IJEES

International Journal of Electrical Engineering and Sustainability (IJEES)

ISSN (online): 2959-9229

https://ijees.org/index.php/ijees/index

Volume 2 | Number 1 | January-March 2024 | Pages 31-44

Research Article

Advancing Sustainable Practices in Manufacturing: An Approach to Intelligent Systems Integration

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Received: November 02, 2023 Accepted: February 05, 2024 Published: February 15, 2024

Abstract: The pursuit of sustainable production endeavors to cultivate product manufacturing methodologies that mitigate environmental ramifications, diminish energy exigency, and curtail depletion of natural resources. In light of evolving consumer preferences and market dynamics favoring digitalization, customization, and adaptability, there is a discernible inclination towards solutions that exhibit reduced environmental footprint. Consequently, within the paradigm of Industry 4.0 (I4.0), there is a perceptible trend towards the incorporation of social and environmental sustainability imperatives into technological solutions. In this context, the articles focus on the establishment of an infrastructural framework that amalgamates industrially pertinent application modules through the synergistic fusion of system reconfigurability and artificial intelligence, thereby fostering the realization of sustainable production objectives. The article tackles four distinct challenges concerning the intersection of flexibility and sustainability within production processes: firstly, the development of infrastructural and methodological tools aimed at assisting companies in navigating the potential of Industry 4.0 (I4.0) towards sustainable production; secondly, the management of configurability and customization options inherent in product manufacturing; thirdly, the efficient management of the flexibility afforded by production systems equipped with rapid reconfiguration capabilities; and fourthly, the integration of hardware and software flexibility through the utilization of reconfigurable robotics and machine learning methodologies. Through the iterative development and interconnection of diverse application modules, we procure a tangible demonstrative entity. This entity serves as a prototypical manifestation delineating, on one facet, an archetypal manifestation of a reconfigurable and adaptable production system. Conversely, it affords novel avenues for scholarly inquiry and comprehension, employing a sensory-driven paradigm that facilitates experiential engagement with industrial and academic domains.

Keywords: Sustainability, Manufacture, Product, Process, Approach

1. Introduction

Sustainability has emerged as an increasingly paramount imperative within the spectrum of human endeavors, thereby rendering the pursuit of sustainable development a cornerstone objective in human progress. Fundamentally, sustainable development espouses the notion that societal, economic, and environmental exigencies ought to be concurrently and comprehensively addressed within the developmental framework [1]. Thus, the ethos of sustainability has permeated various domains, encompassing fields such as engineering, manufacturing, and design. In additional, manufacturers are displaying escalating concern regarding sustainability considerations. This is exemplified by the acknowledgment of the intrinsic interplay between manufacturing operations and the natural milieu, which has assumed pivotal significance in the decision-making milieu of industrial societies [2].

Efforts to engender sustainable development represent a multifaceted and intricate endeavor, entailing the harmonization of diverse elements including technological and engineering facets, economic imperatives, environmental stewardship, public health and welfare, societal aspirations, and governmental strategies, protocols, and policies [3]. Specifically, the pursuit of sustainable manufacturing necessitates the adept balancing and synthesis of economic and environmental societal objectives alongside the implementation of enabling policies and practices. Oftentimes, judicious trade-offs are requisite, given the heterogeneous interests of manufacturers and society at large. Moreover, the availability and utilization of pertinent, cogent, consistent, and robust information pertaining to sustainable manufacturing are imperative for organizations and their managerial cohorts if substantive progress in sustainability within manufacturing is to be realized [4]. Figure 1 illustrates the concept of sustainability as the point where its three main components cross.

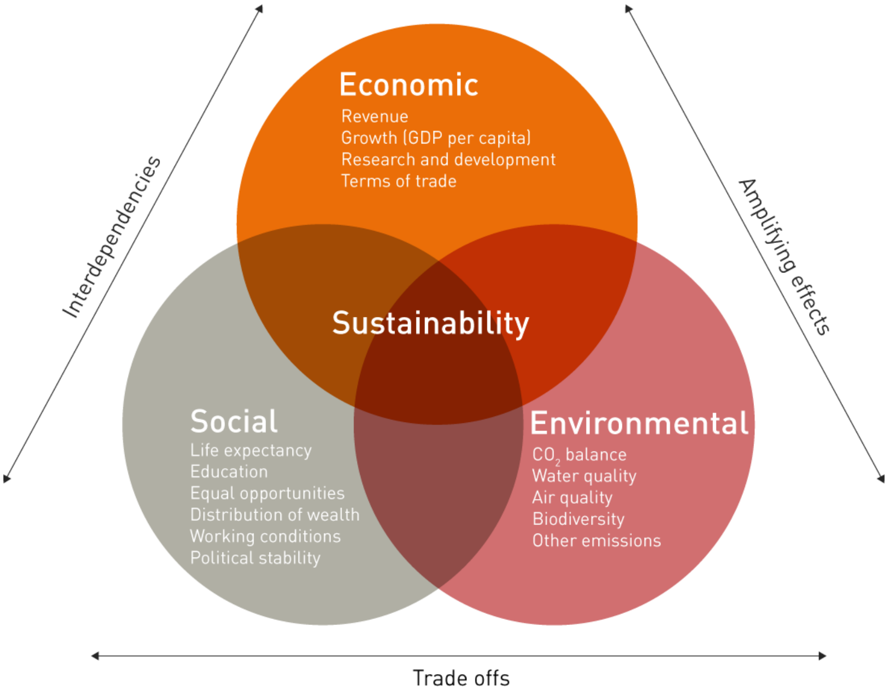


Figure 1. Sustainability as the intersection of its three key parts.

