sustainable practices. It reduces raw material usage by building objects layer by layer, supports decentralized manufacturing, and facilitates product reuse and recycling which are the core principles of circular economy [11, 12]. With AM, new processes and new materials are constantly coming into the market. The previous limitation posed by choice of material is now being overcome with the development of new material having enhanced properties. An example can be seen in a new development involving the combination of material extrusion in the form of fused layer modeling (FLM) of plastic filaments with reinforcement by short and long fibers [51]. The AM FLM has the advantage of being a simple and thus inexpensive technology. AM allows for near-net-shape production, which minimizes material usage and waste. Through its precision, efficient utilization of materials and energy, 3D printing is undoubtedly promoting the principles of sustainability and green manufacturing [3, 42, 48]. Designs for AM enable the use of advanced methods such as, Direct metal laser sintering technology, a laser AM, which reduces waste and improves efficiency. AM techniques such as metal AM and rebar detailing which offer significant potential for reducing waste and optimizing material usage [42, 44, 48]. The use of high-performance materials like aluminum and nickel alloys enables manufacturers to achieve superior results while minimizing their environmental impact.

3.2.4 Laser machining

As environmental concerns rise and industries face increasing environment safety pressures, businesses are looking for smarter, cleaner, and more energy-saving solutions [52]. Energy efficiency in manufacturing has become of great importance in the technological world [53]. One major technology making benefits in the shift toward greener operations is laser machining. At the key of this transformation is the ability of laser machines to reduce waste, lower power consumption, and increase accuracy, the three pillars of sustainable manufacturing [52]. It is reported in the suty [53] that laser processes have the capability to save energy in manufacturing operations. This is why the laser market is growing steadily, and it is expected to reach a global value of $14.52 billion by 2026 [53]. While other manufacturing methods usually result in material wastage due to human error or tool inaccuracy. In contrast, laser machines cut, engrave, and process materials with micro-level accuracy. This level of accuracy ensures that manufacturers use only what's necessary, consistently reducing scrap and raw material consumption. In industries such as automotive, electronics, and textiles, where margins are tight and volumes are high, even a small reduction in waste can translate into massive environmental and financial gains. By selecting an advanced laser machine, manufacturers can use tools that align with circular economy goals [52].

3.2.5 Generative design

This is an AI driven tool used in sustainable manufacturing for the efficient and timely generation of optimized product design. Generative design is a method that uses algorithms and computer processing power to create and optimize designs based on specific goals, constraints, and inputs [54]. It involves investigating a wide variety of potential design options and determining the most effective approaches based on desired outcomes. With the generative design approach, design engineers define the relevant parameters in a product design such as materials, manufacturing methods, loads, and performance targets, and the advanced algorithms of a computer rapidly evaluate thousands of design alternatives [54, 55]. This results in optimal and innovative solutions being delivered in a breath-taking pace or very short time. The process consists of four basic steps: describing the design's objectives and limitations, generating design options using computational algorithms and techniques like artificial intelligence and machine learning, and assessing and improving the designs [54]. The generative design works on the concept that by increasing the geometric complexity of a part, less matrix material tends to be used [51, 54]. This technology is reshaping product development by automating and optimizing solutions that hitherto required extensive manual iteration. Generative design has advantages such as the ability to generate complex geometries and optimal designs considering factors like cost, weight, and strength. It also reduces the need for manual input and iteration during the design phase. The fields of aerospace, automotive, and architecture use generative design in their product development processes, particularly in applications requiring weight reduction, performance enhancement, and customization [55]. AM and generative design are complementary technologies that can be used to improve the design and production of components and finished goods [55]. Generative design can be used to develop components whose design is optimized based on specific criteria, for instance, lightweight, strength [51, 56]. Generative design allows for the creation of optimized designs that utilize the unique capabilities of 3D printing, while AM can produce complex geometries with high precision and accuracy. The combination of AM and generative design has the potential to transform the way we design and build parts and products, achieving better efficiency, usefulness, and creativity [55]. It is reported by the study [51] that the combination of AM with GD has proven successful in the development of metallic components. Conclusively, generative design removes the explorative restrictions imposed by tight timelines and budgets in traditional design by rapidly generating countless alternatives, thereby accelerating development and promoting design breakthroughs. The benefits of generative design in manufacturing can be seen in the areas of accelerated product development, material and weight efficiency, cost reduction, increased innovation as well as sustainability gains [51, 52, 54–56].

3.2.6 Digital twins

Digital twins are real-time data-driven technology that enables manufacturers to collect real-time data directly from an ongoing manufacturing process. They provide real-time, data-driven virtual replicas of physical manufacturing systems by simulating product production processes in a virtual environment. This technology, which is data-driven [15], enables manufacturers to create a comprehensive virtual model that mirrors the real-world performance and behaviour of the system. The data enables manufacturers to streamline their production process, by helping to identify and eliminate inefficiencies such as equipment downtown, or overuse of energy, and enables adjustments to be made immediately before they happen in the physical world and, hence improving overall manufacturing sustainability. This real-time visibility also allows manufacturers to track key sustainability metrics, like energy consumption and waste output much more effectively [9]. With this digital workflow system, manufacturers can collect more accurate data on their operations and use it to drive sustainability initiatives. The integration of Digital twins in manufacturing optimizes energy usage, reduces materials waste, predicts maintenance needs, and minimizes downtime, leading to cleaner, leaner and more sustainable production lines [14]. The primary ways through which Digital twins can contribute to green manufacturing has been listed to include resource optimization, waste and emissions reduction, predictive maintenance for equipment efficiency, sustainable product and supply chain design, real-time monitoring and control, enhanced decision-making and circular economy integration [13, 57], reducing paper waste, and promoting continuous improvement [9]. By providing real-time data and simulation capabilities, Digital twins make data-driven decisions that increase efficiency, decrease environmental impact, and facilitate sustainable strategies throughout the product lifecycle and supply chain. Besides, having a digital record of processes enables continuous improvement through data-driven insights [9]. By embracing digital transformation, manufacturers will not only improve their bottom line, but also contribute to a more sustainable, greener and more responsible future for the industry, and the planet earth as a whole. The key roles of digital twins in sustainable manufacturing can be summarized to includes:

(i) Resource optimization: Digital twins make it possible for manufacturers to monitor and optimize resource usage in real-time, thereby helping to minimize consumption of energy and raw materials.

(ii) Waste and emissions reduction: Simulations enable manufacturing companies to identify and eliminate inefficiencies in their processes, which ultimately leads to minimal material waste and lower emissions.

(iii) Predictive maintenance: Through the analysis of data trends, digital twins can predict equipment failures before they happen, thereby allowing for proactive maintenance. This prevents breakdowns, reduces downtime, and prevents the resource waste associated with emergency repairs or premature equipment replacements.

(iv) Sustainable product and supply chain design: Digital twins have the capability to simulate the entire product lifecycle and supply chain. This supports the design of more sustainable products and optimizes logistics for a reduced environmental footprint.

(v) Real-time monitoring and control: Digital twins provide a dynamic, virtual counterpart to the physical systems, allowing for continuous updates with real-time data. This in effect facilitates dynamic adjustments to processes, thereby ensuring that products stay within specification and prevents costly errors.

(vi) Enhanced decision-making: With the insights generated from the vast amounts of data collected from connected systems, digital twins can promote informed decision-making for sustainability-focused strategies, from factory location to supply chain resilience.

(vii) Circular economy integration: Digital twins are pivotal for implementing the circular economy principle, which promotes reuse, recycling, and responsible resource management throughout the manufacturing supply chain [9, 13, 57].

