sustainability

Perspective

Sustainable Manufacturing for a Circular Economy

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Abstract: The emerging circular economy paradigm and subsequently changing consumption patterns drive the manufacturing industry to more sustainable designs and operations. Not only the environmental standards, but the way firms conduct business in economic and social aspects also comes into the consideration of buyers and investors. In this article, the framework consisting of four sustainable manufacturing pillars of supply chain, materials, design and production, and management and organization is presented so that manufacturers can embrace relevant examples in their business activities and make further transitions toward a circular economy. The analysis revealed several sustainability-oriented agendas and techniques such as sustainable management of supply chains and materials, smart and lean production, servitization, and environmental/social/corporate governance principles can form a virtuous cycle of socio-economic and environmental value creation.

Keywords: sustainable manufacturing; circular economy; sustainable design and production; sustainable supply chain; socio-economic value creation

Citation: Kazakova, E.; Lee, J. Sustainable Manufacturing for a Circular Economy. *Sustainability* **2022**, *14*, 17010. https://doi.org/10.3390/su142417010

Academic Editor: Radu Godina

Received: 31 October 2022
Accepted: 2 December 2022
Published: 19 December 2022

1. Introduction

Being responsible for over 20% of accumulated greenhouse gas emissions, the manufacturing sector has been the third major contributor to the overall global environmental pollution (Figure 1). Given the high awareness of the need for better quality of life, the socio-economic impacts of manufacturing activities are also globally recognized. According to the UN Environment Programme report, both the production and the consumption sides of the industrial cycle carry significant harmful impacts on the environment in the form of toxic gases and acidic substances released, as well as the immense drainage of non-renewable resources [1] (p. 21). Although most of the deterioration can be accredited to the direct emissions stemming from "chemical reactions, and from leaks from industrial ... equipment" [2], indirect outflows also take up a substantial portion of the damage with not only the energy supply needed for running the factories, but the additional wastage created as a product of mass consumption. Hence, manufacturing processes and the industrial supply chain are among the most damaging factors, where timely industrial action and policy intervention are crucial.

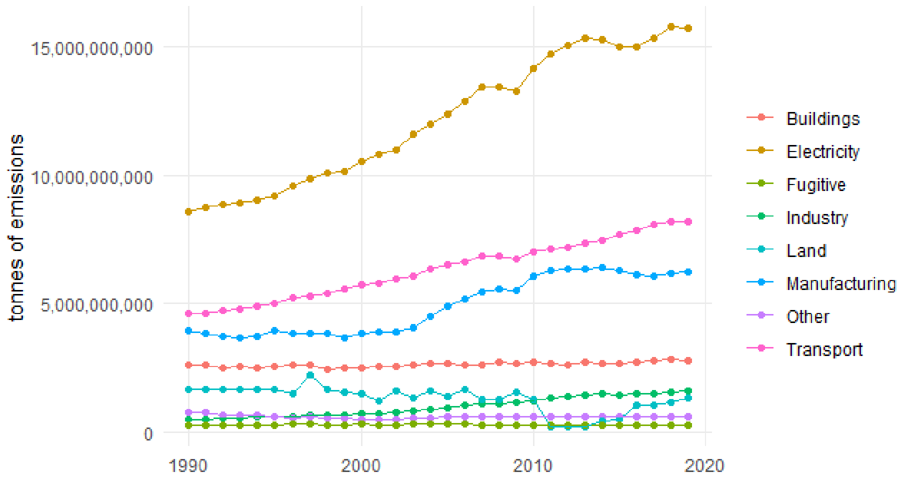

Figure 1. Major contributors to global greenhouse gas emissions [3].

While fossil fuels are mostly used for energy to power industrial activities and produce goods from raw materials, most of the emission-reducing technologies, such as toxic emission capture and storage, are still not in the mature stage of deployment [4] (pp. 1570–1572). For instance, in the US, the environmental damage caused by manufacturing takes up roughly 20% of the total deterioration and is predicted to increase dramatically by around 28% in 2050 given the ongoing trend of intense economic growth (Figure 2) [5]. The industry is constantly driven to take initiative in clean energy deployment and deep decarbonization.

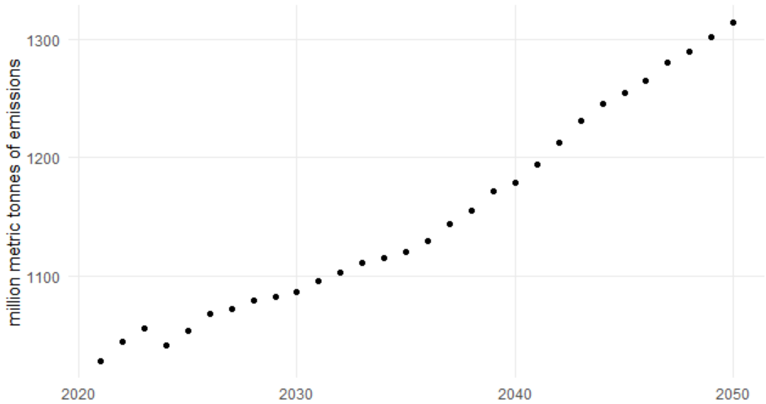

Figure 2. Manufacturing energy-related carbon dioxide emissions, 2021–2050 [6].

In addition to the environmental issues, the manufacturing industry makes significant economic and social impacts. In such major manufacturing nations as China, Germany, South Korea and Japan, the industry accounts for approximately 20% of GDP (Figure 3). The US manufacturing sector hired about 12 million workers in 2019 and accounted for almost 11% of the total output in the economy in 2020 [7]. With such continuous growth in the sector both in terms of incoming investments and value, as well as the industry's significant role in ensuring societal well-being through stable labor expansion and overall national and worldwide economic development, it becomes evident that the idea of sustainable manufacturing encompasses areas beyond simple eco-friendly characteristics of production. To clearly demonstrate the corporate initiatives, over 95% of the world's largest companies now annually report on environmental, social and governance (ESG) as well as managerial achievements with more than 70% pinpointing sustainability as a major competitiveness determinant in the current market and a crucial factor for profitability increase and cost reduction [8].

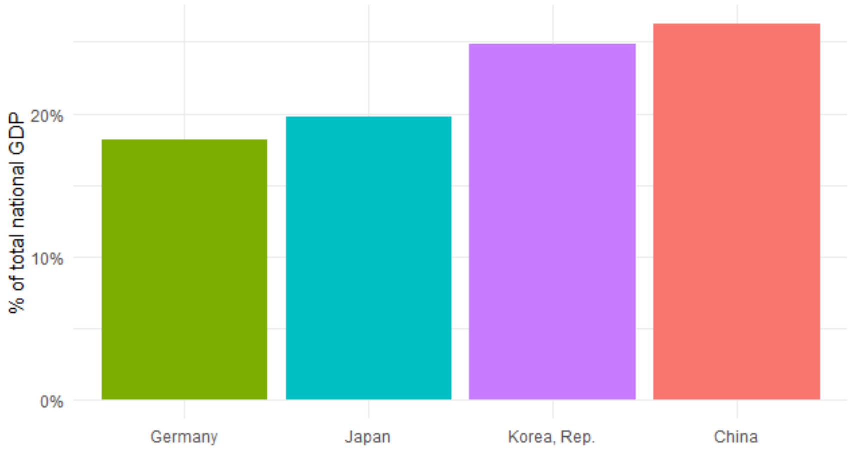

Figure 3. Value added in total GDP by manufacturing sector, 2020 [9].