Sustainable manufacturing endeavors to produce goods via processes that minimize adverse environmental effects, conserve energy and natural resources, ensure safety for employees, communities, and customers, and maintain economic viability. Market trends increasingly favor product solutions characterized by customizability, flexibility, and minimal environmental impact. Within this context, the application of Industry 4.0 (I4.0) technologies is associated with sustainability benefits, encompassing both social and environmental dimensions [5]. The concept of sustainability is commonly delineated across three primary dimensions—social, economic, and environmental—each of which holds intrinsic importance in production endeavors. However, it is imperative to adopt a comprehensive perspective that extends beyond these dimensions. Notably, the International Organization for Economic Cooperation and Development (OECD) underscores the significance of sustainable practices in the eyes of various stakeholders, including investors, regulators, customers, and local communities where companies, including Small and Medium Enterprises (SMEs), operate. According to OECD findings, companies with favorable environmental reputations tend to receive higher ratings from financial analysts. Additionally, modest reductions in energy consumption can yield substantial increases in overall profitability. Moreover, global surveys involving over 5000 participants indicate a growing preference among young workers for employment opportunities that actively engage with or demonstrate awareness of sustainability issues [6].

Manufacturing systems are increasingly required to swiftly accommodate changes in products, processes, and technologies due to factors such as resource constraints, stringent regulations, and volatile market demands. Traditional manufacturing systems, typified by dedicated production lines, rely on inflexible automation and are optimized for high-volume production of a single product or limited variants. These systems often struggle to adapt to dynamic environments characterized by significant variability [7]. Their design and optimization are centered around prolonged operation to ensure long-term economic viability and return on investment. However, the paradigm of manufacturing optimization based on the presumption of consistent demand for standardized products conflicts with contemporary market trends favoring mass customization (MC) over mass production. This incongruity poses a notable challenge for SMEs, particularly concerning investment in automation systems. SMEs may be deterred from such investments due to concerns that automation could compromise their ability to promptly adjust to shifting market demands, thereby diminishing their operational flexibility [8].

The field of Advancing Sustainable Practices in Manufacturing has witnessed a significant influx of researchers in recent years, attesting to its growing prominence and relevance. This surge in scholarly interest can be attributed to the pressing global imperatives surrounding sustainability, coupled with the pivotal role that manufacturing industries play in shaping environmental outcomes. Camarinha-Matos et al., [9] delved into the allocation of responsibility across diverse entities engaged in manufacturing to address different aspects of sustainability. Drawing upon a comprehensive literature survey and insights garnered from numerous research projects and associated initiatives within the domain, the study is systematically structured around various dimensions of Industry 4.0. Furthermore, it offers a concise overview of proposed methodologies and metrics for evaluating sustainability within the context of networked manufacturing. Concluding remarks highlight a series of pivotal research challenges, thus augmenting strategic research agendas in the realm of manufacturing.

Discovering innovative methods to enhance supply chain efficacy poses a significant challenge for manufacturing enterprises amidst the era of globalization and intense competition. Enhancing performance necessitates proactive engagement in networking endeavors, such as forging alliances with other stakeholders within the supply chain. Concurrently, manufacturing entities encounter sustainability concerns stemming from suppliers' practices that diverge from sustainability criteria [10]. In this context, fostering collaborative partnerships with suppliers assumes paramount importance for the effective implementation of sustainable practices and the attainment of competitive advantages. Hence, it becomes imperative for manufacturing firms to adeptly manage their supplier relationships, bolstering suppliers' commitment to sustainability initiatives. The concept of Sustainable Supplier Collaboration (SSC) arises from the fusion of sustainability principles and supplier relationship cultivation. SSC, in essence, extends beyond conventional supplier management paradigms by integrating enduring partnerships with sustainability objectives.

Circular economy (CE) and Industry 4.0 have emerged as prominent concepts in contemporary business discourse, facilitating organizations in fostering a circular flow and optimizing resource utilization through technological advancements aimed at enhancing sustainability practices. The transition toward embracing CE principles and Industry 4.0 technologies holds considerable promise, albeit with inherent challenges. Consequently, this research endeavors to explore the integration of CE and Industry 4.0 within the domain of sustainable supply chain management (SSCM), with the overarching goal of enhancing operational efficiency and sustainability performance [11]. Figure 2 presents the domain SSCM. Through a systematic literature review, this study offers an analysis of the dynamic shifts in drivers and barriers associated with the amalgamation of CE and Industry 4.0, along with their respective applications in operations and supply chain management (SCM). Subsequently, a theoretical framework is proposed based on the findings to guide future research endeavors in this domain.