3.3 Environmental Metrics for Sustainable and Green Manufacturing Practices

The ongoing awareness on sustainable and green manufacturing has made many manufacturers begin adopting green practices and certifications to demonstrate their commitment to sustainability. For example, it is reported that CNC machine tools support these initiatives by providing the capabilities needed to meet stringent environmental standards. CNC machines can be used to produce parts with minimal waste and energy consumption, aligning with certifications such as ISO 14001 for environmental management [4, 10]. Moreover, most of the digital technologies are now being integrated into the broader sustainability strategies, such as the use of renewable energy sources and eco-friendly materials. Manufacturers can pair CNC technology with renewable energy systems, like solar or wind power, to further reduce their carbon footprint. All these give rise to different metrics for determining the degree of operations of manufacturing concerns within the sustainability and green manufacturing regime. Accordingly, the following environmental metrics have been set out as the parameters for evaluating the impact of digital tools on sustainable and green manufacturing practices.

3.3.1 Reduction in emissions

The traditional machining processes are reported to generate significant amounts of dust, fumes, and other pollutants. However, the digital fabrication and precision machines like the CNC machines produce cleaner, more controlled operations with less environmental impact. Sustainable manufacturing emphasizes reducing carbon and other toxic emissions. The use of advanced filtration systems and coolant recycling within CNC machines also helps to reduce the release of harmful substances into the environment [4, 10]. Through automated controls and lean production enabled by precision machinery, emissions are continuously monitored and mitigated [16]. By minimizing waste and optimizing resource use, digital machine tools such as CNC, laser cutting and 3D printing machines also help reduce emissions and pollution [4, 52]. Several manufacturing processes, such as printing, etching, and welding, involve the use of solvents, inks, and chemical treatments which are known to release hazardous substances like volatile organic compounds, toxic gases, and pollutants, that pose significant risks to both human health and the environment. However, Laser machines usually offer a clean alternative. For instance, Laser marking does not require any inks or additives. It uses concentrated beams of light to alter the surface of a material, creating permanent markings without harmful by-products. Similarly, laser cleaning reduces rust, paint, and contaminants from surfaces using high-power pulses, without the need for abrasive materials or chemical agents. Hence, by investing in the right laser machines, manufacturers can reduce their dependency on toxic harsh materials and improve workplace safety, thereby contributing to a healthier ecosystem and safer work environment [52]. Digital twins enable businesses to monitor their energy consumption in real-time, allowing them to adjust processes and reduce energy waste, leading to significant cost savings and a smaller carbon footprint [13]. Digital tools are becoming increasingly important for creating a more effective energy efficiency policy [57]. A report by the study [58] indicated that adopting digital technologies reduces energy intensity. Moreover, improving energy efficiency is essential for companies striving toward sustainable development. Through reduction in energy consumption, firms have not only lowered their operational costs but have also decreased their carbon emissions, in addition to complying increasingly with the stringent global environmental regulations. Moreover, energy efficiency positively impacts a firm's brand image, attracting environmentally conscious consumers and investors. According to the study [35], improving energy efficiency is significant for achieving carbon emission reduction and promoting the transformation of green economic development.

3.3.2 Waste minimization

Digitalization is the process of leveraging digital technologies to transform business operations, enhance efficiency, and create added value [59]. Digitalization as a concept includes digital transformation which promotes sustainable and green manufacturing practices. According to the study [60], digital transformation is the use of digital technologies to transform business processes, enhance value creation, and enable new business models. It involves the integration of digital technologies into the various aspects of human lives, which in the case of sustainable and green manufacturing is fundamentally reshaping how companies approach waste reduction in manufacturing [59, 60]. Digitalization in manufacturing is about transforming processes and systems to be more efficient, transparent, and ultimately less wasteful. At the core of digitalization is the provision of tools and infrastructure needed to optimize resource use, minimize waste generation, and improve waste management technology, which revolutionizes waste management through smarter collection, advanced sorting, and resource recovery, thereby enabling circular economy practices. The notable circular economy strategies as listed by the study [6], include such manufacturing practices as extending the life of products, repairing products, reusing, remanufacturing and upcycling them, and recycling at the end of their lifespan in order to reduce the demand on extracting materials, reduce energy consumption for manufacturing, and reduce waste generation. One of the key ways by which digital and precision machines like the CNC machine tools support sustainable manufacturing is through their inherent design precision and efficiency. Unlike the traditional machining methods, which can generate significant amounts of scrap material due to their inaccuracies and trial-and-error adjustments, CNC machines follow exact specifications programmed into their control systems and operate with a high degree of accuracy, which minimizes material waste. This precision ensures that only the necessary amount of material is used, reducing waste and making the most of available resources [3, 4, 45–47, 61]. By improving part accuracy and reducing trial-and-error cycles, both CNC, laser cutting and 3D printing technologies help lower scrap rates and reuse support materials, leading to a reduction in overall industrial waste [19]. Through digital fabrication and precision machines, manufacturers are committing to sustainable manufacturing, and resource optimization can further be enhanced by the use of data-driven insights which can enable manufacturers to reduce resource and production costs by optimizing energy use, shrinking waste, and augmenting process efficiency [15].

3.3.3 Reduction in energy consumption

The rapid development of digital technology, together with its widespread adoption has provided a feasible solution for improving energy efficiency and environmental conditions [35]. These modern digital technologies like the CNC machines, which incorporate advanced technologies that optimize power usage, such as energy-efficient drives and motors, are designed to operate efficiently, and hence ultimately contributes to reduced energy consumption [4]. Moreover, it has been reported that the ability to run machines for extended periods without human intervention, which allows for continuous production cycles, can be more energy-efficient in comparison to manual processes. With digital fabrication and precision machines, resource optimization can further be enhanced by the use of advanced materials and cutting techniques. The CNC and laser cutting machines can handle a wide range of materials, including those that have lower environmental impact regardless of whether they are recyclable or not. Furthermore, these precision machining technologies also enable the use of materials that can be reclaimed and reused, thereby further contributing to sustainability efforts in the industries. It has been reported that Laser machines are remarkably and smoothly energy-saving. The CO_2 lasers, fiber lasers, and diode lasers consume far less power while maintaining high output speeds [51]. Additionally, because these machines require fewer tool changes and less maintenance, the overall power footprint of the production process is reduced. In addition, fiber lasers are better known for converting electrical energy into laser output more smoothly than conventional systems. This translates into lower greenhouse gas reduced electricity bills, a major benefit for the planet and the bottom line [52]. With the right laser machine, manufacturers allow businesses to integrate energy-saving advanced technologies into their operations, ensuring long-term environmental guidelines and cost savings. Besides, the Smart control systems and high-efficiency machining strategies, especially when using digital twins, can reduce energy usage by aligning operations with energy demand forecasts and machine learning models [22]. Improving energy efficiency is critical to achieving affordable, clean energy goals [35], and hence sustainable and green manufacturing.

3.3.4 Recyclability and circular economy

Digital and precision driven-technologies such as the CNC, Laser and 3D printing technologies support the principles of circular economy, by enabling the production of standard parts that can be easily disassembled, repaired, or recycled [4, 5]. The precision of CNC machining ensures that components fit perfectly together. This facilitates the reuse, easier disassembly and recycling of the parts at the expiration of their service life or lifecycle. This has awoken the consciousness of manufacturers towards designing products with their end-of-life phase in mind. This allows for easier disassembly and recycling, and ultimately contributes to a more sustainable manufacturing process [4]. According to the study [5], the application of circular approaches in manufacturing in the Netherlands led to a 30% decrease in the demanded primary resources and a 25% decrease in industrial waste. Additionally, the circular economy models have been used in China to reduce CO_2 emissions in heavy industries by 20%. While Japan at the same time, has managed to recycle 80% of its plastic waste, and Germany has applied regenerative technologies into construction to reduce the usage of natural resources by 35% [5].

