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Can Companies Assess Sustainable Manufacturing Practice?

Joosung Lee [1,*] and Elena Kazakova [2]

[1] Enterprise School, Soonchunhyang University, Asan 31538, Republic of Korea
[2] Graduate School of International Studies, Yonsei University, Seoul 03722, Republic of Korea; elenakazakova@yonsei.ac.kr
* Correspondence: jsl@sch.ac.kr

Abstract: While firms actively try to adopt sustainable manufacturing practices, no assessment framework has been readily available for them to measure and manage their production efforts for sustainability. In this study, an assessment framework for a firm's sustainable manufacturing is developed, and applied to the case of a major chemical company in Korea. Detailed assessment criteria are proposed based on reviews of the latest literature, and the scoring results of the company are presented. In addition to resource saving and environmental sustainability, the socio-economic impacts of the manufacturing industry are captured and evaluated in the framework. The case study and assessment results show that the company has innovative technologies and management practices, while it must still achieve larger-scale outcomes in environmental as well as social dimensions. This paper further contributes to advancing sustainable manufacturing by demonstrating a method for measuring a firm's status with respect to sustainable manufacturing and a concrete case for other companies to utilize in their initiatives in this area.

Keywords: sustainable manufacturing assessment; ESG case study

1. Introduction

The manufacturing sector has long been identified as an essential generator of socioeconomic and industrial growth, with an estimated value of over 16% of global GDP [1]. Indeed, in 2022 alone, the manufacturing industry contributed approximately USD 5 trillion to the Chinese GDP, with the US showing a similar favorable trend with the sector generating around USD 2.5 trillion of the total GDP in 2021 [2]. As a result of such prominent influence of industry at a global scale, the idea of sustainable manufacturing is specifically recognized as a "business imperative", where environmental, social and economic standards are to be prioritized above short-term monetary aspects, yet highlighted as being beneficial for the firms' long-term competitive and financial stance [3].

The overall concept of sustainable manufacturing can be judged as precise guidelines specifically coined for the sector to address and adhere to the larger Sustainable Development Goals (SDGs) advocated by the UN. According to previous research, the end-goal of the initiative within a given industry should be the creation of, and contribution to, a circular economy, under the four pillars of supply chain, materials, design and production, and management and policies [4]. Corporate governance in this case is encouraged to take a major role in ensuring the transition toward the sustainable prosperity of the company [4]. That is because management is in charge of setting and executing short- and long-term policies and strategies, as well as planning solutions and objectives for the supporting companies of the other proposed pillars, which strongly imply a globally scattered network of resources. As such, managerial decision-making is largely expected to set the environmental and socioeconomic responsibility, adhering to the SDG tone for all the corporate and geographical layers of the firm [5]. This clearly suggests that when assessing the success of corporations in sustainability metrics, while quantifiable achievements are to be taken into account, the review and evaluation of green, socially and economically responsible

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Citation: Lee, J.; Kazakova, E. Can Companies Assess Sustainable Manufacturing Practice? *Sustainability* **2024**, *16*, 5259. https://doi.org/10.3390/su16125259

Received: 5 March 2024
Revised: 14 May 2024
Accepted: 6 June 2024
Published: 20 June 2024

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strategies, tools and practices determined and implemented by the higher layers of the corporation also need to be highlighted.

Having identified the overall sustainable manufacturing framework encompassing the supply chain, materials, design and production, and internal corporate and externally imposed standards, it is now important to propose an integrated assessment framework that is aimed at characterizing and evaluating a firm's assessable performance metrics within the highlighted pillars, as well as the pro-sustainability strategies in progress. The latter are argued to be crucial for reviewing and specifically benchmarking the management of a manufacturer or manufacturing network of an organization in question. This, we argue, allows the proposed framework to be less inclined to presume ethical flaws related to accounting for solely quantifiable end-performance metrics or solely ongoing sustainable strategic plans, both of which tend to reflect fast corporate greenwashing and misleading of socially responsible consumers for short-term financial gains [6,7].

Thus, based on an extensive literature review, the present paper attempts to design a sustainable manufacturing assessment, which could account for sustainable end products and processes, as well as plans for and other aspects of manufacturing still in progress of green and socioeconomically responsible transformation. We also apply the developed framework to a case study of one of the leading South Korean manufacturers, LG Chem, to validate the framework, and practically demonstrate how a firm's sustainable manufacturing cycle, stemming from managerial strategic decisions, can be monitored and evaluated for further efficiency improvement and weakness identification.