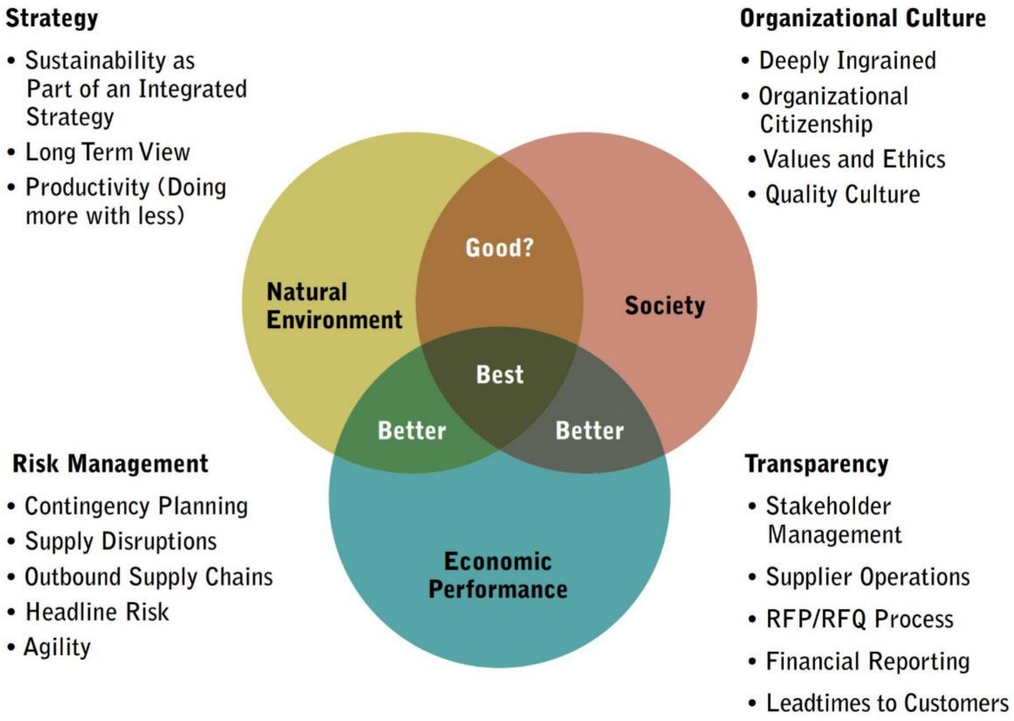


Figure 2. The domain of sustainable supply chain management (SSCM).

According to Dirocco et al., [12], a refined synthesis protocol has been devised for belzutifan, a novel inhibitor targeting HIF-2α intended for the treatment of Von Hippel–Lindau (VHL) disease-associated renal cell carcinoma (RCC). The efficacy of prior supply and commercial pathways was hindered by a protracted 5-step sequence necessary for the introduction of a chiral benzylic alcohol using conventional methodologies. Through the identification and directed evolution of FoPip4H, an iron/α-ketoglutarate dependent hydroxylase, a direct enantioselective C–H hydroxylation of a basic indanone starting material was enabled. While this catalytic transformation laid the groundwork for a significantly enhanced synthesis approach, numerous other pivotal innovations were concurrently introduced. These include the formulation of a base-metal-catalyzed sulfonylation, a KRED-catalyzed dynamic kinetic resolution, and a straightforward SNAr reaction conducted in aqueous media. Collectively, these advancements culminated in a markedly abbreviated synthesis route (comprising 9 steps as opposed to the original 16 steps) and a 75% reduction in process mass intensity (PMI). Furthermore, the revised protocol eliminates the dependency on third-row transition metals and toxic solvents, thereby enhancing the sustainability profile of the synthesis process.

There has been a growing emphasis on advancing sustainable practices in manufacturing industries worldwide. This emphasis stems from heightened concerns regarding environmental impact, resource conservation, and social responsibility, prompting manufacturers to adopt sustainable approaches across their production processes. The introduction provides an overview of the imperative for sustainable practices in manufacturing, highlighting the importance of integrating sustainability into operations. By embracing sustainable principles, manufacturers can mitigate their environmental footprint, enhance operational efficiency, strengthen stakeholder relationships, and contribute to global sustainability goals. The methods outlined focus on utilizing tools and models to assess and execute sustainable manufacturing practices, customizing products for adaptable and environmentally-friendly processes, and emphasizing strategic planning and operational management. Additionally, the article presents the realization of a sustainable and flexible manufacturing system, addressing sustainability and flexibility across various production levels. It aims to advance the current state of the art by addressing four principal challenges: provisioning support tools for Industry 4.0 in sustainable production, managing product configurability, navigating flexibility in production systems, and integrating hardware and software flexibility through reconfigurable robotics and machine learning methodologies.