3.3.5 Supply chain integration

Data plays a critical role in identifying and implementing sustainable practices in any manufacturing organization. As it provides visibility and the needed attention into areas of operations in an organization where energy is being wasted, processes are inefficient, or excess materials are being used. Sustainable manufacturing goes beyond the factory walls to the entire supply chain of an organization. As proper utilization of data helps manufacturers monitor the environmental impact of their suppliers, and making sure that they are sourcing materials responsibly and efficiently, thereby promoting the overall sustainability of their products [9]. Data analytics enables manufacturing companies to coordinate and synchronize procurement, production, and distribution processes, for greater efficiency and flexibility. The integration of data analytics in manufacturing enables companies to predict demand, plan production, optimize inventory, reduce lead times, improve quality and customer satisfaction as well as foster collaboration among stakeholders [15, 61, 62]. All these ultimately work together to lower the environmental and social impact of manufacturing world-wide. Sustainability in manufacturing does not stop at switching to renewable energy sources or reducing emissions it includes rethinking and redesigning the whole manufacturing system of an organization with a view to identifying areas of inefficiencies, and to take actions minimize resource usage, and enable informed decisions that are based on acquired and analyzed data [9].

3.4 Digital Fabrication Tools/Software

The following are a brief overview of the key software/digital tools supporting sustainable manufacturing and green economy.

3.4.1 3D max

The Autodesk 3DS Max is formerly referred to as 3D Studio and 3D Studio Max was developed and produced by Autodesk Media and Entertainment. It is a 3D modeling, 3D detailed characters rendering, and animation software, mainly used for photorealistic designs, and complex scenes for film and TV commercial studios, video games developer, and design visualization of manufacturing processes and product prototypes [63]. It has a flexible plugin architecture and must be used on the Microsoft Windows platform. Other 3D Max features include shaders (like ambient occlusion and subsurface scattering), dynamic simulation, particle systems, radiosity, normal map creation and rendering, global illumination, a customizable user interface, and its own scripting language [63].

3.4.2 Automatic computer-aided design

This is a CAD software that is often deployed for precise 2D and 3D drafting, design and modeling with solids, surfaces, mesh objects, with documentation features and so on [46]. AutoCAD is a general drafting and design application software employed in the industry by many professionals such as architects, project managers, engineers, interior designers, graphic designers, city planners and so on, to prepare technical drawings [64]. It offers precision drafting tools for creating efficient and sustainable layouts in product and factory design [46, 47, 64–67].

3.4.3 Blender

This is an open-source software tool for the creation of 3D models and animation which supports all the 3D pipeline. It has a flexible python-controlled interface, with provision for adjusting layouts, colours, size and even fonts [68]. It usually includes production ready camera and object tracking, which allows the user to import raw footage, track the footage, mask areas and see the camera movements live in your 3D scene. Thereby eliminating the need to switch between programs [68]. Blender is now being deployed for numerous short films, advertisements, TV series and feature films. Blender can also be used to draw directly in a 3D viewport, creating opportunity for unsurpassed workflow freedom for story-boarders and 2D artists. Blender has a comprehensive array of modeling tools, such as full N-Gon support, edge slide, insert, grid and bridge fill, advanced sculpting tools and brushes, multi-resolution and dynamic subdivision, 3D painting with textured brushes and masking as well as Python scripting for custom tools and other add-ons. These make it easy for creating, transforming and editing models. This open-source tool is ideal for prototyping and simulating sustainable product designs in 3D environments. This open-source software has been utilized by such professionals as designers, developers, engineers and even artists to make exceptional products [68].

3.4.4 ZBrush

This is a digital sculpting, modeling, texturing and painting software used to create highly detailed 3D models [69]. With its customizable tools and features, including more than 200 proprietary brushes, enables you to work with polygons the same way you would with actual clay [69]. It is primarily used in sculpting and prototyping, as it allows designers to rapidly iterate low-waste design alternatives. It uses a proprietary pixel technology which stores lighting, colour material, orientation and depth information for the points making up all objects on the screen [69, 70].

3.4.5 Autodesk fusion 360

Autodesk fusion 360 is a cloud-based tool which enables product design, 3D modeling and manufacturing, providing a fully featured CAM, CAE, and polycrystalline diamond product development platform, with extensive CAM functionality [71]. It integrates CAD, CAM, and CAE in a single platform, promoting sustainable design through simulation, generative design, and digital prototyping. It is a versatile design platform that enables designers and engineers to bring their ideas to life through a comprehensive suite of integrated design and engineering tools. It promotes real-time collaboration capabilities, by creating an ideal platform for teams to work remotely across multiple locations and different devices. Fusion 360 supports a variety of stages in the product lifecycle, including design, analysis, and manufacturing [46, 71]. The manufacturing capabilities within Fusion 360 includes CAM toolpaths for CNC manufacturing, AM processes, as well as documentation for the manufacturing phase. These integrated capabilities make for streamlined process planning and setup, which ensures a smoother transition from digital models to physical products. This integration of design, engineering, and manufacturing into a single platform represents a significant innovation targeted at facilitating seamless and efficient workflows from the concept stage of a product to the production stage [47, 48, 71].

3.4.6 SolidWorks 3D computer-aided design and computer-aided manufacturing

SolidWorks 3D CAD makes it possible to produce products faster, and reach the highest levels of efficiency in day-to-day product development work. The user-driven enhancements and a relentless R&D focus on user experience has made SolidWorks 3D CAD not just powerful, but both easy to learn and fun to use. SolidWorks is a 3D CAD software for creating parts, assemblies, technical drawings, and simulating parts [46, 47, 72, 73]. It offers dedicated tools for efficient product design, from sketching to documentation. This enables faster and more accurate product development. SolidWorks 3D CAD makes it possible to produce products faster, and reach the highest levels of efficiency in the day-to-day product development work. The user-driven enhancements and a relentless R&D focus on user experience has made SolidWorks 3D CAD not just powerful, but both easy to learn and fun to use. However, SolidWorks CAM offers efficient CNC machining with rules-based approach, tool path generation optimization. In general, SolidWorks 3D CAD and CAM offers life cycle assessment tools and materials efficiency tracking for greener designs. It is used in a variety of industries, including industrial equipment, medical devices, high tech, home and lifestyle and more [46, 47, 72, 73].

3.4.7 Inventor hardware security modules and hardware security modules computer-aided manufacturing

These are CAM tools that are optimized for CNC manufacturing with in-built simulation for machining time, energy use, and material utilization analysis. The hardware security modules (HSMs) are hardened, tamper-resistant hardware devices that strengthen encryption practices by generating keys, encrypting and decrypting data, and creating as well as verifying digital signatures [72, 74]. The Inventor HSM is a fully integrated CAM application for Inventor and Inventor LapTop (LT). It provides for effective generation of high quality 2D, 3D, 5-axis milling, and turning toolpaths for high-speed machining, depending on your version of Inventor HSM [74]. It is designed from the beginning to work inside inventor's environment, and provide a logical extension of the parametric Inventor environment into the CAM world, working to create high-quality toolpaths within minutes. Furthermore, the HSM provides unmatched modeling and simulation capabilities of Inventor mechanical design solutions to CAM processes, resulting in improved design quality and reduced product development time [47, 74]. The HSMs are frequently deployed to:

(i) Meet and exceed established and emerging regulatory standards for cybersecurity.
(ii) Achieve higher levels of data security and trust.
(iii) Maintain high service levels and business agility [47, 72, 74].

The Inventor LT software allows you to introduce 3D mechanical CAD into your 2D workflow in a cost-effective manner. This Inventor software, gives you additional capabilities that validate assembly design form, fit and function [47, 71, 72, 74].

3.5 Integration Patterns and Challenges of Digital Tools in Sustainable Systems

Digital tools are usually assessed based on key performance and sustainability indicators which are discussed as follows.