Thus, the motivation of this article is to investigate the theoretical and practical basis for sustainable manufacturing beyond the simple production of "goods with minimum use of energy and natural resources, [and] maximum profit" into "economic and social dimensions" that touch upon the human-factor-based standards of equity and equality, and corporate responsibility [10] (p. 288). The objectives of this perspective article are to update the industry, policy makers and various stakeholders on the broader scope of sustainable manufacturing in the current circumstances and to report its latest practices to be taken into consideration for further innovative explorations and actions both within the academia and the industry. The research methodology is based on an overview of the latest studies and an analysis of leading company cases on sustainable manufacturing terminology and initiatives.

The analysis includes latest research and articles from scientific and business journals and digital platforms, as well as official documents on sustainable policies from governments and international agencies, published from 2010 to 2022. The reviewed cases are recent innovative sustainable actions initiated by global actors in such key sectors as retail, textile, biologics and medicine, food and beverage, automobile, and IT industries, which are reflected in the companies' corporate business and ESG reports, as well as official statements communicated by the management through digital channels. For the purpose of analyzing the statements and reports, a systematic review was administered using the framework of sustainable manufacturing for a circular economy, further described in Section 3.

2. Identifying the Scope of Sustainable Manufacturing

In its extensive form, sustainability has become the benchmarking standard for business management, which shapes the firm's external reputation for customers and investors and affects the decision-making at each level of the organization. Broadly, the major elements of sustainable manufacturing can be summed up as (1) high quality, affordable, and safe products/services available for people around the world, (2) profitable industry growth to create jobs and economic development, (3) conservation of the environment, energy, and natural resources, and (4) continuous improvement in safety and soundness in all factory floors along the value chain. Given this, sustainable manufacturing implies an integrated system of business and production operations comprised by sourcing, design and production, material use, and business management that is aimed at minimizing harmful environmental effects, promoting equitability and economic growth in a circular manner, and maintaining health and safety for humans involved in the processes.

In this section, we review the latest literature and its content to draw an up-to-date definition of sustainable manufacturing. As stated above, over the past couple of decades, the sustainable manufacturing concept has been broadened beyond a simple environmental scope. According to the U.S. Environmental Protection Agency, sustainable manufacturing is understood as "the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources" [11]. In addition to that, sustainable manufacturing is also highlighted to be promoting "employee, community and product safety" [11]. The urgency for the social and economic extension to the basic ideas of sustainability and development is further highlighted in academia. It is often argued that "social motivations are less dominant" [12] (p. 364) and are often overlooked in industry in favor of apparent green practices and aspirations.

Moldavska and Welo suggest that the stagnation or lack of sustainability practices in the manufacturing industry, including those beyond environmental initiatives, can be attributed to the unsettled unification of various theoretical approaches to sustainable manufacturing [13]. This lack of consensus between defining the scope and the essence of sustainable manufacturing as either a goal or a process significantly hinders the development in the industry. To address the identified concern, sustainable manufacturing is suggested to be identified as "a complex behavior pattern", which encompasses short- and long-run business objectives for environmental, social, and economic good as the end goal [13] (p. 752). In this sense, the key actions framed as "sustainability-oriented practices", such as initiation, implementation, and evaluation of sustainability metrics, should be implemented by an organization to reach the ultimate status of sustainable manufacturer beyond the potentials to "enhance natural environment" or "decrease the pollution" [13] (pp. 749–750). The research offers an integrated view on the concept of sustainable manufacturing, which touches upon the issues of not simply adjusting production activities into more environmentally conscious practices, but also the idea of manufacturing *for* sustainability, where it can be overviewed as a sustainability enhancer through its positive economic and social impact.

In a similar manner, Pang and Zhang propose the interconnected system where green manufacturing practices are embedded into a complex scheme, consisting of regulatory guidelines and immediate industry actions for adhering to higher environmental, social and economic standards [14]. In order to survive and prosper in a competitive and heavily regulated environment, manufacturers are expected to facilitate green innovation and, as a result, produce positive social and economic value. Thus, advanced "basis for policy decisions" and evaluation tactics are necessary, creating a cycle between the inner environmentally conscious manufacturing system itself and the external larger framework of economic social ecosystem [14] (p. 97).

As such, it can be concluded that the sustainability in manufacturing is a highly complex issue which touches upon the fields outside of the simplistic perception of green eco-friendly tactics but encompasses the regulatory, social and economic systems. However, the linkages between the theoretical vision of sustainable manufacturing and practical ideas of circular economy and managerial practices have not been addressed in sufficient detail. Such emerging concepts as reverse logistics, servitization and ESG management for net-zero production and socio-economic value creation challenges are to be examined through concrete industry cases for further research and strategy formulation. The following section examines the ways in which manufacturers operate their business functions in line with the given challenges.

3. The Key Areas of Sustainable Manufacturing

The systemic view of the sustainable manufacturing theories and practices is represented by the four areas as follows: sustainable supply chain, materials, design and production, and management/organization and policy-making that achieve the industry's sustainability and support the circular economy (Figure 4). Currently, manufacturing companies are increasingly held accountable for the whole of their product lifecycle "from cradle to grave . . . including emissions from raw materials, manufacture, transport, storage, sale, use and disposal" as stated by the World Business Council on Sustainable Development [15]. Although the regulations are imposed in the form of voluntary standards rather than direct sanction-based rules, stakeholder pressure is expected to continue globally for the corporations to place the sustainable issues high on their managerial agenda. Many manufacturers are already making a proactive transition to circular economy strategies since the model can provide not only the environmentally friendly image, but social and financial benefits for the firm. For instance, it is estimated that circular economy activities could save as much as $700 million of annual material costs in production and reduce a half of CO2 emissions by 2030 [8] (p. 17).

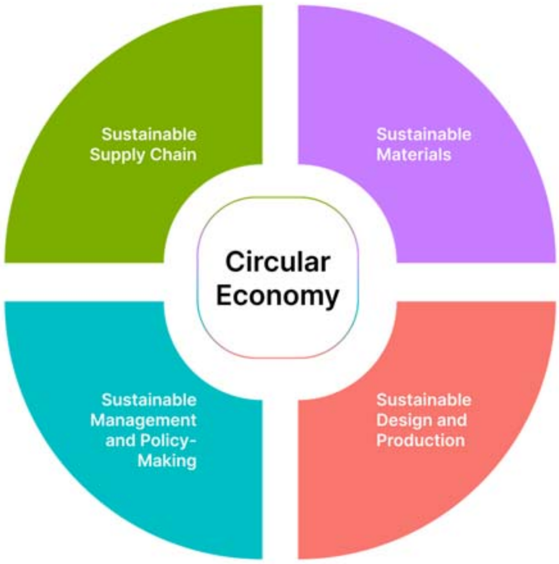

Figure 4. Sustainable manufacturing for a circular economy framework.