Section 2 delves into the discourse surrounding sustainable manufacturing, highlighting its significance and implications within industrial contexts. **Section 3** elaborates on the methods employed, with a particular emphasis on customizing products to foster adaptable and environmentally-friendly manufacturing processes. Furthermore, strategic planning and operational management strategies are underscored as crucial enablers for facilitating adaptable and environmentally-friendly manufacturing operations. Lastly, **Section 4** encapsulates the ensuing discussion and conclusions drawn from the preceding discourse.

2. Sustainable Manufacturing

The nexus between manufacturing activities and their environmental impact is steadily gaining recognition. Contemporary perspectives within manufacturing organizations now acknowledge the necessity of integrating considerations for progress, profitability, productivity, and environmental stewardship. Enhancing environmental stewardship and sustainability has emerged as pivotal objectives for manufacturing enterprises, alongside the imperative of maintaining profitability and productivity. These facets are increasingly perceived as integral components of the strategic agenda pursued by manufacturing entities.

A. *Manufacturing and the Environment*

Manufacturing strategies have predominantly revolved around assessing production processes through the lens of the volume/variety matrix pertaining to products. In contemporary discourse, however, manufacturing strategies have evolved to encompass a broader spectrum of considerations, extending beyond mere product and process evaluations [13]. This modern approach incorporates additional parameters such as organizational practices and philosophical underpinnings, thereby yielding a more comprehensive and nuanced perspective on manufacturing strategy. Moreover, this contemporary framework acknowledges the technological dimension inherent to manufacturing operations, recognizing the significant influence exerted by technological advancements on manufacturing processes and outcomes [14]. The intertwining of manufacturing operations with the natural environment is progressively being recognized. Efforts to integrate considerations of environmental impact within manufacturing strategies often involve the utilization of expressions designed to assess the environmental impact (EI) on society. Among these expressions, a common formulation is $EI = P \times A \times T$, where P, A, and T represent population, affluence, and technology, respectively. The constraint of population is inherently challenging, while affluence is increasingly sought after by individuals. Consequently, technology, characterized as the organizational knowledge base, emerges as a pivotal variable that can be enhanced to mitigate environmental impact. Within the realm of technology, which encompasses the knowledge domain of an organization, efforts to reduce environmental impact are paramount. The category of technology pertinent to environmental considerations in manufacturing is influenced by the following three factors [15-17]:

- Product: In the domain of manufacturing strategy aimed at fostering environmentally sustainable products, a pivotal approach entails integrating a design process that systematically evaluates environmental ramifications throughout the product's lifecycle. This approach commonly incorporates methodologies such as Design for Environment (DFE) and Life Cycle Analysis (LCA).
- Designing products with environmental benignity in mind not only facilitates their initial market introduction but also sustains their viability over time. For instance, product flexibility enables the implementation of environmental enhancements such as material substitution while concurrently preserving competitiveness. As the trend towards heightened product customization is anticipated to reduce product life cycles, the significance of flexibility is expected to amplify accordingly.
- Process: Environmental enhancements within manufacturing processes are intrinsically associated with a suite of strategies encompassing reduction, reuse, recycling, and

remanufacturing. A paradigmatic approach, known as zero-emission or closed-loop manufacturing, conceptualizes the manufacturing system as an industrial ecosystem. This approach mandates the integration of waste or by-product reuse mechanisms within the manufacturing system, thus necessitating robust capabilities for pollution prevention, such as substitution, and waste reuse. Moreover, the ethos of flexible manufacturing necessitates the incorporation of material flexibility within manufacturing equipment. This enables the accommodation of fluctuations in material flows, thereby bolstering sustainability while concurrently upholding competitiveness. Notably, the adoption of more efficient and recyclable packaging designs exemplifies a tangible avenue through which sustainability in packaging can be augmented.

- Practices: A significant environmental determinant shaping organizational manufacturing protocols pertains to ISO 14000 certification. While this certification framework can provide foundational support for organizational practices, its mere attainment does not guarantee substantive environmental enhancements. Rather, practices must be strategically employed to drive manufacturing improvements, leveraging complementary initiatives such as benchmarking and performance measurement. These mechanisms serve as strategic tools for managerial endeavors, aiding in the formulation and perpetuation of novel environmental programs and technological advancements within manufacturing operations.

These three factors exhibit areas of intersectionality and mutual dependence, fostering synergistic relationships. While technological advancements may originate from within an organization, the majority of developments, particularly those of strategic environmental significance, stem from collaborative efforts across multiple organizations, often with governmental involvement and endorsement. Notably, industry consortia play a pivotal role in this regard, exemplified by initiatives like the European Eureka program, the National Center for Manufacturing Sciences in the United States, and Eco factory in Japan. Each of these consortia maintains a pronounced research focus on environmentally conscious manufacturing practices and technologies. Consortia assume heightened significance in nations characterized by limited technology transfer and diffusion across industries, such as Canada and the United States.