3.5.1 Energy efficiency

Energy efficiency in manufacturing is of crucial importance in the increasingly technological world of today [53]. According to the study [75], through digitalization, businesses can streamline processes, minimize energy waste, and make informed decisions that will enable more efficient resource utilization and reduced environmental impact. Digital tools have revolutionized how manufacturing industries approach energy efficiency policies across all sectors worldwide [59]. Furthermore, it is reported that by leveraging technology, industry operators and governments alike could be able to create data-driven insights into their energy usage and identify areas of improvement. Moreover, digital tools also provide the opportunity to automate processes and reduce the manual labour costs associated with tracking efficiency measures. In addition, digital solutions make it possible for stakeholders to collaborate in real-time on initiatives that will help meet environmental goals while at the same time increasing cost savings for businesses and consumers [59]. Energy-efficient digital tools reduce idle times, optimize power consumption, and dynamically adjust speeds and feeds to lower consumption [23].

3.5.2 Waste minimization

Digital simulations prior to physical production reduce prototype iterations and enable low-waste batch manufacturing processes [29]. Digitalization provides the infrastructure and tools needed to optimize resource use, minimize waste, and improve waste management practices in manufacturing industries [61]. However, at the individual levels, digitalization manifests as smart home devices that optimize energy consumption, while minimizing electricity waste. It also means easy access to online platforms for buying and selling used goods, thereby extending the lifespan of products and decreasing the demand for new ones. Application Apps that track food consumption can help prevent food waste, which remains a significant contributor to landfill overflow and greenhouse gas emissions. Many businesses are now leveraging digitalization through supply chain optimization, predictive maintenance, and smart manufacturing. Supply chain optimization usually reduces transportation inefficiencies, minimizing fuel consumption and emissions. Moreover, predictive maintenance uses sensors as well as Data Analytics to identify potential equipment failures before they happen, thereby preventing costly breakdowns and the waste of materials and energy involved in repairs or replacements. Smart manufacturing supported by digitalization utilizes data-driven insights to streamline production processes, which eventually leads to material waste and improving product quality. On its part, governments utilize digitalization to improve waste management infrastructure, monitor environmental compliance to regulations, and carry out citizen enlightenment campaigns on waste management and other waste reduction activities. Additionally, digital tracking systems can be used to monitor waste streams, identifying sources of pollution and for optimizing collection routes. The online platforms can be used to educate and enlighten the masses or citizens about recycling programs and other waste reduction strategies. These systems also help in the enforcement of environmental regulations as well as holding environmental law offenders accountable [61]. Besides, digitalization supports the concept of circular economy which lays great emphasis on material use and reuse as much as practicable. It has been reported that digital technologies make it easier to track materials, connect producers and consumers, and facilitate the reuse and recycling of products. The digital platforms can be deployed to provide environmental impact information, where alterations to the environment due to organizational activities, product use or services, resource depletion, pollution and habitat destruction. Marketing of products in a manner that empowers consumers to make more informed choices [61].

3.5.3 Production adaptability

Production adaptability revolves around implementing innovative technologies, redesigning products for eco-efficiency, and moving towards a circular economy using practices such as recycling and waste reduction. Adaptability enables manufacturers to minimize their environmental manufacturing impact, while building more resilient and cost-effective operations [2, 5]. Smart systems and cloud-based digital twins allow for quick reconfiguration of manufacturing systems, enabling responsiveness to demand without resource overuse [30]. The key roles of production adaptability in sustainable manufacturing include:

(i) Waste reduction and resource conservation: This requires manufacturing companies to be able to adapt their processes to minimize waste at the source and also to efficiently use energy and raw materials. This involves adopting recycling initiatives and converting waste into valuable by-products.

(ii) Innovation and green technology: Production adaptability is very critical for integrating new green technologies in solving existing environmental problems. This often involves opting for renewable energy sources, optimizing production processes, and using such advanced manufacturing systems as AI, IoT.

(iii) Circular economy: Through the adoption of a more circular model, manufacturers can reduce their dependence on raw materials and minimize the landfilling use of waste. This is usually achieved by designing products for longevity and repurposing materials for new uses, via upcycling.

(iv) Improved efficiency and resilience: The adaptation of sustainable practices can lead to greater operational efficiency and productivity. It also builds resilience by reducing reliance on scarce resources and making operations less vulnerable to climate-related disruptions.

(v) Meeting market and societal demands: Manufacturing companies that adopt greener manufacturing practices can leverage their public image and stay competitive as consumers and regulators become more environmentally conscious. This involves not only creating products that are socially responsible but also economically viable.

(vi) Enhancing worker and community well-being: The concept of adaptability supports the creation of safer work environments and improves the health of both workers and their host community through the reduction of harmful emissions and pollution [2, 5].

Despite the benefits, challenges include high setup costs, interoperability issues across platforms, data security concerns, and the steep learning curve for workforce upskilling. Production adaptability is essential for sustainable and green manufacturing because it allows companies to respond to environmental challenges by reducing waste, conserving resources, and adopting cleaner production methods.

3.6 Ethical Issues on Widespread Industry Applications of Precision Mechanics and Digital Fabrication

Globally, advanced manufacturing technologies have gained rapid adoption across North America, Europe, and Asia. While sustainability benefits are significant, there exists some ethical concerns which include the following.

3.6.1 Digital divide

Digital technologies have opened a world of opportunities, but not everyone or region of the world has equal access to the internet, and the advanced technologies associated with them. According to the study [76], digital transformation is generating fundamental changes in the manufacturing sector, with digital technologies enabling the retrieval and analysis of data in real time, and allowing the connection of machines and elements of the physical world, to communicate with each other. Access to advanced technologies is uneven, leaving small enterprises and developing nations behind. The digital divide refers to the gap between those with and without access to information communication technology [77]. The digital divide poses a significant challenge to the global adoption of advanced manufacturing technologies by creating a gap in access to the necessary internet, devices, and digital skills. This inequality prevents many regions and smaller companies across the world from participating in digital transformation. This state of affairs has led to a widening gap in manufacturing competitiveness and resulted in economic disparities [77]. In a study designed to examine the digital divide as a barrier to the adoption of technology by small, medium, and micro enterprises (SMMEs) in the agribusiness sector in the city of Tshwane, South Africa, it was reported that the high cost of technology/online platforms, limited funds and a lack of technical know-how are some of the obstacles faced by SMMEs in the adoption of information and communication technologies [57].