Circular economy is, then, proposed to be a set of closed-loop activities "designed to replace end-of-life waste disposal with material reduction, reuse, recycling, and recovery" [8] (p. 17). Its broader focus encompasses sustainability tactics far beyond generic recycling initiatives and attempts to prolong the life cycle of a single resource or material [8] (p. 17). As such, a circular economy, based on the principles of minimizing negative environmental impact and consumption of resources and maximizing economic benefits, can be the desirable end-goal of industrial initiatives concerning sustainable manufacturing [16] (pp. 1–2). On the path to zero-emission and zero-waste generation, the 3Rs of the manufacturing process in a circular economy are the following: reduce (minimizing the consumption of natural resources), reuse (materials and parts) and recycle (for additional value creation and proper disposal) [16] (p. 1) with detailed variations [17]. The proposed R backbones of the production approach suggest the benefits not only for factories, which can now gain significant cost advantage from reintroducing and reutilizing scarce resources, but also for the environment by significantly cutting down the amount of newly manufactured goods and materials.

In the following subsections, each of the four pillars of sustainable manufacturing that are connected to the circular economy's building blocks is discussed with the reference to environmental, social, and economic value determined.

3.1. Sustainable Supply Chain

3.1.1. Reverse Logistics as the Ultimate Green Supply Chain Initiative

The concept of supply chain sustainability generally encompasses the manufacturer strategies and efforts in evaluating and minimizing their harm while maximizing the advantageous effects of their product and service output on the environment and society [18]. Sustainability, in this sense, is almost always understood through the prism of green, environmentally sparing tactics throughout the stages of packaging and shipping. To introduce the initial forms of sustainability within the supply chain, manufacturing companies often opt for regional production and storage hubs to shorten delivery and return streams for swifter inspection, disposal, and parameter management [19].

The implementation of regional hubs and local production, then, can be understood as a straightforward and widely spread instrument of sustainability, which actively minimizes the initial wastage and potentially aims at creating circular economy and linkages through connecting the entirety of the supply chain back to front. As such, within the circular economy system, such a concept as reverse logistics has become a critical issue and most advocated-for sustainable action aimed at transitioning to the closed-loop entirety of manufacturing operations, which are originally focused solely on evaluating the product "shipped and delivered on time" as the ultimate last stage of the product life cycle [20]. Instead, reverse logistics considers the cases of proper disposal or recovery of the manufactured goods through the process of recycling and reusing, thus following the principles of sustainable manufacturing in regard to the environmental aspect. As such, the end-of-life of the product serves as the beginning renewal stage of its further life cycle, largely benefiting the protection of nature and minimizing toxic and e-waste, as well as avertable drainage of resources utilized for production. Moreover, reusing the materials allows the firms to regain the value of finite resources forming a more efficient production line [21] (p. 309). By analyzing the products' end-of-life data, manufacturers are also able to largely contribute to its further business value by designing a product with more user-oriented, and hence desirable and robust parameters, simultaneously extending its usage lifecycle and introducing an efficient disposal process for product disposal and potential reusage [8] (p. 17).

Being responsible for over 6% of the greenhouse evaporation and more than 1.7 million tons of litter [22], the food and beverage sector can serve as one of the significant innovators in the field of reverse logistics as the industry has undergone major transformations in pursuit of sustainable manufacturing. As the production process of bottles for drinks is an inevitable part of the food industry, the American Beverage Association of major soft drinks producers has united to pursue the initiative of "Every Bottle Back" to reduce the amount of recyclable plastic that is not being reused [23]. Having set a goal of creating 100% recyclable bottles, including tricky caps and labels, the Coca Cola Company and other major industry players have upgraded over 600,000 recycling containers in the US. As a result, the Association is expecting to not only significantly reduce the environmental damage caused by the production activities, but more importantly establish an efficient circular flow of raw materials utilized in the production process to prolong the life cycle of existing resources and regain their value.

3.1.2. International Labor Relations in Manufacturing Supply Chains

In pursuit of accelerating business and shareholders' value through improved profitability and reduced costs, with the help of open markets, organizations have started actively outsourcing parts of their supply chains on a global level [24]. The phenomenon has been largely promoted as a beneficial innovative initiative for both the developed and developing economies for the past 30 years in terms of enhanced labor opportunities and equally shared value between the core and the outside labor power [25]. For instance, according to Brookings, with more than ⅔ of the current production cycle being broken into at least two separate geographic locations, global value chains (GVC) are especially fruitful when considering the notion of each economy's comparative advantage. Whereas one entity is either unable to or uninterested in efficiently accumulating and utilizing specific, difficult to access resources and capabilities directly, another party can offer their facilities, materials, and human power as it is in the case of Vietnam, which has been one of the largest manufacturing and assembling value contributors globally. In addition to attracting solid investment into the developing economy, such a stance of a worldwide supply chain contributor has also allowed the country to boost their employment rates, granting over 12 million positions open in the exporting firms. In general, the trend for following export-led manufacture-focused industrialization path has been a go-to standard for several developing countries,] who have been largely pursuing efficiency- and resource-seeking foreign investments [26]. Thus, it has been generally assumed that the global supply chain

(GSC) is, in its essence, a widely forward-looking direction of the current production and trade patterns, where both the poor and the rich harvest benefits without more specific focused regards to the environmental, social, economic and other ethical issues GSCs and GVCs entail.

However, the negative sides of the GSCs cannot possibly be overruled from the picture of evaluating the current cross-border supply chain management of multinational corporations. Highlighting the idea of prosperous comparative advantage, global and, in some cases, domestic supply chains are some of the largest sources of further uneven distribution of value and growth on a global scale. According to IMD, whereas GSCs are intended to generate wealth and stimulate technological, economic, and social advancement of the Global South economies, they instead continuously force and deepen the gap benefiting the rich or "a narrow set of firms" and trapping the developing economies within the limitations of ensuring the completion of "low value-added and labor-intensive tasks". In the end, failure to capture value from exporting resources and capabilities to the advanced economies leads to the absence of prospects for future industrial transformation within the system [27]. Thus, not simply economic and growth-related perspectives for the developing economies, but the distorted notions of just and fair supply and value chains are often disregarded when reviewing the global supply network. In this sense, supply chain sustainability can no longer be treated from a single dimension perspective dealing with only environmental aspects, which have been largely discussed previously. Instead, under the umbrella term of supply chain sustainability, it is now essential to take into consideration all major "societal challenges" [28] (p. 8) when reviewing and administering the issue at hand, including the human rights agenda, long-term economic impact, as well as flexibility and resilience of the current supply networks.