B. *Manufacturing and Sustainability*

Sustainable manufacturing emerged as a derivative concept of sustainable development, a term first coined in the 1980s to address multifaceted concerns including environmental degradation, economic growth, globalization, social disparities, among others. The concept of sustainable production was formally introduced at the 1992 United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, serving as a blueprint to facilitate the transition of both companies and governments towards sustainable development agendas. Ongoing scholarly endeavors, undertaken by numerous researchers, continue to explore and elucidate these interconnected domains. Various definitions delineate the scope of sustainable manufacturing and production [18-20]. For instance, the U.S. Department of Commerce delineates sustainable manufacturing as the creation of manufactured products that utilize processes minimizing adverse environmental impacts, conserve energy and natural resources, prioritize the safety of employees, communities, and consumers, while maintaining economic viability. Conversely, the Lowell Center for Sustainable Production characterizes sustainable production as the generation of goods and services employing processes and systems that are non-polluting, conserve energy and natural resources, ensure economic viability, guarantee safety and health for workers, communities, and consumers, and foster social and creative fulfillment for all labor participants [21-23].

C. *Needs to Enhance Manufacturing Sustainability*

The present analysis underscores the imperative of integrating sustainability principles, design for environment strategies, life cycle assessment methodologies, and other pertinent tools within manufacturing frameworks and associated decision-making structures. Various specific requirements are identified to further bolster sustainability within manufacturing [24-27]:

- Approach: A more holistic and integrated approach towards sustainability is warranted, one that encompasses economic, social, environmental, and other pertinent dimensions. Such an approach, extending beyond individual company boundaries, holds potential to foster greater sustainability across the manufacturing sector.
- Methods and tools: Augmented methodologies and tools tailored for manufacturing are essential to nurture and fortify sustainability endeavors.
- Data: There is a pressing need for more detailed, comprehensive, and robust datasets to underpin environmental impact assessments and sustainability evaluations throughout the entire product life cycle. Standardization of such data, wherever feasible, is imperative.
- Manufacturing company practices: Manufacturing enterprises should embed sustainability principles into their operational fabric comprehensively. Beneficial practices include enhanced measurement and monitoring of sustainability metrics, establishment of company policies and governance structures prioritizing sustainability, intensified efforts to mitigate environmental footprints, cultivation of a corporate culture and working environment supportive of sustainability objectives, heightened awareness of sustainability among suppliers and customers, responsive adaptation to their sustainability requisites, and proactive engagement with the community to advocate for sustainability.
- Government policies: Governments and relevant regulatory bodies must integrate stronger considerations of sustainability, environmental factors, and clean processes into policies, programs, and operational frameworks. This necessitates collaborative efforts among internal and external stakeholders.
- Research: Collaborative research initiatives, spanning industry and academia, are imperative in the domains of sustainability, manufacturing, design, and environmental impact to drive meaningful advancements and innovations.

To sum up, advancing sustainable practices in manufacturing requires a multifaceted approach that integrates economic, social, environmental, and other pertinent dimensions. Such a holistic approach, extending beyond individual company boundaries, holds promise for fostering greater sustainability across the manufacturing sector. Augmented methodologies and tools tailored for manufacturing are essential to support and fortify sustainability endeavors effectively. Furthermore, there is a pressing need for more detailed, comprehensive, and standardized datasets to underpin environmental impact assessments and sustainability evaluations throughout the product life cycle. Figure 3 illustrates the key contributors to sustainable manufacturing. In this regard, manufacturing enterprises must embed sustainability principles into their operational fabric comprehensively, encompassing measurement, governance, mitigation efforts, corporate culture, supplier and customer relations, and community engagement. Governments and regulatory bodies should integrate stronger considerations of sustainability into policies and operational frameworks, necessitating collaborative efforts among stakeholders. Additionally, collaborative research initiatives spanning industry and academia are imperative to drive meaningful advancements and innovations in sustainability, manufacturing, design, and environmental impact.

Figure 3. Key contributors to sustainable manufacturing.

D. Importance of Manufacturing Sustainability

The imperative for companies to adopt sustainable manufacturing measures and strategies is manifold and progressively gaining recognition within contemporary discourse. For instance, the escalating attribution of climate change to anthropogenic activities underscores the potentially severe ramifications, prompting heightened awareness of the imperative for mitigative action [28-31]. Concurrently, the acknowledgment of resource scarcities and non-renewability, encompassing essential elements such as energy, materials, and water, underscores the vulnerability of operations to such constraints. Moreover, the global economic downturn witnessed in recent years has catalyzed scrutiny regarding the sustainability and resilience of prevailing business paradigms prioritizing economic growth at the expense of broader environmental and social considerations [32-35]. Consequently, pressures for sustainable manufacturing practices have mounted from diverse stakeholders, including employees, investors, suppliers, customers, competitors, communities, as well as governmental and regulatory entities.

3. Methods

The methods center on the utilization of tools and models aimed at assessing and executing sustainable manufacturing practices. Additionally, they focus on customizing products to facilitate adaptable and environmentally-friendly manufacturing processes. Moreover, strategic planning and operational management are emphasized to enable adaptable and environmentally-friendly manufacturing operations. Furthermore, modules are designed with a focus on reconfigurability and learning to augment the flexibility and sustainability of production processes.