3.6.2 E-Waste and obsolescence

The obsolescence of the electrical and electronic equipment is termed technological waste or simply e-waste. The e-waste has been identified as the fastest growing waste stream in the world presently, and is reported to be driven mainly by the rapid socio-economic development and technological advancement around the world today. Frequent hardware and software upgrades contribute to rising electronic waste. The e-waste includes the disposed outdated or obsolete electrical devices, such as mobile phones, DVD players, computers, laptops, televisions, generators, and freezers, running into millions of tons annually, which are discarded from their original owners because of their rather short lifetime. The hazardous chemical components of e-waste have potential adverse impacts on ecosystems and human health, if not managed properly. This presents an imminent challenge to achieving SDGs [78]. As the majority of this e-waste is finding its way into the developing countries which are poorly equipped when it comes to handling the e-waste, due to their lack of inventory data, waste management policies and advanced technology for environmentally sound management [78], as well as robust recycling infrastructure, thereby pushing many electronics to be discarded as general waste [79], with its adverse consequences. Additionally, the absence of comprehensive regulations, such as robust Extended Producer Responsibility (EPR) schemes, hinders effective e-waste management [80]. E-waste and obsolescence pose huge challenges to sustainable manufacturing, because it creates a cycle of rapid consumption and disposal, generating toxic waste and straining natural resources [80]. It has been acknowledged that rapid production cycles which rely heavily on the mining of virgin raw materials, is environmentally costly and also depletes finite resources [81, 82]. This has become a problem to manufacturing as it tends to undermine the goal of resource conservation when devices are frequently replaced, and creates the need for new manufacturing strategies such as designing for durability, repairability, upgradeability, recyclability and other key principles of circular economy [83, 84]. It has been observed by the study [85] that the products with short lifespans are responsible for the growing volume of the e-waste, which contains hazardous materials such as lead, cadmium and mercury that harm public health in particular, and the ecosystems in general, if not properly disposed. According to the study [78], the lack of an efficient e-waste management system in Bangladesh was the cause of death for approximately 15% of the illegal child laborers employed in this sector, and 83% were found to be exposed to long term health problems. Furthermore, Islam et al. [86] reported that improper management of electronic waste significantly impacts negatively on the health of human, plants, aquatic organisms and the environment, especially water, air, and land, causing significant harm to them. Moreover, poor handling of e-waste results in landfills' noxious chemicals release, causing earth's surface impact, and human health issues. It has been reported that there is credible evidence indicating that toxicants including heavy metals like lead (Pb), cadmium (Cd), and mercury (Hg), as well as persistent organic pollutants (POPs), and other hazardous elements including copper, chromium, nickel together with halogenated organic substances such as chlorofluorocarbons (CFCs), polybrominated biphenyls (PBBs), poly chlorinated biphenyls (PCBs), and brominated flame retardants (BFRs): emanating from e-waste are responsible for the pollution of the terrestrial ecosystem, when they are released into the environment through leachate migration and open burning, posing significant ecological and public health risks. Additionally, the pollutants from the e-waste alter soil fertility, reduce crop productivity, disrupt aquatic ecosystems, and increase bioaccumulation in food chains [86]. These ultimately have several adverse consequences on both the environment, plants, aquatic organisms and human health. Furthermore, it has been documented by many authors for instance, that the regular exposure of humans to these pollutants usually cause toxicity to the respiratory, circulatory, nervous, immune, endocrine, urinary and reproductive systems, inflicting damage to such human organs as the heart, kidneys, brain, liver, skeletal systems and reproductive systems. Besides, the pollutants from the e-waste have been linked to many pregnancy-related issues such as still births and malformed new-born babies, in addition to increased infant deaths [86]. Moreover, it has been reported that in India, more than 1 million poor people are involved in e-waste handling [87]. Additionally, statistics show that about 50,000 tons of e-waste is usually dumped in landfills annually, which ultimately impacts negatively on the Lyari and Arabian Seas with adverse consequences on marine ecosystems. The following solutions have been identified by studies [78] and [85] as part of the viable and effective ways for resolving the challenges of e-waste and obsolescence globally:

(i) Adoption of circular economy principles: The adoption of a circular economy model has been advocated. This involves designing products for durability, repairability, upgradability, and recyclability.

(ii) Extended producer responsibility: As part of policies and regulatory frameworks for sustainable manufacturing, manufacturers should be made to take responsibility for their products' end-of-life phase through EPR schemes, which incentivize better design and proper recycling programs.

(iii) Sustainable design: Sustainable design principles such as modularity, and standardization of components should be adopted and incorporated in designs, so as to extend the life of devices and make them easier to repair and recycle.

(iv) Technological innovation: The development and deployment of advanced recycling technologies, such as automated disassembly and AI, can help increase the efficiency of recycling processes and enable better recovery of valuable materials.

(v) Global action and collaboration: The global nature and impact of e-waste requires international actions through collaborations and policies to assist low-income countries manage waste and prevent the export of these environmental problems [85].

3.6.3 Job displacement

There are a lot of cries and arguments that manufacturing automation is taking jobs away from humans and giving the same to machines and industrial robots thereby threatening the traditional labor markets. According to McKinsey Global Institute [40] on the impact of automation on workforce displacement, automation is expected to displace a significant number of jobs, with some estimates predicting that between 400 million and 800 million jobs could be displaced globally by year 2030. It is believed by people around the world that digital transformation: the process of converting various information from analog to digital format, will eliminate some of the pre-existing jobs or professions [40]. It was reported by the study [39] that whereas low-skilled jobs are particularly vulnerable, the higher-skilled positions are equally being increasingly exposed to the impact of sustainable automation on employment, with the ultimate potential of widening economic inequality [39]. This has elicited calls for socially responsible workforce retraining programs. However, the advocates of sustainability in manufacturing have argued that sustainable manufacturing and a green economy are more likely to contribute to job creation than displacement, although the transition to digital manufacturing technologies can cause temporary job losses in specific industries like coal mining and fossil fuels [88]. Moreover, the effect of sustainable manufacturing practices on employment can be more significant in regions that are heavily reliant on traditional non-green industries. A report by the study [88] indicated that whereas the growth of sectors such as renewable energy (like solar, wind), energy efficiency, sustainable transportation, waste management and green construction will create new jobs, there is no doubt that the transformation of existing sectors can also lead to new employment opportunities. It has been reported that the new green economy will require a workforce with new skills, including both technical and soft skills, which will necessitate training and education programs to ensure a smooth transition for the workforce. However, there is no gainsaying the fact that some traditional jobs, particularly those with high-carbon footprints or emissions, or resource-intensive processes, could lead to a decline in opportunities for human employment. There is no doubt that the technological advancements in sustainable manufacturing will continue to drive more transformations as the manufacturing industry continues to evolve. The existing industries, including manufacturing can be transformed to become more sustainable, leading to new jobs in areas like developing and manufacturing clean technologies, and improving resource efficiency. According to the study [89], automation in manufacturing will create new job opportunities, especially in fields such as AI development, data analytics, and information technology, with some other reports suggesting that automation could create as many new jobs as it displaces. Furthermore, it has been argued that the automation driven by precision and digital technologies utilized in sustainable manufacturing usually leads to increased labour productivity, which tends to offset some potential job losses [89]. Part of the strategies already conversed for the mitigation and management of the negative impacts of automation in sustainable manufacturing includes Policy and planning, which entails developing government policies that will drive investments and social protection programs, such as strengthening social safety nets, unemployment benefits, and job placement services to help displaced workers transition, that will help displaced workers transition to the new reality, and ensure effective management of the switch to new technologies and minimize job losses. Reskilling and training of workers to adapt to the new changes, by acquiring new skills and competencies through training and development programs to remain relevant in the evolving job market has also been suggested as a way out [89]. Moreover, getting people to focus on human-centric skills particularly on jobs that require creativity, complex problem-solving, and interpersonal skills, which are less likely to be automated have also been advocated. In addition, it has been advocated that green economy initiatives focusing on and promoting social inclusion should be designed to create decent jobs for all, regardless of gender and age. Finally, it has been suggested that deliberate policies aimed at supporting workers and communities affected by the transition to new technologies should be designed to enable them acquire the skills, resources, and support needed to transition to new jobs [39, 89].