The agility and resilience factors have been specifically emphasized as significant drawbacks of the GSCs during the COVID-19 pandemic, where stagnant cross-border trade and overall communication have exposed the vulnerabilities related to the "distributed global business models optimized for minimum costs" only [27]. This is to say that when putting all at stake of routinely minimizing the costs and enhancing efficiency of production, risks associated with the social issues are generally ignored or rather diminished. Putting an emphasis on efficiency and lower costs of fragmented GSCs and GVCs often leads to widespread inappropriate work conditions and endangered occupational health and safety within the workplaces; these factors are tightly connected, but geographically and managerially distanced from the producing corporations in charge of the network. A recent study on sustainable supply chains administered by Harvard Business Review identified that multinational firms find it more and more challenging to obtain suppliers at lower levels of the network who are able or willing to commit fully to "fair labor practices and environmental protections" [26] (p. 93). As such, the unregulated bottom-up violations result in "financial and social risks" for the top-level producing corporations due to the lack of proper understanding of sustainability on a level beyond only green initiatives at each component of the GSCs. In a similar manner, the UN Global Compact proposes a new framework of supply chain management largely based on the idea of sustainable procurement, which urgently highlights "human rights, fair labor practices … and anti-corruption policies" as integral and essential components of the present-day sustainability agenda within supply networks, where the corporation in control or a specific sustainability chief executive is expected to be in charge of ensuring the environment, social, and governance (ESG) performance metrics of the supply chain participants [24].

3.2. Sustainable Materials

Moreover, in response to exposed vulnerabilities and risks, recent research has identified it essential for manufacturers to transition in a large portion to a class of sustainable materials, which can be produced and reproduced "in required volumes without depleting non-renewable resources" and harming the ecosystem [29]. Accordingly, bio-based synthetics such as polymers and natural materials such as glass can be categorized as sustainable options for production as the usage of finite resources is not expected in the production, allowing the reduction of negative effects caused by traditionally utilized petroleum intensive materials. In addition to less harmful effects on the environment, sustainable materials are also proposed to be more durable, making them more favorable as an option in big-scale manufacturing in the long run [30]. However, sustainable materials are also promoted to be utilized in small-scale production for furniture and fabrics as in the case of IKEA, who is aiming to promptly switch to solely "renewable or recycled materials" such as cotton, wood, renewable-based plastic, recyclable metal, wool and bamboo by the year of 2030 [31]. In general, the transition to sustainable materials is often referred to as crucial due to the projected 10% loss of biodiversity and grand global environmental stress by the year of 2050, which will no longer allow the industry to harvest and utilize any of the natural resources and materials for production [32].

The progress of the circular economy notion in manufacturing is also especially evident in the transition from a simple waste reduction/prevention into a "sustainable materials management" circular model, essentially recognizing the materials at the standard end of their life cycle as the new potential production resource by conserving or recovering them. Significant advancements have been made from the policy-making perspective with zero waste and waste management programs across the globe, where Japan is recognized as one of the leading sustainable materials advocates [33] (p. 553). Through the program of "Sound Material-Cycle Society", the government of Japan has been aiming to tackle the problem of mass consumption and waste, as well as potentially raise national economic productivity via turning the exhausted materials into fresh capital. Founded upon the principles of 3Rs in response to the "economic stagnation" and other domestic and global challenges, Japanese sustainable material policies encourage the reuse of secondary raw materials through enhancement of proper disposal and recycling principles, share economy and accessible education, as well as constant benchmarking of the Resource Productivity index for the "resource circulation throughout the entire lifecycle" [34] (p. 32). With the index showing evident positive trends in the recent years, in 2018, Japan set a goal of achieving a rate of almost ¥50,000 to 1 ton of natural resources exploited, which is almost double the level of productivity of 2000 [35] (p. 3).

In this sense, biopolymers, or specifically biologically derived biopolymers, have been considered some of the most environmentally conscious, efficient, and widely used sustainable materials [36] (p. 2). Allowing multiple manufacturing-based sectors, ranging from medical to food industries, to gradually transition from non-biodegradable, often toxic materials, biopolymers continue to be the engine of circularity in the manufacturing activities from the beginning of one product's life cycle up until the emergence of the new one. With most biopolymers being conditionally compostable and biodegradable, these environmentally benign materials allow proper waste minimization and management for the products at the end of usage [37] (p. 465). Moreover, derived from primarily bio wastes such as agricultural trashes, or chemically modified from previously market-downgraded recycled materials, both natural and synthetic biopolymers allow the manufacturing industry to reintroduce previously exhausted production components in the new production line [38]. Biopolymers also represent an economically beneficial and viable alternative to the standard petroleum-based polymers, which are derived from the environmentally and financially costly process of burning fossil fuels [39]. For instance, Coca Cola has been forecasted to reduce its bottle production costs significantly through the PlantBottle transformative initiative with the corporation aiming at becoming free of its volatile petroleum dependence by 2030 and ensuring complete circular production through recycling and reusage of "plant-based" materials by the same year [40]. As such, the two essential characteristics of biopolymers, such as cyclicity of the resources and their economic viability, make them an appealing sustainable choice for the manufacturers in drug delivery, tissue engineering, construction, food, and other industries in response to the enforced policies and changing customer and investor perspectives [36] (p. 1).

3.3. Sustainable Design and Production

The product design stage is the defining phase of the manufacturing process as it essentially determines the costs, materials, and shapes of the future output. As such, the sustainability factor of the unfolding manufacturing process is also decided upon at the product design stage. Sustainable product design essentially entails redesigning parts of a particular product to enhance its environmental performance, reduce its disposal cost and raw material waste to either extend the product life cycles or intentionally develop them with the purpose and ability to be continuously reused or recycled. Given the innovative capabilities of rapid prototyping, additive manufacturing and 3D printing, companies can rely on them to ensure the sustainability factor of their product design at the very beginning stages of development without high costs and futile raw material usage. Sustainable initiatives in further stages of the manufacturing processes, advocated throughout the systems of smart and lean manufacturing, are also beneficial for lessening the environmental damage caused by the sector and transitioning it to a more sustainable pathway.

3.3.1. Transforming Conventional Manufacturing to Sustainable Smart Production

The undeniable immediate action to reduce the industrial carbon footprint is to navigate the already existing production processes into less emission-intensive levels. As discussed in the report published by the United States Environmental Protection Agency (US EPA), the main opportunities lie within the alternative fuels and energy efficiency agendas, as well as enhancing the pro-sustainability training process of employees directly involved in the manufacturing processes [2]. As such, the urgent need for standards, state-of-the-art technologies and proper facilities and resources, which are potentially able to prompt the fundamental transition from traditional to smart lean production, is largely emphasized.

Principally referred to as “inadequate” or “virtually nonexistent”, the standards for manufacturing have been found highly ineffective concerning the global goal of raising the levels of sustainability and efficiency of resources utilized in the production process. Both Morris in her report of the US National Institute of Standards and Technology (NIST) [5] and Abubakr et al. in the recent research on smart manufacturing have highlighted a major loophole in the current manufacturing modelling and regulations, which rely heavily on “the old paradigm” [41] (p. 1) of conventional manufacturing process models (UMPs) and blueprints and outdated green assessment criteria.