A. Tools and models for evaluating and implementing sustainable manufacturing practices

Initially introduced in the 1990s, sustainable production represents a concept of longstanding significance rather than a recent innovation. J. Elkington notably advocated for the adoption of the

"Triple Bottom Line" (also known as the "Triple P" framework), which integrates economic considerations inherent to industrial management with environmental and social dimensions within a unified framework. Elkington posited that by embracing this multidimensional approach within the business model, it becomes feasible to enhance the quality and sustainability of delivered products, mitigate the impacts across the entire production and post-consumer phases, while concurrently fostering company growth. Nevertheless, contemporary realities indicate that some companies may still lack a comprehensive understanding of their current state and encounter challenges in implementing more sustainable strategies. The primary objective of this study is to address the initial research inquiry, namely, whether companies possess the capability to expeditiously evaluate the potential advantages derived from the adoption of Industry 4.0 (I4.0) technologies, particularly concerning sustainability considerations. In pursuit of this objective, our approach aims to develop an evaluation tool designed to facilitate swift and straightforward assessment of companies' positioning across the three sustainability pillars. These measures are instrumental in enabling users to comprehensively explore and ascertain the interplay between individual metrics and their respective impacts on distinct sustainability dimensions. There exists empirical evidence suggesting that the assessment of a parameter's impact necessitates consideration across multiple sustainability pillars. It is evident that an indicator may yield benefits across multiple pillars or, conversely, engender benefits for one pillar while incurring costs for another. Furthermore, evaluating whether a measure influences more than one sustainability dimension allows for a holistic approach to problem-solving, facilitating the identification of meaningful and practicable parameters for organizational application. Figure 4 delineates the categorization and clustering process to which each measure under scrutiny is subjected.

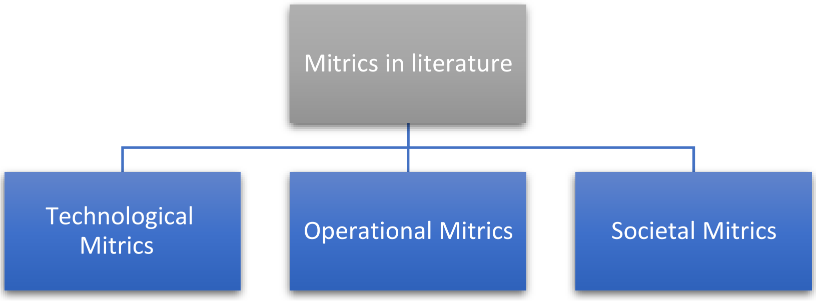
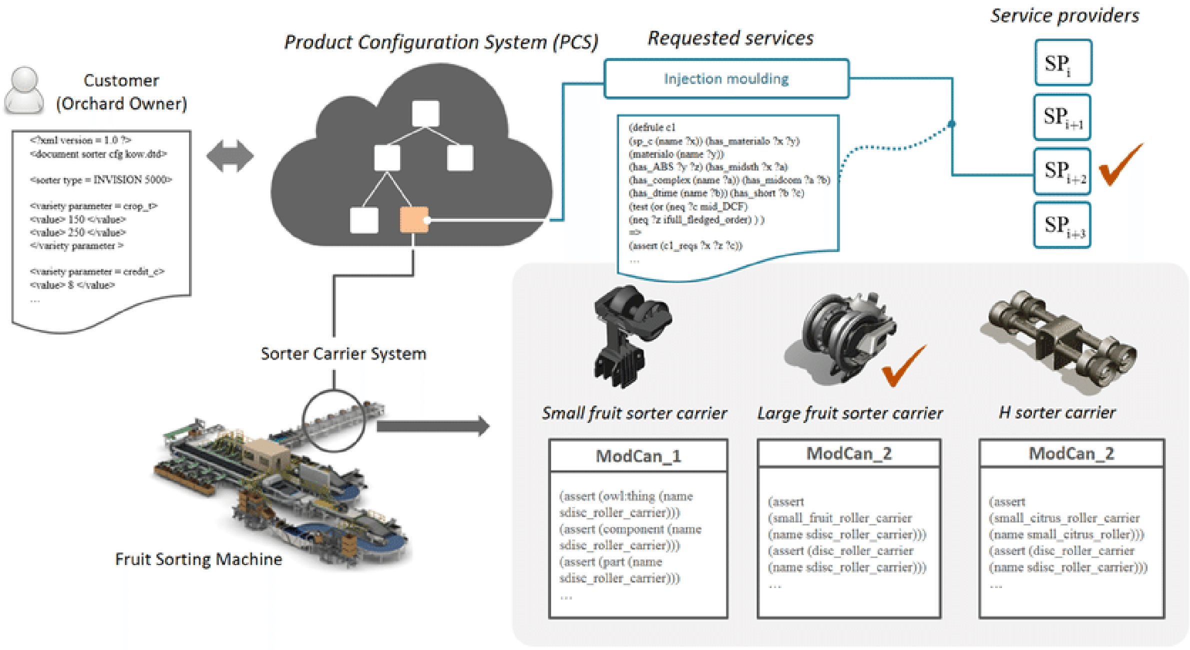


Figure 4. The categorization and clustering of sustainability measures based on diverse dimensions and criteria.