3.6.4 Data security and privacy

The entire manufacturing industry is facing huge challenges that may lead to data loss in manufacturing organizations. In the era of Industry 4.0, where manufacturing plants' activities are increasingly becoming interconnected and automated, prioritizing data privacy is not just a regulatory requirement but a business imperative. According to the study [15], The global data privacy software market has been experiencing exponential growth, following the adoption of the IoT across various industries, causing the CAGR to rise to 40.9%, thereby underscoring the importance of data privacy and security. Hence, the relevance of data privacy cannot be overstated. Moreover, the use of advanced technologies such as real-time digital twins introduces vulnerabilities in terms of intellectual property and industrial espionage. The more data is produced, processed, and stored in more places, protecting it from unauthorized access and breaches becomes more complex and critical [90]. With manufacturing processes becoming more digitized and the reliance on data-driven decision-making increasing daily, the potential risks associated with unauthorized access to sensitive information have become heightened and very critical. The manufacturing organizations nowadays maintain a lot of data which includes everything from proprietary designs and production algorithms to supply chain logistics and customer information. This makes them attractive targets for cybercriminals and competitors seeking to gain a competitive edge or disrupt operations. Any breach in data privacy of these organizations not only compromises the confidentiality of their sensitive information but also undermines the integrity and availability of critical systems and processes. The impacts of any lapse in data security or inadequate data privacy measures in manufacturing companies can be profound and far-reaching, often resulting in issues ranging from intellectual property theft to operational disruptions [91], to downtime, supply chain issues to the loss of business continuity [92]. These can have very serious consequences, leading to wasted capacity, unhappy customers, lost revenues and compliance and legal outcomes. Data protection and security in the manufacturing industry refers to the practices and controls which manufacturers implement to protect sensitive information while also ensuring the integrity, confidentiality and availability of data in their networks, systems and processes. Additionally, data protection and security also involve protecting critical data from unauthorized access, modification, disclosure and loss. It also plays an important role in preventing cyberattacks and disruptions that could impact negatively on manufacturing operations and business continuity [92]. The loss of critical data could occur in an organization due to cyberattacks, tech infrastructure failures, human error or natural disasters. Data loss in the manufacturing industry can have several significant consequences, such as production disruptions, downtime and increased costs, quality control issues, supply chain disruptions, compliance and regulatory issues, loss of intellectual property, and reputational damage [92]. Data protection and security are of significant benefits to manufacturers. They help safeguard intellectual property, trade secrets and sensitive manufacturing data, and hence preserve a company's competitive advantage. By preventing unauthorized access and data breaches, manufacturers can protect their innovations and prevent competitors from gaining an unfair advantage over them. The challenges to data privacy in manufacturing industries as listed by the study [91] include the following:

1. Legacy systems: Many manufacturing plants still rely on legacy systems that were not designed with cybersecurity in mind. These outdated systems may lack essential security features, making them vulnerable to cyber threats.

2. Interconnectedness: The proliferation of IoT devices and interconnected networks has expanded the attack surface for potential breaches. Each connected device represents a potential entry point for cyber attackers if not adequately secured.

3. Supply chain risks: Manufacturers often collaborate with numerous suppliers and partners across the globe, increasing the complexity of securing data throughout the supply chain. Weak links in the supply chain can expose manufacturing plants to third-party breaches and cyber-attacks.

4. High cost of cybersecurity experts: It is a stark fact that skilled, experienced cybersecurity professionals are hard to recruit, hire and retain. This leaves many manufacturing companies with real gaps in their cybersecurity workforce. Besides, these resources are becoming increasingly expensive, and may put them out of reach of some companies.

5. Employee awareness: Insider threats pose a significant risk to data privacy in manufacturing. Employees, intentionally or unintentionally, can compromise sensitive data through actions such as negligent handling of information or falling victim to social engineering attacks.

3.7 The Imperative of Data Privacy Compliance

Regulatory bodies worldwide are increasingly imposing stringent regulations to safeguard data privacy and protect consumer rights. In the manufacturing sector, compliance with regulations such as the General Data Protection Regulation and the California Consumer Privacy Act is essential for avoiding hefty fines and reputational damage. Furthermore, adhering to industry-specific standards such as ISO 27001 (Information Security Management System) and National Institute of Standards and Technology Cybersecurity Framework can help manufacturing plants establish robust data privacy practices and demonstrate their commitment to safeguarding sensitive information.

3.8 Best Practices for Enhancing Data Protection, Security and Privacy in the Manufacturing Industry

To mitigate the risks associated with data privacy breaches, manufacturing companies should implement robust data protection measures, including regular data backups, secure storage, access controls, encryption, employee training, cybersecurity measures and disaster recovery plans. According to the study [90], manufacturers need to implement strong access controls, regular security audits, employee training on security best practices, data encryption practices, and incident response plans, in order to prevent and mitigate risks associated with cyberattacks. Specifically, manufacturing concerns can implement the following best practices:

1. Data encryption: Implement robust encryption protocols to protect data both in transit and at rest. Encryption helps ensure that even if unauthorized parties gain access to the data, they cannot decipher it without the encryption keys.

2. Strengthen network security: Manufacturers are increasingly interconnected through digital networks and internet-connected devices Robust cybersecurity measures are necessary to defend against cyberthreats, such as hacking, malware, ransomware and phishing attacks. This includes implementing firewalls, intrusion detection systems, antivirus software and conducting regular security audits to protect their networks.

3. Access control: To prevent and mitigate risks associated with cyberattacks, manufacturers need to implement strong access controls [90]. Enforce strict access controls to limit employee access to sensitive information based on their roles and responsibilities. Implement multi-factor authentication mechanisms to prevent unauthorized access to critical systems and data. Manufacturers can further enhance network security with strong access controls, regular patch management and employee training and should always use encrypted communication protocols, VPNs and network activity monitoring.

4. Regular audits and assessments: Manufacturers can enhance the security of their equipment and infrastructure by conducting regular risk assessments, implementing physical access controls, network segmentation and regular software updates. By adopting these measures, manufacturers can protect their equipment and infrastructure from threats, ensuring operational continuity and minimizing potential disruptions. The failure of a company to evaluate its data could make the company lose competitive edge to other manufacturing companies that take meaningful and decisive action on gathered insights. Additionally, the company could suffer from issues related to quality control or experience unexpected downtime from an equipment failure that might otherwise have been identified and taken care of [90]. Conduct regular audits and risk assessments to identify vulnerabilities in systems and processes. Proactively addressing weaknesses can help prevent potential data breaches before they occur.

5. Employee education and training: Training programs and awareness campaigns help educate employees about data protection best practices, such as password security, phishing prevention and proper handling of sensitive information [92]. Employees should be educated about the importance of data privacy and security through comprehensive training programs. Raising awareness about common cybersecurity threats such as phishing attacks and social engineering tactics to help employees recognize and respond to potential risks effectively.

6. Ensure compliance with regulations in the manufacturing industry: Manufacturers may be subject to various data protection regulations, depending on their industry and geographical location. Compliance with regulations such as the General Data Protection Regulation or industry-specific standards like ISO 27001 helps ensure data protection and security. Establishing compliance programs tailored to the manufacturing industry is essential. To comply with regulations specific to the manufacturing industry, organizations can follow key best practices, including

developing policies, procedures and guidelines addressing regulatory obligations, and employee responsibilities and training programs.

7. Incident response plan: Develop a robust incident response plan outlining procedures for detecting, responding to, and recovering from data breaches. Regularly test the effectiveness of the plan through simulated cyber-attack scenarios to ensure readiness in the event of a real incident. Proper documentation and record-keeping of compliance activities are necessary for audit purposes [92].

To mitigate the consequences of data loss, manufacturing companies should implement comprehensive data protection and security measures, including data backup and recovery strategies, robust cybersecurity measures, regular data audits and effective disaster recovery plans. According to the study [90], 48% of IT decision-makers are of the view that improving data management practices should be a top priority for manufacturing organizations in 2025. By implementing robust security controls, fostering a culture of cybersecurity awareness, and staying abreast of evolving threats and regulations, manufacturing companies can reduce the risks of data breaches and protect their most valuable assets. In doing so, they can not only safeguard their competitive advantage but also uphold the trust and confidence of their customers and stakeholders in an age where data privacy is very critical.

4 Benefits of Precision Mechanics and Digital Fabrication

The integration of precision mechanics and digital fabrication technologies delivers significant improvements in process efficiency, resource utilization, and overall sustainability performance. These combined systems enable optimized control over design, production parameters, and material usage, thereby enhancing manufacturing outputs while minimizing waste. According to the study [23], direct digital manufacturing systems unify the strengths of both paradigms—precision-based subtractive processes and digitally driven additive or automated workflows—resulting in improved input–output ratios, higher design flexibility, and measurable improvements in environmental indicators.