To be more specific, the NIST article suggests that the physical and digital paradigms of manufacturing processes are pictured as stand-alone phases, where the machines and the digital resources are not integrated enough. Thus, it leaves out the potential of employing the wide scope of the real-life data available to automate several processes and establish new baselines for the production according to the new significantly lower expected levels of energy and raw materials consumption. As proposed by the new NIST guide, physical UMPs can be appropriated in digital format as virtual models for gathering the existing data. Such digital transformation will make it possible for manufacturing model specifications and processes to be easily shared between factories and institutions to ensure the spread and advancement of knowledge on the sustainable optimization of the equipment and production chains.

In order to encourage such an innovative approach within the manufacturing industry players, stimulus in the form of a “stick” for the current manufacturing enterprises is crucial [5]. In this regard, Morris further argues that the NIST proposed standard guides on sustainability evaluation and the key performance indicators are expected to serve as direct drivers of the smart transformation. Acting as “basic measurement tools” of efficiency and sustainability of production, standards are to ensure a more environmentally friendly behavior within the industry on a regulatory level. In turn, it is predicted to urge the preservation and analysis of the existing practical knowledge and stimulate further scientific research for the continuous improvement in smart, green-oriented manufacturing. In a similar manner, the Italian Institute for Environmental Protection and Research has also suggested the development of an updated set of monitoring principles, which could further advance the existing zero-emission green Action Plan in Europe [42]. Fundamentally, the solution is expected to raise new indicators and more appropriate standards of the usage of resources and the level of the environmental footprint of manufacturing processes allowed. Therefore, the leading global economies are intending to first drive the industrial green initiative on a regulatory basis to then proceed to a complete emission-free and environmentally friendly production on a worldwide scale.

Abubakr et al. propose the advantage of specific technological concepts which are already applicable in manufacturing. In this sense, the new features, such as reliance on big data instead of complete isolation of information and the overall implementation of Internet of Things (IoT) and Artificial Intelligence (AI) technologies, are major boosters of the transition from conventional factories to smart production. To be more precise, the ability to harvest the existing pool of data is possible through the usage of smart sensors presented in the new generation of manufacturing assets, which collect and store data on several indicators ranging from the energy consumption amount to the output levels. In turn, IoT and machine learning techniques can be used to analyze and further share essential insights into the levels of environmental consciousness of the manufacturing site and the stages of the process that can be improved for a more sustainable outcome [43]. As a result, a fully automated manufacturing site where the levels of energy consumption, raw materials usage, and other key productivity indicators are constantly re-adjusted to their maximum efficiency without manual intervention is possible. Hence, large-scale factories can hope to achieve full automation of every process not simply without cost compromise, but through the additional improvement of the major processes and the reduction in expenses.

The given automation smart techniques are already heavily utilized in the first generation of smart manufacturing nowadays, additionally showcasing the effectiveness of them not only from the theoretical viewpoint of earlier discussed regulations, but in the practical realm. For instance, the US-based company Ericsson, known as one of the leading telecommunication equipment providers, has reformed their Tallinn factory into a smart digital-reliant production site. Ericsson Tallinn is not only concerned with the workplace safety and agility of the factory, but also seeking to achieve peak sustainability index through the implementation of wireless 5G connectivity technologies, IoT and AI [44]. Having identified their 5G capabilities as the key technology in putting the factory under the "smart" category, the company relies on it to foster the interconnected infrastructure of the whole factory for further optimization of energy and raw materials employed. On the other hand, the Tesla Gigafactories are implementing a more direct environmentally friendly approach. While also promising to operate under smart methods, the Gigafactory will actively utilize solar panels and other equipment for the potential transformation of the facility into renewable energy powered mode only. The car manufacturer is also aiming at creating similar versions of factories around the world, which will follow the most up-to-date standards of green production and sustainability. Such a feasible trend, which fosters market competition in larger production scope and cost-saving benefits on top of sustainability prospects, can become another pushing point for the factories, which are still reluctant to pursue the implementation of smart technologies in their production processes.

3.3.2. From Physical Products to Integrating Goods and Services

Servitization has been introduced as an effective business model which promises to actively pursue the circular economy's sustainable principles and greater industrial green aspirations. Generally described as "industries using their products to sell services" [16] (p. 3), the servitization model takes into consideration all the 3Rs of the circular economy by directly eliminating the waste, promoting the sharing of existing products and capabilities through the shift from traditional continuous manufacturing to Product-as-a-Service (PaaS) and integrated Product-Service (PS) systems. Both models attempt at solving not only environmental, but also more specific market problems of satisfying customer needs rather than simply creating a product, which further highlights the need for the shift for companies reluctant to embrace the zero-emission and other environmentally friendly concepts [45]. As such, the existing research is heavily focused on emphasizing the advantages of the current servitization models represented in multiple industries and potential greater benefits for companies, customers, and the environment.

One of such techniques under the servitization model is focused specifically on the reusing and reducing part of the proposed methodology, where a manufacturer remains the sole owner of a product and simply offers the goods as a service on a lease or subscription. In this case, the ownership rights do not transfer to a customer and a single product may be rented out and reused by several consumers until it no longer holds the appropriate economic value [46] (p. 361). For example, Correa in his research on sustainable servitization pointed out Xerox's copy machine and GE's jet services as some of the most renowned first-mover cases of a manufacturer providing their physical goods as rent assets, directly following the PaaS model. What is more important, Xerox has further improved their PaaS system by not simply leasing out their copiers to companies, but rather providing a service in the form of establishing proprietary "printing islands" in office buildings and directly copying the papers for the clients under the Managed Print Services program [47]. As of now, the company is aiming at achieving net-zero by 2040 through the radical servitization transformation and complete shift to the model of Everything-as-a-Service (XaaS) [48]. This transformation will become the driving point for Xerox in decreasing the production level of their machinery, which will significantly reduce their production costs, energy consumption, usage of raw materials and levels of toxic wastage caused by manufacturing [49]. Moreover, Xerox is actively pursuing actions in reducing the harmful environmental effects of both its products and services. Inevitably being based on the model of constant utilization of natural resources for paper production, Xerox has initiated a PS program called PrintReLeaf, which attempts to give back to the forestry system [50]. As such, the manufacturer employs their AI and IoT capabilities to measure the customer's paper expenditure and replants the equal number of trees that were harvested to produce the customer's paper consumption. This way, Xerox is making an effort at creating the circular sustainable flow of their production cycle by offering not only their immediate product as a service, but also handling the damaging environmental impact caused by the subproducts of their service.