2. Literature Review

As a part of the total sustainable manufacturing initiatives, it is important to reiterate the significance of recognizing quantifiable estimates, such as clear-cut results in improving efficiency in terms of the ecological and socioeconomic footprint of the industrial activities. Generally, these may include environment-related achievements associated with the Reduce–Reuse–Recycle (3R) circular economy mandates aimed at net-zero commitments [8], as well as socioeconomic achievements that are highly influenced by the concept of Corporate Social Responsibility (CSR), all of which are aligned with the creation of a circular economy and the overall SDG agenda [5,9]. For the environmental part specifically, reduction in emissions, waste generated, materials transition and efficient allocation of exhaustible resources could be regarded as proper calculable estimates to assess the progress of the sustainability of a manufacturer in line with the 3R rules of responsible industry processes [10]. For the socioeconomic part of the sustainable projection, the US department of energy primarily identifies worker-related metrics, including employment, employee satisfaction and basic needs coverage rates [11]. Some of the larger community-related measurements, such as the rates of public trust and product responsibility, number of responsible partnerships formed and the overall financial performance, can also be regarded in the same dimension [5,11].

However, it might be argued that the approach of only taking into consideration end products and finished transformative sustainable processes with quantifiable achievements and metrics might be flawed. In some cases, sustainability estimates and other numerically backed-up claims could be considered easily manipulated to attract socially responsible consumers and investors, or to comply with imposed regulations. For example, in the case of one of the leading fast food manufacturers, McDonald's, a completed and actively reported transition from plastic to paper straws was eventually revealed to be in effect not a greener alternative, as the company's chosen *green* material was ultimately non-recyclable or reusable, albeit organically produced [12,13]. Indeed, specifically environmental-related corporate claims tend to be over-exaggerated, while actions implemented are only perceived to be sustainable, but realistically result in adverse outcomes, due to the pursuit of short-term gain [14]. That is largely because the effects of the seemingly pro-ecological innovation are not weighed at each product lifecycle stage, where green material usage at the manufacturing phase could potentially lead to failure of the waste-management

system of the firm. Hence, it is possible to conclude that it is crucial for a sustainable manufacturing-assessment system to consider immediate and quantifiable results, which are directly linked to the manufacturing process itself, while also attending to those outside of its limited scope. Similarly, the acts of numerically overstating employee diversity and directly manipulating data to produce false claims in regard to essential employee satisfaction rates could be seen as another issue associated with relying solely on finished sustainable achievement indicators [15,16]. Along this line, some of the previously suggested sustainable manufacturing-assessment frameworks assume that managerial actions "must be formulated" in response to revealed weaknesses in achievement-based indicators to pursue structural changes, rather than short-lived bursts of sustainability [17]. All the discussions could then be viewed as heavily accentuating the evolving ongoing nature of the sustainability level in any sector to be evaluated.

It is undoubtedly operational activities and numerous enablers in the form of digital solutions, such as smart manufacturing facilities and equipment, methodologies, physical and digital tools, which essentially allow a firm to transform its processes into an ecologically and socioeconomically ethical value creation chain [4]. Despite that, the point that could be suggested is that not only can the implemented solutions and achievements be assessed, but also the initiated or currently ongoing transformative processes, strategies and tools selected. It could be argued that given the revealed importance of reviewing and evaluating the impact of sustainable transitions on the whole product life cycle, it is the corporate governance that is required to enable and oversee the extent of sustainability of manufacturing practices. As such, the earlier discussed sustainable manufacturing framework for a circular economy can be regarded as the basis for designing an assessment system for green and socioeconomic impact, and the progress of a manufacturing organization (Figure 1) [4]:

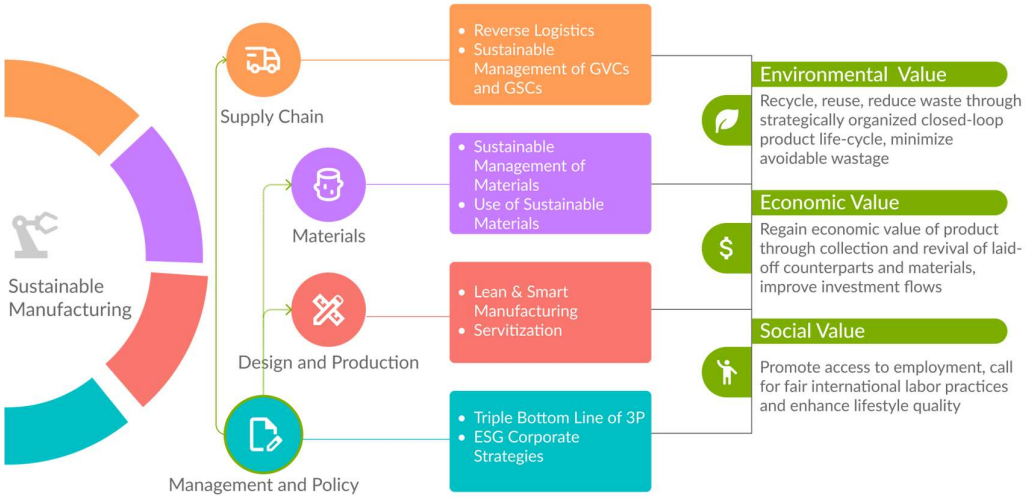


Figure 1. The Sustainable Manufacturing Areas [4].

In this sense, the strategies selected by the higher managerial structure for the sustainable transformation of manufacturing processes are essential to review to assess the quality and extent of long-term sustainability and its planning claimed via end results and quantifiable achievements. That is because the green and socially responsible mechanisms are to be dictated and set at the internal Environmental, Social and Governance (ESG) higher organizational level, which should feed into the whole firm's manufacturing network [4]. These mechanisms include not only direct rulebooks on sustainability practices and ethics within each level of the pipeline, but more importantly, a specific ESG board responsible for adjusting the organizational structure to sustainable goals and aiming to demonstrate quantifiable achievements through creating clear-cut general long-term vision, plans and a socially responsible corporate mindset. Without such governance, it

might be suggested that the detailed practices within each sustainable manufacturing pillar cannot be introduced and established, or, as has been demonstrated, lead to adverse outcomes due to disregarding the entirety of the product life cycle. Indeed, it has been revealed that low sustainable outcomes, capabilities and the overall "weak" performance of manufacturers are highly correlated with the lack of "internal. . . goals, strategies, and schedules" [18]. This, in turn, results in a manufacturer being unable to realize the potential of green and socioeconomically responsible processes and practices for communal and industrial welfare.

Then, the circular economy manufacturing technologies and practices determined and applied could be valuable assessment criteria alongside quantifiable achievements and end solutions. These may include tools, practices, strategies and support systems that together enable the firm to achieve ultimate sustainability of its manufacturing processes through setting the backbone of decarbonization and efficient usage and productivity of scarce resources on the environmental side, and value creation and extension of communal benefits on the socioeconomic side. Accordingly, innovative initiated processes of lean manufacturing, which include efficient data management and smart factories, reverse logistics and a sustainable supply chain, were identified as ongoing long-term methods to achieve sustainable manufacturing [19–21]. Although rarely providing measurable attainments independently, such practices, tools and strategies have proven to be the essential foundation for improving the sustainability of a firm, and displaying the long-term nature of the maintained agenda to adhere to the SDG. In addition to clearly demonstrating environmental advantages, such processes aid with socioeconomic value creation, as it inherently aids with the overall manufacturing productivity and efficient allocation of resources, including workers and their time, as well as improving workplace safety and making the manufacturing industry a more accessible working environment for different social layers [22,23]. All in all, sustainable support systems, practices and tools are all argued to build and sustain an imminent basis for the creation of a circular economy within the manufacturing sector. As such, such highly qualitative, ongoing processes and plans must be closely considered in a potential assessment framework, and cannot be ignored in favor of solely numeric end-performance metrics.

3. Methodology: Development of a Sustainable Manufacturing-Assessment Framework

By combining the sustainable manufacturing indicators and major sustainability areas identified in the literature review, an assessment framework based on 6 key dimensions and detailed measurements is proposed (Table 1). As has been largely discussed above, the managerial corporate governance decisions and responses to sustainability issues are suggested as the core of the framework, where essentially the evolving, in-progress planning and decision-making is to be taken under consideration alongside quantifiable end solutions, projects and products. To be more specific, the first dimension for sustainable manufacturing assessment is the corporate strategy to make necessary investment and voluntary compliance plans, and to prioritize social responsibility and green prosperity for sustainability.