A comparative assessment between direct digital manufacturing systems and traditional manufacturing approaches shows that these integrated technologies provide distinct sustainability advantages, including:

(i) Substantial material savings: AM can reduce raw material usage by up to 90% in specific applications because it builds components layer-by-layer rather than removing excess material as in subtractive methods [90].

(ii) Enhanced energy efficiency in CNC machining: CNC systems equipped with real-time feedback and adaptive control mechanisms significantly lower energy consumption by dynamically adjusting parameters such as cutting speed, feed rate, and spindle load based on material and tool conditions [91].

(iii) Reduced post-processing through hybrid manufacturing: Hybrid platforms that combine AM with precision milling enable the production of geometrically complex components with minimal secondary operations. This reduces machining time, material waste, labor requirements, and overall energy expenditure [92].

These improvements strongly support sustainability drivers and align with global objectives such as the UN SDG 12 on responsible consumption and production, reinforcing the role of precision-enabled digital systems in achieving environmentally conscious manufacturing pathways [90].

4.1 Role of Precision Mechanics in Sustainable Manufacturing

Precision mechanics is foundational to enhancing the sustainability of manufacturing systems by ensuring higher accuracy, reducing material waste, and increasing energy efficiency. The use of ultra-precise tooling and CNC machining minimizes tolerances, which reduces the need for rework and optimizes resource utilization [93]. Furthermore, precision-based systems improve the durability and life cycle of manufactured products, aligning with the principles of sustainable product design [94]. Advanced precision systems enable closed-loop manufacturing processes, where real-time monitoring and correction minimize energy loss and reduce emissions [95]. These systems are particularly vital in sectors such as aerospace and medical device manufacturing, where sustainability must not compromise performance or safety.

4.2 Impact of Digital Fabrication on Environmental Performance

Digital fabrication techniques most notably AM and subtractive processes integrated with digital design have significantly improved environmental outcomes across production sectors. AM, for example, allows for material usage optimization by fabricating parts layer-by-layer, thus minimizing scrap [96]. This leads to a substantial decrease in material waste compared to conventional subtractive methods. Furthermore, digital fabrication supports localized, on-demand production, which reduces transportation emissions and inventory costs [97]. In some documented cases, the energy consumption of optimized 3D printing processes has been shown to be lower than that of traditional methods for specific geometries and small batch sizes [98].

4.3 Industry Applications and Innovation Pathways

Precision mechanics and digital fabrication technologies are rapidly gaining traction across various high-impact industries due to their transformative potential in enhancing sustainability. Sectors such as automotive, aerospace, and biomedical engineering are at the forefront of integrating these tools into their production systems, as a result of the need to reduce environmental footprints while maintaining performance and reliability standards. In the automotive industry, for example, manufacturers are increasingly adopting digital twins and AM to optimize electric vehicle components. These technologies enable light-weighting strategies that improve energy efficiency and extend vehicle range. Through virtual simulations, digital twins facilitate real-time testing and iterative refinement, reducing the need for physical prototyping and associated waste. Similarly, aerospace firms utilize precision CNC machining and hybrid additive-subtractive processes to fabricate components with stringent tolerances, minimizing material use and improving structural performance. Biomedical engineering has also embraced digital fabrication for patient-specific prosthetics and implants. 3D printing technologies allow for customization based on anatomical data, reducing surgical times and improving health outcomes. Furthermore, companies like Siemens and General Electric have pioneered smart factories that integrate precision mechanics with real-time data analytics, enabling closed-loop feedback systems for energy optimization and predictive maintenance [99, 100]. These smart manufacturing ecosystems represent a shift toward intelligent, autonomous production that aligns economic gains with environmental stewardship. Emerging innovation pathways are expanding the frontier of what is possible with precision and digital fabrication. AI-assisted design for manufacturability is streamlining product development by automatically optimizing geometries for minimal waste and efficient processing closed-loop sensor systems are increasingly deployed to enable predictive maintenance and adaptive control, thereby extending equipment life and reducing downtime. Another breakthrough is the emergence of micro-factories—compact, decentralized production units equipped with precision tools and digital fabrication systems. These scalable setups offer localized manufacturing solutions, lowering transportation emissions and supporting circular economy models by enabling recycling, remanufacturing, and on-demand production at the point of use [101]. Collectively, these innovations reflect a paradigm shift toward decentralized, intelligent, and ecologically sound manufacturing infrastructures.

4.4 Sustainable Applications of Precision Mechanics and Digital Fabrication Technologies Across Industries

The applications of these technologies are very wide and varied from cutting metal sheets in solar panel frames to making components in electric vehicles, the applications of laser machines in industries are wide-ranging. The major sectors benefiting immensely from the applications of green technology include:

(i) Automotive: Lightweight components and precise welding for electric vehicles
(ii) Aerospace: Lightweight high strength and ultrahigh precision components
(iii) Textile: Eco-friendly laser engraving and cutting
(iv) Electronics: Fine electronic part-production without harmful chemicals
(v) Renewable energy: Laser welding for solar and wind energy components
(vi) Packaging: Laser perforation for biodegradable packaging solutions

As demand for eco-friendly solutions rises, so does the need for advanced technology, dependable tools [52], and advanced materials with sophisticated properties.

4.5 Challenges and Implementation Barriers to the Widespread Adoption of Precision Mechanics and Digital Fabrication in Sustainable and Green Manufacturing

Despite the promising benefits and technological maturity of precision mechanics and digital fabrication, several barriers continue to impede their widespread adoption within sustainable manufacturing ecosystems. One of the foremost challenges is the high initial financial requirement. The acquisition of advanced equipment such as ultra-precision CNC machines, industrial 3D printers, and supporting software platforms entails significant capital investment. This cost burden is particularly prohibitive for small-to-medium enterprises, which often operate under tight financial constraints and lack access to favorable financing structures [102].

Another critical challenge is the shortage of skilled labor. Operating and maintaining these complex systems demand a specialized workforce proficient in mechatronics, CAD/CAM systems, materials science, and digital controls. The current educational and vocational training systems in many regions have yet to catch up with these evolving skill demands, leading to a persistent skills gap that hampers effective technology adoption [89].

Moreover, while some AM technologies offer material savings, their energy demands can be substantial in large-scale or high-volume production. For instance, certain metal-based 3D printing techniques require high-temperature operations and post-processing steps that offset the sustainability benefits, particularly when powered by non-renewable energy sources [103]. This paradox underscores the importance of lifecycle analysis in assessing true environmental impact. The limited availability of empirical data that quantifies the long-term economic and environmental advantages of these technologies is another significant barrier. Many existing studies focus on laboratory-scale demonstrations or single-case applications, which do not offer the broader insights needed for strategic industry-wide implementation. Furthermore, life cycle assessments that integrate both additive and subtractive processes remain underexplored, making it difficult to compare hybrid systems or justify their use over conventional methods. Policy-related challenges also persist. The absence of standardized regulatory frameworks guiding the sustainable implementation of digital fabrication technologies creates ambiguity for manufacturers seeking compliance. Without clear guidelines on emissions, material sourcing, or end-of-life management, the integration of these technologies remains piecemeal. Geographic disparities exacerbate the issue, as access to precision equipment, skilled personnel, and digital infrastructure is often concentrated in high-income regions. Developing and emerging economies may lack the infrastructure and institutional support to scale these innovations equitably.

Furthermore, the human dimension of technological transition is frequently overlooked. Research on workforce adaptation, retraining programs, and social impacts of automation in precision manufacturing environments is insufficient. In the absence of deliberate planning, these shifts risk widening socioeconomic inequalities and causing resistance among stakeholders accustomed to traditional production models.

Finally, standardization issues and resistance to change within legacy manufacturing environments pose additional hurdles. Integrating green digital solutions often requires overhauling existing workflows, retraining personnel, and reconfiguring supply chains pertinent issues that can face internal pushback due to perceived risks and operational disruptions [104].