Another example of circular production servitization is the Product–Service model initiated by Hyundai Automotive Enterprise, largely discussed by Han et al. in the article on "product-related" servitization. Hyundai, the company which is best known for their car and car parts manufacturing capabilities, has undertaken one of the most innovative solutions in servitization models by initiating proprietary remanufacturing and service stations for "recovering mechanical sub-assemblies", which come directly from their customers who have purchased Hyundai cars in the past [16] (p. 11). As such, by actively pursuing circular economy business model of reusing and fixing old car parts and directly recycling those which are no longer of a proper market value, Hyundai does not simply reimburse the whole production system in pursuit of zero-emission and more efficient waste management goals, but also significantly lowers its manufacturing costs and prolongs the whole lifecycle of their physical products and complementaries. Hence, the reusing and recycling of Hyundai directly promotes the pillars of the circular economy by shifting the focus from production of new goods to continuous market flow of the existing products, services, and materials.

In the end, reverse logistics methodology, transition to sustainable materials and sustainability-oriented product design make up the proper management framework, which suggests taking into consideration the entire product's life cycle: from material extraction to its end-of-life management. This way, it is possible to uncover alternative ways to "conserve resources and reduce costs" by reviewing each stage closely to cut down the usage of toxic materials or completely transform the end-of-life management of the product by disassembling it and allowing it a second life [51]. To ensure such an approach, the manufacturer is largely expected to maintain close, servitization-based communication with its consumers to extend the usability of the product to the fullest by offering proper maintenance and return at the end of life.

3.4. Sustainability Management and Policy-Making

However, sustainability encompasses a broader concept, going beyond the ideas of adhering to environmentally friendly tactics and ensuring the zero-emission goal achievement as it inevitably touches upon and affects the society and economy. In this sense, "navigating the turbulence" is an inevitable step that each manufacturing company has to take in regard to their sustainable management to further preserve their reputation, as well as adhere to the political, economic and social pressure [26]. In response to such vulnerability, major multinational corporations are largely expected to address the problems in a prompt manner through enforcing efficient sustainable management at all levels of their manufacturing process in order to protect their operations and reputation. This is to say that even if a manufacturing corporation is highly committed to promoting sustainability at the top level, "headquarters" of their value chains and significant violations of sustainability goals at other levels of the chains may "discredit any global efforts", as well as cause significant social and economic damages [24]. To further stimulate market efforts and emphasize manufacturing sustainability as a societal challenge, the UN Global Compact has initiated standardized guidelines of the Decent Work Toolkit for Sustainable Procurement, the Guide to Traceability and the Practical Guide for Continuous Improvement, which point out such aspects as human rights and anti-corruption in addition to environmental protection [24].

The companies are then encouraged to plan out and introduce sustainability into their business models through long-term prospects for collaboration and value generation rather than relying simply on "short-term financial considerations" [24]. The framework of the 3Ps of sustainability standing upon the idea of the Triple Bottom Line of People, Planet and Profits has become the stepping stone for a prosperous, forward-looking production formation [52]. The People component here is vital as the whole concept revolves around humans, namely consumers, investors, and workers, who are in need of "higher social and environmental standards" due to worsening conditions of both spheres and general market inclinations [28]. Accordingly, corporations are expected to plan, produce, and deliver sustainability of manufacturing operations in all aspects of the network, starting from utilizing particular green materials, ensuring safe working conditions and environmentally conscious packaging to implementing innovative decisions in new servitization-based revenue models within the circular economy. Moreover, sustainable initiatives in production are found to be leading to increased profitability with a total of 18% higher ROI among sustainability-oriented corporations [53]. This represents the correlation between sustainable management and value performance of business despite general beliefs in the trade-off between productivity and commitment to higher ethical standards. Finally, the Planet aspect of the sustainable strategy is specifically concentrated around the finite number of natural resources actively utilized as raw materials in production, which not only results in consumption greater than can be afforded, but also pollution, climate change and biodiversity loss [52]. Key stakeholders increasingly expect the product makers to address sustainability issues above.

Internal Sustainable Management Initiatives

Based on this, according to the MIT CTL and CSCMP, almost 50% of all multinational corporations have already incorporated long-term, urgent plans and strategies for sustainable management, while at least ⅓ of other manufacturing companies seem to refuse or postpone implementing such initiatives [54] (p. 14). Moreover, most of the sustainability-oriented multinational corporations have put special emphasis on societal challenges discussed above, such as "child labor, forced/slave labor, and worker welfare/employment quality" [54] (p. 14). Whereas indicating that the majority of executives and, in general, top companies recognize sustainability as an integral part of any current production and business line such an inclination towards "non-negotiable" social issues clearly demonstrates the shift towards broader, more integrated definition of sustainability in the industry going beyond environmental duties [54] (p. 14). Given that, management and organizational structure should parallel the corporate effort by the alignment of profit-making with the ESG requirements in order to make the manufacturing sector fully sustainable through the direct ESG tactics.

In this sense, the governance notion takes the lead in forming the overall concept of sustainability in the manufacturing industry as a sector with primarily physical output-based goals. Despite that, governance here, in particular, is not simply about constructing a strictly theoretically formal rulebook to ensure the corporation's eco-friendliness, diversity and inclusivity, but promoting sustainability as an imperceptible moral and ethical standard through transparency and dialogue within all the levels of the organization. As such, the whole network of stakeholders involved, starting from manufacturers and suppliers to the headquarters at the managerial level, are expected to be committed to the shared idea of the long-lasting prosperity of the corporation and the potential benefits it can offer the society and the environment [55]. According to the McKinsey report, strong ESG propositions lead to significant financial, resource-saving and productivity-related uplifts, as well as healthy and favorable relations with the customers, the government, and the investors. The commitment of all stakeholders involved, specifically in the manufacturing industry, where the network of actors is tightly linked together in the chain of production, logistics and transportation, is especially crucial for both establishing and promoting ESG ideas. The manufacturing industry is one of the examples, where the managerial practices have long been aiming to address sustainability from the viewpoints of both the advantages of recovering asset value and minimizing waste to recover and promote the financial and environmental sides, as well as the making of socially conscious, educated decisions for the social good.

Subsequently, the notion of circular economy's reverse logistics again comes into light under the imperatives of sustainability. Focusing on non-linear waste-reducing and environmentally sustainable manufacturing lines among production companies can support their internal smooth transition to ESG principles and further adherence to them [56]. Among such actions is implementation of net-zero energy and emission control and monitoring, as well as workforce-empowering technologies and equipment, which are being continuously accelerated within Industry 4.0′s automation tightly embedded into the sustainability objectives. Namely, Samsung Biologics department in their most recent report has disclosed its corporate activities and metrics in response to economic, societal, and environmental challenges, where climate change response strategies take a significant part of the company's most urgent goals. In order to shift to a low-carbon and transition fully to a 3R carbon-neutral production in the long run, Samsung Biologics is continuously building energy reduction plants, chemical substance and water reuse facilities with promising results of over 30% lower emission rate in 2022 in comparison to 2021 [57] (p. 76). Moreover, the biopharmaceutical industry is one of the major producers of hazardous wastes, such as toxic, chemical, sharp, infectious types of litter, which cannot be recycled or disposed of in an ordinary manner [58]. In order to address industry-specific waste management issues, in 2022, Samsung Biologics introduced an AI-based recycling collection robot, which facilitates the system of recycling potentially recoverable materials [57] (p. 81).