The second dimension is organizational supports, well-established rules and structures to drive sustainable manufacturing, where the managerial control provides such systems for other corporate layers based on the larger primary strategy to adhere to the pro-environmental and pro-socioeconomic planning to achieve value creation and the extension of communal benefits to the external community. These dimensions of the designed framework allow the advocated and documented sustainability agenda actively sought after by a manufacturing corporation to be directly captured, capturing the main procedures, policies and deals in work, as well as green and social advancements to be made. This accords with the previously identified "evolving landscape" of the sustainability metrics and goals [24], as well as the key premise that environmentally friendly and socially responsible organization should stem from governing managerial activities [25].

Table 1. The Sustainable Manufacturing-Assessment Framework.

Sustainable Manufacturing-Assessment Area	Detailed Indices
Strategy	Vision and Investment
	Energy and Emissions Reduction Plan
	Social Responsibility
Supports	Organization
	Champion/Mindset
	Rules and Structure
Tools	Smart Factory/Equipment/Ecological Machining Methods
	Data on Materials and Processes
	Logistics Network
	Digital Transformation/Virtual Manufacturing
Practices	Value Chain (Sustainable Supply Chain, Life Cycle Analysis)
	Production Efficiency Increase/Cost Reduction
Achievements for the Environment	Reduced Energy and Resource Consumption
	Committed Action (Emissions Reduction, RE100, Net-Zero)
Achievements for Socioeconomic Value	Worker Welfare, Human Rights Improvement
	Safety
	Partnership

As such, the tools largely selected and pursued at a higher corporate level, and utilized in manufacturing processes, serve as the fundamental enablers in transitioning the concept of sustainability from corporate governance initiation strategy and support into direct practices and potential achievements, creating an efficient sustainability network in a manufacturing firm or facility. The third proposed dimension encompasses both hardware and software tools, such as smart and lean manufacturing facilities and equipment, ecological machining methods including sustainable CNC tooling and dry cutting, and information systems that aid a manufacturer with productivity that is also responsive to sustainability issues. These may include smart factories, servitization techniques, big data usage, virtual manufacturing and other essential methods adhering to the concept of Industry 4.0, which have a proven record of aiding businesses with directly adapting manufacturing to the newly selected green and socially responsible objectives, while also designing more informed strategies and support systems in the long run [26,27].

The value chain-wide production practices ranging from a more sustainable supply chain to RE100 and net-zero actions and achievements [28], which can largely be quantified and directly assessed, are proposed as the fourth dimension of the framework. To be more specific, supply chain-related indices include sustainable sourcing, procurement and vendor selection. Also a life cycle analysis should have material assessment and holistic management of a product from making to disposal with a sustainability viewpoint.

Finally, the fifth and the sixth dimensions of the proposed framework are numeric achievements in reduced energy and resource consumption, as well as reported quantifiable environmental performance via committed actions; and achievements in social value creation, including worker welfare policies and benefits, plant safety metrics, human rights improvement indices and partnerships for sustainability, all largely adhering to the general SDG goals discussed in the literature review. Weights can be determined and applied depending on the firm's priority and expert opinions. In this case study, equal weights are assumed when assigning the final sustainability score. The possible categorical scores have the ranking of Low, Medium and High, to indicate the level of sophistication achieved by

a company within the specific index, and are assigned empirically via systematic review adhering to the framework.

4. Case Study: LG Chem Leads Sustainable Manufacturing and Promotes a Circular Economy

To demonstrate the applicability of the proposed sustainable manufacturing-assessment framework, we selected one of the South Korean manufacturers in the field of refined biochemical products and chemical sciences, LG Chem. As the company's business objectives are focused on product creation from materials creation to reuse or disposal, it is widely recognized for the development of petrochemicals, renewable plastics, advanced battery materials and drug and vaccine solutions, with an estimated operating profit of USD 640 billion in the third quarter of 2023, and the leading rank in brand value among global competitors [29,30]. Despite direct involvement in a toxic waste- and carbon emission-intensive industry, LG Chem has claimed to pursue highly green and socially responsible business growth strategies and operational techniques under the "three new growth engines" and the 2050 Net-Zero initiative that is largely aimed at fostering innovative solutions and improving existing processes for sustainability within all the corporate layers [31]. According to the company, the 2050 Net-Zero approach is only one of the five major sustainability agendas, where LG Chem is set on maintaining its carbon emission levels at that of 2019 by 2030, and reverting them completely by 2050, by reducing footprint by 10 million tons annually [32]. The other four objectives include renewable energy transition for all business sites (RE100), environmental protection, responsible supply chain and, finally, the promotion of a circular economy to ensure the advances in other objectives by commercializing mechanical and chemical recycling, leveraging biomaterials, reducing landfill wastes to zero, quantifying supply chain carbon footprint for all product lifecycles and assessing social impact along the whole value chain [33].