Overcoming these challenges is essential for unlocking the full sustainability potential of precision mechanics and digital fabrication. It requires a coordinated approach involving technological innovation, workforce development, supportive policy instruments, and robust research frameworks. Only through such integrative strategies can these technologies evolve from promising alternatives to mainstream solutions in the global pursuit of green manufacturing.

5 Findings and Recommendations

5.1 Review Findings

The integration of digital precision technologies within modern manufacturing is proving to be not only an environmental imperative but also a strategic business advantage. Forward-thinking industries that adopt these innovations early are better positioned to lead in the global sustainability movement, capturing new markets and appealing to environmentally conscious consumers. Beyond their ecological benefits, these technologies also support agile manufacturing strategies through modular and scalable production systems. Digital fabrication, in particular, enables on-demand customization, lean inventory models, and resilient supply chain architectures. These attributes underscore a vital transition for manufacturers, from theoretical exploration to practical implementation, which is anchored in a vision of intelligent, low-impact, and adaptive industrial systems.

5.2 Recommendations

5.2.1 Technological adoption strategies

To fully harness the transformative benefits of precision mechanics and digital fabrication, industries must pursue structured and proactive adoption strategies. A phased implementation approach is advisable, beginning with pilot programs that introduce ultra-precision CNC machining, digital twins, and AM in controlled environments. These pilot programs will help mitigate resistance to change by providing empirical data on return on investment and environmental performance. Additionally, partnerships between technology developers and manufacturers can foster critical knowledge transfer and lower entry barriers. The integration of IoT platforms and machine learning into these systems is another key enabler that will facilitate predictive maintenance, energy optimization, and dynamic resource management across production lifecycles [50, 97].

5.2.2 Policy and regulatory frameworks

Robust and forward-thinking policy frameworks are essential to accelerate the adoption of sustainable manufacturing technologies. Governments and regulatory agencies need to introduce financial incentives, such as tax reliefs, subsidies, and low-interest loans to support companies transitioning to greener practices. Furthermore, clear environmental regulations must be established to guide the application of digital fabrication and material use. These should include a much more robust, mandatory life-cycle assessments for electronic products, since the composition and structure of the electronic trashes are quite convoluted, holding around 1000 or more additional substances, with some hazardous, and others non-hazardous [86]. This will engender the articulation of effective pollutants' emission tracking protocols that will foster manufacturing accountability. A coordinated effort between policymakers, industry players, and academic institutions is required to shape adaptable, future-proof regulatory structures that keep pace with the rapid evolution of manufacturing technologies [23, 98].

5.2.3 Educational and workforce development

A digitally-enabled and sustainable manufacturing sector is heavily dependent on a technically skilled and adaptable workforce. There is an urgent need to reform educational curricula, particularly within engineering and vocational institutions, to integrate subjects on digital manufacturing, automation, environmental responsibility, and data-driven production. As part of efforts towards workforce development in digital fabrication and precision mechanics, mastercam has introduced an educational initiative called "full online Mastercam University" designed to shorten the learning curve and equip the next generation of the workforce with some of the skills necessary for the technology needed for sustainable manufacturing. Upskilling initiatives, including technical workshops, modular certifications, and industry-academia exchange programs, are critical for equipping workers with competencies in system integration, programming, and smart machinery operation. Investment in lifelong learning ecosystems by both public and private sectors will ensure that workers remain relevant and agile in the face of rapidly changing industrial landscapes [102].

5.2.4 Future research directions

Though the theoretical promise of precision and digital fabrication technologies is well documented, there are still several areas that require more rigorous and long-term empirical investigation. One key research priority is the development of comprehensive lifecycle assessment models capable of evaluating the environmental trade-offs associated with emerging fabrication methods, particularly hybrid and closed-loop systems. Equally important is the exploration of cost-effective implementation models tailored to the needs of small-and medium-sized enterprises, which often lack the capital and infrastructure of larger firms. Additionally, future studies should examine the socio-economic implications of decentralized micro-factories, particularly their potential to reshape global supply chains and foster localized production hubs. A detailed investigation of the impact of widescale adoption of ultra-precision and digital technology on the labour market is equally important. Integrating renewable energy systems such as solar and wind into digital fabrication infrastructures will also present a promising frontier for achieving greater energy autonomy and environmental performance.

6 Conclusions

Technology, though not a complete panacea, remains an effective and indispensable catalyst for the sustainable transformation of modern manufacturing. Precision mechanics and digital fabrication offer viable, scalable solutions to address some of the most pressing ecological challenges within the industry. Yet, their potential can only be fully realized through holistic strategies that encompass not just technological deployment, but also enabling policies, robust education systems, and continuous innovation. The convergence of these elements is critical to forging a resilient and ecologically responsible manufacturing sector. As industries navigate this green transition, precision and digital tools will be central in balancing economic growth with planetary stewardship. Moreover, 3D printing stands out as a particularly promising technology in advancing sustainability efforts. Its capacity to reduce material waste, support circular economy principles, and enable highly efficient use of resources positions it as a cornerstone of next-generation manufacturing. As AM systems mature, they are also accelerating the decentralization of production, enabling on-demand fabrication and distributed manufacturing models. This shift will increasingly allow companies to produce components closer to the point of use, reducing logistical complexities and operational costs, while significantly lowering environmental impacts.

Sustainability in CNC machining is crucial for minimizing environmental impact while maintaining high manufacturing standards. By reducing waste, optimizing resource use, and enhancing energy efficiency, CNC machining plays a significant role in sustainable manufacturing. The industry must continue to embrace eco-friendly practices, leveraging emerging technologies like AI, Machine learning and AM to further improve sustainability. Manufacturers are encouraged to prioritize sustainability, not only for regulatory compliance but also for the long-term benefits of cost savings, improved brand reputation, and customer loyalty. Together, we can drive the manufacturing sector towards a greener, and more sustainable future.

CNC machine tools are integral to the shift towards sustainable and green manufacturing. By providing precision, efficiency, and resource optimization, CNC technology helps reduce waste, lower energy consumption, and minimize environmental impact. As manufacturers continue to embrace sustainability, the role of CNC machine tools in supporting these efforts will become increasingly important, driving innovations that align with the principles of a circular economy and a greener future.

As industries across the globe transition to greener, and sustainable manufacturing practices, laser technology is proving to be a crucial game-changing tool. With advantages such as reduced waste, energy saving, chemical-free processing, and long-lasting lifespan, laser machines are improving businesses to meet environmental goals without compromising on productivity and quality. Finally, it can be said that any technology which focuses on the reduction of production cost, elimination of material waste, minimization of energy consumption, and general optimization of product performance without increasing product cost and environmental carbon footprint, will ultimately advance sustainability and green manufacturing practices. With precision mechanics and digital fabrication technologies producing such results, it goes without saying that when these technologies are properly deployed in industries, the outcome will go a long way in promoting global manufacturing sustainability.

Overall, the integration of precision machining and digital fabrication technologies in the manufacturing industries will deliver a wide range of benefits to the organizations that adopt them and to the global environment. Thereby cementing the positive contributions of these technologies in sustainable and green manufacturing practices, and ultimately incentivizing their adoption and acceptance. By addressing the current challenges and focusing on future research directions, the field can continue to evolve and provide more efficient, more sustainable, safer and more eco-friendly products.

Author Contributions

Conceptualization, P.A.O. and G.C.U.; methodology, P.A.O.; software, G.C.U.; validation, P.A.O. and G.C.U.; formal analysis, P.A.O.; investigation, P.A.O.; resources, P.A.O.; data curation, P.A.O.; writing—original draft preparation, G.C.U.; writing—review and editing, P.A.O.; visualization, P.A.O.; supervision, P.A.O.; project administration, P.A.O. All authors have read and agreed to the published version of the manuscript.

Data Availability

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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