However, Samsung Biologics does not simply address only the green elements of sustainability tactics, but largely focuses on the human aspect of the "Environment, Safety, and Health" part of its business. Safety training, work environment standards and risk prevention have been pinpointed as the focus of the corporate ESG report, where Samsung accentuates the importance of regular efficient health management among its employees within all the levels of the organization [57] (pp. 72–73). Targeting such an aspect of their internal corporation structure, Samsung Biologics expresses its aspirations in fostering durable growth of the company and ensuring a reliable cooperation with its partners. As a result, Samsung Biologics effectively demonstrates that sustainability in regard to societal challenges also fosters the organization's productivity and efficiency, as well as evident business growth through strengthened labor-management cooperation, female leadership, safety-led leadership and enhanced work–life balance [57] (p. 69). Proving to enhance Samsung Biologics' long-term sustainable growth, the company's most recent survey showed an upward trend in the employees' corporate satisfaction, which further facilitates the company's positive reputation in regard to efficiently communicating and addressing immediate societal challenges.

By making a sustainability department with a C-level officer and an ESG committee on the Board of Directors, sustainable manufacturing leaders work across many functions, including investor relations, operations management, and finance [59]. This indicates that sustainability in manufacturing is increasingly evolving around capturing long-term value for all stakeholders, not only shareholders. In many manufacturing firms, the management responsibility of ESG programs is often allocated to investor relations personnel, financial or marketing teams. More organizations, however, are making a stronger commitment to ESG by designing special sustainability-oriented positions, such as Chief Sustainability Officer, a Vice President or Director of Sustainability [60]. Ultimately, it is proposed to be the major responsibility of the CEO to oversee and advance a wide range of ESG strategies for a meaningful result. As clearly illustrated throughout the article, a company's sustainability strategy can successfully unfold in all triple dimensions for the benefit of the environment, people and business when guided by the corporate management in a concerted, ceaseless manner.

4. Results

Based on the content analysis of the current theories and practices executed and proposed in sustainable manufacturing for circular economy, a summary framework highlighting environmental, economic, and social value of the objectives can be drawn (Figure 5). The framework emphasizes the importance of sustainability of the methods and operations at each pillar of sustainable manufacturing including (1) supply chain, (2) materials, (3) design and production, and (4) management/organization and policy-making.

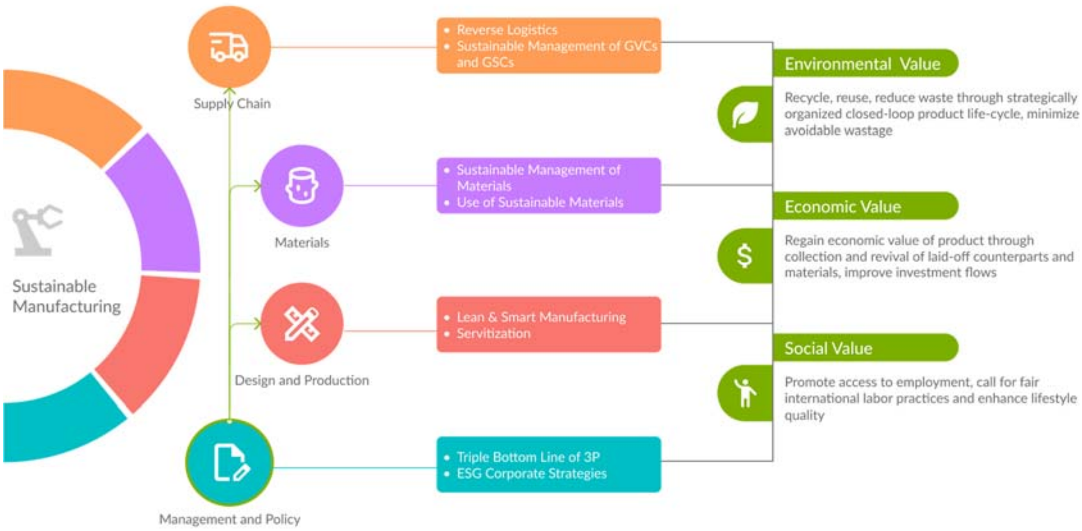

Figure 5. Sustainable Manufacturing Pillars: Summary of Reviewed Theories and Practices for Environmental, Economic and Social Value.

To begin with, reverse logistics and implementation and management of GSCs were identified as two of the most prominent sustainability- and circular economy-oriented initiatives at the supply chain level. Although offering valuable eco-friendly and socioeconomic developmental characteristics in theory, the actual alignment between the effects proposed and achieved was proven to be challenging in terms of the social aspect of GSCs specifically. On the other hand, sustainable practices within the Materials area directly solve the shortcomings of the social element by introducing non-toxic and biodegradable raw materials into the industry, which has demonstrated to significantly enhance the quality of human lifestyle in addition to dramatic positive impact on the environment and economy. In a similar manner, the processes and operations of smart manufacturing and the innovative servitization business models of PaaS and PS were found to be encouraging the cyclicity of the 3R system for minimization and prevention of waste, as well as improving the value of the product manufactured and offered in the early development stages. Lastly, framework of Triple Bottom Line and the ESG investment standards applied internally through ESG committees and aligned strategies further supplemented the practices at the managerial and policy levels through the significant emphasis on socioeconomic and green thresholds and principles of corporate responsibility.

It can be further noted that the managerial tactics and straightforward guidelines and benchmarks formed under the corporate governance take the major role in the framework of sustainable manufacturing for circular economy. Overall, proper synthesized and centralized system of green, social, and financial objectives set by internal ESG boards and top managers who are committed to ethical and responsible corporate behavior for long-term organizational growth was identified to be essential for ensuring adherence to sustainability at all levels of the manufacturing business. Written guidelines and rulebooks, as well as behavior, morals and ethics raised of all stakeholders involved directly affect not only the successful execution of practices overviewed, but also whether the frameworks and goals are accepted and adhered to throughout the whole pipeline, as can be seen from the cases represented.

5. Discussion

Subsequently, each case overviewed and analyzed can serve as the basis for understanding the current landscape of sustainable initiatives in manufacturing for a prosperous circular economy and identifying potential areas for improvement and further research and argumentation. Based on this proposition, Table 1 provides an outlook on the recent Environmental, Economic and Social agendas within the manufacturing industry.

The table largely suggests that both the Environmental and Economic aspects of the circular economy initiatives in manufacturing are at the mature stage of development, being actively advanced and continuously improved through clear-cut business and managerial agendas, which in turn generate analyzed practices throughout the entirety of the manufacturing pipeline.