B. *Customization of products to enable adaptable and environmentally-friendly manufacturing*

By its inherent definition, mass customization production settings necessitate the agile and expedited manufacturing of small batches of products. Ideally, customers should be afforded the opportunity to customize their products freely, leveraging the manufacturing system's capabilities. This entails the system seamlessly translating customization requests into technical specifications, thereby minimizing the physical divide between configuration and production. In integrating sustainability considerations, customers should also be apprised of how their customization requests influence this aspect, empowering them to make informed decisions. In alignment with this premise, the subsequent challenge under scrutiny contributes to addressing the second articulated research question, namely, whether customers possess genuine opportunities to engage in customizing their desired products while conscientiously considering sustainability aspects. The study endeavor to investigate this matter through the conceptualization and development of a Smart Product Configuration System (SPCS). Figure 5 displays a scenario of the product configuration process. Indeed, product configurators represent a pivotal tool in bridging the divide between customer preferences and manufacturing capacities, operating within both business-to-business (B2B) and business-to-consumer (B2C) contexts, employing diverse methodologies such as rule-based, model-based, and case-based approaches.



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(has_ABS ?y ?z) (has_midsth ?x ?a)
(has_complex (name ?a)) (has_midcom ?a ?b)
(has_dtime (name ?b)) (has_short ?b ?c)
(test (or (neq ?c mid_DCF)
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Figure 5. A scenario of the product configuration process.

Various research methodologies investigate the utilization of diverse computational algorithms to facilitate product configuration, ranging from multi-objective frameworks to fuzzy logic and constraint satisfaction problems. The challenge inherent in mass customization initiatives, coupled with the adoption of advanced computational techniques such as deep learning methodologies, underscores a semantic disparity between customers and suppliers, particularly within business-to-consumer (B2C) relationships, where customers may lack sufficient expertise in unfamiliar product domains. Addressing this semantic gap, certain studies propose the introduction of a needs-based system, designed to translate natural language inputs into product specifications. However, within Engineer-to-Order (ETO) industries, the customer order decoupling point is situated early in the value chain, necessitating the integration of design and engineering activities into the value chain system. Consequently, beyond semantic specification descriptions, product design and engineering endeavors must be tailored to meet specific customer requirements. In this context, our study explores the integration of product design and engineering within the early stages of product configuration, facilitated by SPCS characterized by a dual functionality: firstly, through its front-end interface, providing users with a graphical user interface (GUI) for customizing desired products and submitting production requests, while receiving sustainability feedback from the system; and secondly, through its backend, serving as an integral component of the Multi-Agent System architecture

C. Strategizing and managing adaptable and environmentally-friendly manufacturing operations

Following product configuration, a pivotal component of production systems pertains to the planning and execution of production processes. Manufacturing Planning Systems (MPS) are primarily concerned with the planning of materials and resources. These systems can be seamlessly integrated with Enterprise Resource Planning (ERP) frameworks and typically operate on extended time scales, varying based on the sector, ranging from days to months. Conversely, Manufacturing Execution Systems (MES) are tasked with overseeing pertinent modules within a production line and must possess the agility to respond swiftly to unforeseen events as illustrated in Figure 6.

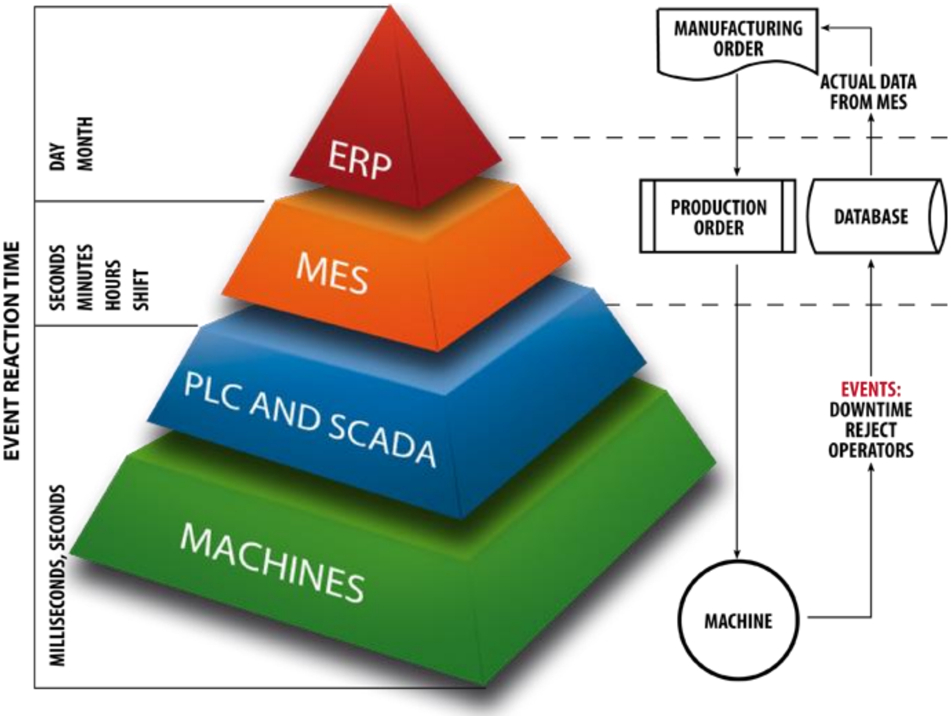

Figure 6. A scenario of the manufacturing execution systems (MES).