Indeed, in 2022 it became the first Korean company to conduct a full local "product to shipping" Life Cycle Assessment (LCA), to evaluate the environmental impact of its manufacturing processes [29]. Based on the recent results obtained and previously declared agenda of "carbon neutral growth" in 2020 [34], LG Chem has been showing prominent assessable achievements in the areas of neutralizing its ecological footprint and making positive contributions to society via the creation of renewable energy, materials and techniques that can be assessed on all-round metrics, as well as displaying a clear-cut long-term agenda to adhere to the SDG goals through the top–down planning of business processes. Overall, it is evident that the vision of the corporation in regard to sustainability is well-established, with the top managerial layers recognizing ecological and socioeconomic responsibility as the "company's core competitive power" that is essential for efficient and prosperous growth [35].

The major foundation enabling the manufacturing in sustainability endeavors across all its value chain levels from corporate governance to operational processes is the "Cradle-to-Grave" methodology [33], which approaches product manufacturing from both upstream and downstream operations, allowing the pre-end product creation environmental and social impact to be monitored and controlled, as well as guaranteeing proper disposal, byproduct reuse or recycling. This framework largely aids LG Chem in meeting their key circular economy target by designing a closed wasteless, resource-saving and socially adequate loop of materials usage, production and management processes. As such, it is possible to integrate the existing LG Chem's Cradle-to-Grave approach with the earlier identified sustainable manufacturing framework based on the four pillars of materials, supply chain, production and management; and review the company's success in sustainable manufacturing objectives of strategy, supports, tools, practices, achievements for the environment and achievements for socioeconomic value, according to the present proposed assessment framework (Figure 2). As has been discussed, it is precisely the corporate governance design-making and planning in the form of higher management of the company that directly sets the tone of the sustainability agenda for the entirety of the value

chain of a manufacturing company through specific strategy, supports, tools and practices that directly feed into the pillars of supply chain, production and materials selection. It is possible to apply this sustainable manufacturing framework onto LG Chem to identify and qualitatively assess the extent of sustainability within the phases of their Cradle-to-Grave value creation process accordingly, as well as evaluate specific Achievements related to green and socioeconomic areas.