In particular, as for the Environmental factors, the common features, such as minimizing greenhouse gas emissions (GHG), reducing pollution and maximizing the firm's resource efficiency could be identified. Among the practical solutions for approaching the objectives is decreasing the overall factory production in order to avoid excessive burning of fossil fuels in the manufacturing stage through the implementation digital prototyping and modeling, as well as circular channels and methods allowing the closed-looped lifecycle of a good or a material. Moreover, direct initiatives for reducing the carbon and other toxic footprints of manufacturing activities through establishment of centralized disposal systems and transition to natural, biodegradable, and recyclable materials are also widespread in the industry. Finally, the firms are actively pursuing the goal of minimizing the utilization of scarce resources and instead focusing on recovering and reintroducing already existing components and products into the market, which also embodies significant economic value for the business. This is to say that the Economic layer of sustainability is heavily emphasized by both the industry players to showcase their profitability and cost-saving methods to investors, and the policymakers to attract more manufacturers to the circular economy playground.

Table 1. Discussed sustainable manufacturing practices for circular economy through the lens of Environmental (Planet), Economic (Profit), and Social (People) Values.

	Environmental Planet			Economic Profit	Social People	
	GHG *	**Pollution**	**Resource Efficiency**	**Profitability and Cost-Saving**	**Working Conditions and Employee Relations**	**Public and Communities**
Reverse Logistics: Coca-Cola's Every Bottle Back	Minimizing usage of factories to manufacture new materials and products	Reusing and refurbishing goods at the end of life cycle	Initiating circular flow of raw materials and goods through firm-led centralized circular channels	Streamlining the resource/product back into the production pipeline or reintroducing directly into market		
Green GSC and GVC Management: UN Global Compact Guide	Controlling dead mileage, green optimizing transportation and introducing performance baselines	Minimizing carbon footprint of the entirety of supply chain	Encouraging the creation of resource-efficient supply and value chains	Enhancing reputation and investment flows	Centralizing control over labor practices, promoting fair standards and rights	Establishing mutual exchange of workforce and capabilities between economic South and North
Sustainable Management of Materials: Sound Material-Cycle Society	Minimizing emergence of new production cycles and burning of fossil fuels	Reducing wasteful and toxic disposal	Promoting circularity of goods and raw materials	Turning exhausted material into fresh capital and overcoming economic stagnation		Spreading education on accessible higher quality lifestyle
Sustainable Materials Implementation: Bioplastics	Shortening the period of product degrading stage in the landfills	Providing a compostable and biodegradable materials	Reintroducing bio-wastes and laid-off components and materials by chemically modifying them	Representing beneficial and viable alternative to the standard petroleum-based polymers		Promoting principles of non-toxicity, biodegradability and aiming at utilizing primarily natural materials at core
Smart Manufacturing: Tesla's Gigafactory, Ericsson, etc.	Implementing digital methods of rapid prototyping, 3D designs and virtual testing	Analyzing and predicting necessary for efficient workflow production levels through AI and big data	Assessing and predicting necessary resource and material usage level without over exhaustion	Improving throughput, prompt decision-making and minimizing downtime	Maximizing workplace connectivity and substituting hazardous manual labor by machinery	
Servitization: Hyundai, Xerox	Offering goods as a service on a lease or subscription	Providing centralized firm-led product and subproduct circularity channels for reuse and reimbursement	Initiating proprietary remanufacturing and service stations for product and parts recovering	Lowering new manufacturing costs and prolonging the whole lifecycle of a single marketable good and complementaries through additional recovery and repair services		Maintaining close relationship with the customers and the public, learning and solving market needs promptly as soon as they are advocated
ESG Corporate Strategies: Samsung Biologics	Controlling and monitoring thresholds at every level of the production process, building energy reduction plants and facilities	Introducing new data-based technologies for proper disposal of hazardous waste, promoting specific standards for handling toxic wastage across all levels	Recovering certain valuable non-biodegradable materials		Promoting sustainability as an imperceptible moral and ethical standard through transparency and dialogue within all the levels of the organization, enhancing corporate satisfaction through employee trainings and benefits	Reducing public risk of handling or dumping hazardous waste through setting proper guidelines and centralized system and channels for recycling, reusing, and repairing

* Greenhouse gas emissions.

However, it can be inferred that the Social layer is still left underdeveloped industry-wise despite numerous challenges brought up, including the risk of spreading gruesome labor practices and unfair employment conditions at the lower levels of the manufacturing chain, which tend to be geographically out of reach for the firm headquarters in control of establishing the social standards. While it is advised that organizations construct a sustainability rulebook and promote the values on psychological level as well, it is often found difficult to benchmark and measure the effects of the incentives given the presence of key external stakeholders, such as local communities, which has a dramatic impact on the firm's reputation. Thus, the factual and practical condition of the social aspects of sustainability in manufacturing should be put under a more detailed examination as most cases show that social improvements often appear to be positive externalities of environmentally friendly practices rather than its own direct objectives or results.

In this sense, there is a vivid distinction between proactive and passive approach to societal issues undertaken. While internal social welfare practices provide clear-cut techniques and metrics such as education and incentives for employees' enhanced welfare, positive external social practices for customers, local communities and the general public can be transfigured as a byproduct of main green operations and processes. Due to this complex nature of social factor of sustainability, the case of disassociated international labor standards in GSCs revealed sustainable societal objectives and practices to be highly prone to abuse and misinterpretation. As such, it is essential to recognize the potential negative connotations of seemingly sustainability-oriented frameworks and take into consideration potential ways to resolve them both in the academia and the industry through real practices and further research.

6. Conclusions and Recommendations

The emergence of the circular economy is a promising progression toward more sustainable manufactured goods with a prolonged life to minimize energy and resource use as well as the environmental damage caused by the overall industrial cycle. With continuous re-enhancement of a good's economic value, the circular economy is expected to be the enabling system behind sustainable materials, logistics, production and disposal processes. Industry-wide sustainable practices should be driven by top management as corporate social responsibility starts from the head organization rather than its hubs and lower-level facilities, which are responsible for fragmented pieces of the manufacturing pipeline. It is, therefore, important to design a centralized structure, which could initiate sustainability at all four pillars discussed and ensure that all the related levels act in a congruous manner.

The social aspects of sustainability for the manufacturing sector requires more precise and metrics-oriented approach. The geographically scattered nature of manufacturing pipelines makes the industry vulnerable to social challenges such as lack of fair labor standards, diversity and employee safety. It is essential to further investigate the origins of such issues in manufacturing and identify possible ways to reduce the risks by setting explicit indicators and standards for measuring and comparing manufacturers' performance in social realm of sustainability.

Author Contributions: Conceptualization, J.L.; methodology, J.L.; software, E.K.; validation, J.L.; formal analysis, E.K.; investigation, J.L. and E.K.; resources, J.L. and E.K.; data curation, E.K.; writing—original draft preparation, E.K. and J.L.; writing—review and editing, E.K.; visualization, E.K.; supervision, J.L.; project administration, J.L.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. This research was supported in part by Soonchunhyang University's research project #2022-1346.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was supported by Soonchunhyang University's research project #2022-1346.

Conflicts of Interest: The authors declare no conflict of interest.

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