Traditionally, manufacturing facilities have been governed by hierarchically structured monolithic MESs, adhering to the ANSI/ISA 95 and IEC 62264 architecture. These systems are often only loosely interconnected with MPS, frequently relying on human intervention for communication and coordination. While this approach offers the advantage of centralized control over pertinent data and operations, it is accompanied by the drawback of maintaining and testing a complex system architecture. Within the framework of Industry 4.0 (I4.0), a Multi-Agent System (MAS) serves the critical function of interconnecting numerous software entities while endowing them with intelligence and communication capabilities. Specifically, the term "agent" denotes a software program that embodies a dual nature: firstly, it orchestrates the operations of a physical production machine, facilitating tasks such as transmitting and receiving machine signals and inquiring about anticipated task durations. Secondly, it represents the machine within the cyber network of agents, undertaking functions such as interpreting messages received from other agents, scheduling tasks for the machine, and communicating pertinent information to other agents regarding job durations, completion status, or any associated delays.

D. Modules designed for reconfigurability and learning to enhance the flexibility and sustainability of production processes

The fourth and final challenge is intricately linked to the third research question, namely, how can automation, automatization, and recent advancements in information technologies and artificial intelligence assume a central role in ushering in a new era of flexible and sustainable manufacturing? However, distinct from the third challenge outlined in the "Planning and Control of Flexible and Sustainable Production Processes" section, this challenge aims to address the issue of module-level reconfigurability within manufacturing systems. The objective is to imbue flexible production systems with a critical feature: the capacity to swiftly adapt to new processes and products to accommodate custom demands. In light of this objective, the fourth and final major challenge we confront pertains to the development of production modules that: (1) are easily reconfigurable, both at the hardware and software levels, to render them accessible even to non-professional users; and (2) are capable of incorporating various sustainability aspects at the production level. To fulfill these dual objectives within our proposed demonstrator, we envisage the integration of two complementary production modules: the Human-to-Machine (H2M) transfer manual assembly station and the Modular Robotic

Module (MRM). The former module serves to extract knowledge from manual assemblies, which is subsequently transferred to the latter module for automatic execution.

4. Discussion and Conclusion

In recent years, there has been a growing emphasis on advancing sustainable practices in manufacturing industries worldwide. As concerns about environmental impact, resource conservation, and social responsibility continue to escalate, manufacturers are increasingly compelled to adopt sustainable approaches throughout their production processes. This introduction provides an overview of the imperative for sustainable practices in manufacturing, highlighting key areas of focus and the importance of integrating sustainability into manufacturing operations. Through concerted efforts to embrace sustainable principles, manufacturers can not only mitigate their environmental footprint but also enhance operational efficiency, improve stakeholder relationships, and contribute positively to global sustainability goals. Moreover, the methods center on the utilization of tools and models aimed at assessing and executing sustainable manufacturing practices. Additionally, they focus on customizing products to facilitate adaptable and environmentally-friendly manufacturing processes. Moreover, strategic planning and operational management are emphasized to enable adaptable and environmentally-friendly manufacturing operations. Furthermore, modules are designed with a focus on reconfigurability and learning to augment the flexibility and sustainability of production processes. This article presents the realization of sustainable and flexible manufacturing system. The study comprehensively addresses sustainability and flexibility across various production levels to harness their respective benefits from a holistic perspective. Specifically, The article endeavors contribute to advancing the current state of the art by addressing four principal challenges: (1) providing support tools to explore the potential of Industry 4.0 (I4.0) in the context of sustainable production; (2) managing the configurability and customization options of products; (3) effectively handling the flexibility afforded by a production system equipped with rapid reconfiguration capabilities; and (4) integrating hardware and software flexibility through the utilization of reconfigurable robotics and machine learning methodologies.

Author Contributions: Conceptualization, M. H.; methodology, M. H.; validation, M. H.; formal analysis, M. H.; investigation M. H.; resources, author; data curation, author; writing—original draft preparation, M. H.; writing—review and editing, author; visualization, author; supervision, author; project administration, M. H.; author has read and agreed to the published version of the manuscript.

Funding: This article received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The author would like to extend their sincere gratitude to the Department of Aeronautical Engineering, College of Civil Aviation, Misrata, Libya, for their support and guidance throughout the research process.

Conflicts of Interest: The author(s) declare no conflict of interest.

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