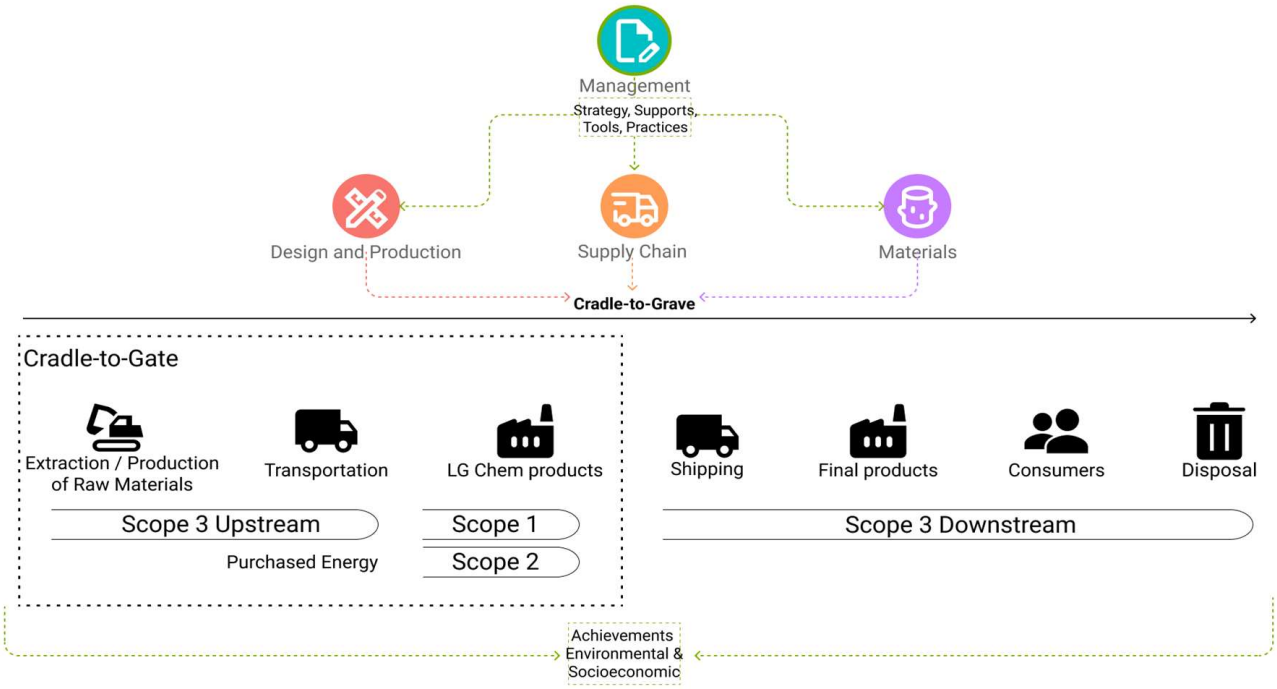


Figure 2. Application of Sustainability Manufacturing and Sustainability Manufacturing-Assessment Frameworks on LG Chem's Cradle-to-Grave Value Chain.

4.1. Sustainable Management

A company's sustainability strategy can successfully unfold in all environmental, human and business dimensions when guided by the concerted effort of top management, as have previously been advocated. The top managerial layer of LG Chem may serve the exemplary case of such top–down sustainability agenda, where the competitiveness of the manufacturer is presumed to be directly correlated with the sustainability metrics and objectives made and reflected in "all business processes, strategies, investments", and across the entirety of the value chain [36]. Championing sustainable transition and ESG initiatives in the manufacturing industry, the company's ESG committee and the CEO himself have been actively promoting the scope and variety of specific corporate positions and individual job training to further improve the green and socioeconomic stance of LG Chem. For the ESG committee specifically, three-quarters of the board consists of independent directors, which ensures less biased evaluation of the company's attainments in the field and fact-based sustainability reporting [29]. Since the establishment of the committee in 2021 and the 2050 Net-Zero agenda in 2020, LG Chem has been consistently showcasing clear improvements in all environmental, social and economic target areas, such as more efficient resource and waste management, pollution limitation and community-related metrics [29]. For example, the number of LG Chem's suppliers that initiated a sustainability assessment increased in 2 years by almost 5 times from its initial number in 2020. LG Chem is keen on expanding its sustainable innovation capability through the co-creation of renewable energy and responsible supply chains. As such, with the well-established strategy and support of corporate executives, LG Chem plays a central role in nurturing a circular economy ecosystem for sustainable manufacturing as an industry overall.

Apart from directly forming partnerships and collaborations with the present industry leaders, LG Chem's management has been demonstrating open innovation growth strategies in Korea. The corporation decided to invest USD 134 million to support ESG initiatives of ESG tech medium and small firms to extend the offer of potential collaboration to them under a strategic plan to advance a closed-loop ecosystem for key materials and sustainable supply chain [37]. Moreover, such a vision has led to the company pioneering its own Global Innovation Challenge to create a sustainable world, together with startups that want to scale their solution for global-sized impact in circular plastics, carbon utilization, renewable hydrogen and sustainable batteries [38]. As the company's first global event focused on startup collaborations, the LG Chem Global Innovation Challenge is intended to give startups and ventures globally working on sustainable solutions the opportunity to co-commercialize their technology, while advancing the existing ESG capabilities of the manufacturer. One of the major vision points declared by the managerial board of LG Chem for the event is to build a circular sustainable economy through global partnerships and direct funding in battery materials, drugs and other green development fields by 2025. By identifying and working with those with disruptive technologies worldwide, LG Chem is planning to expand its reach within the whole sustainable manufacturing network [39].

To obtain full control over the sustainability factor of the entire Cradle-to-Grave manufacturing network, the managerial layer of LG Chem has taken initiatives to expand internationally beyond the direct manufacturing processes of Scopes 1 and 2 that require the control of both direct and indirect carbon emissions, and has been proactively responding to the challenges of climate change within Scope 3 largely on a preemptive scale, before the newly announced reporting requirements. This is to say that although before 2024 it was simply a recommended practice to evaluate and inform about carbon emissions through the entirety of the value chain, including logistics and product disposal stages [40], LG Chem has been taking internally standardized actions regardless of the lack of strict regulation to track and minimize the harmful effects of its manufacturing processes [29]. Further, unlike most manufacturing companies whose capabilities fall outside of Scope 3 and dealing with the production processes and operations solely, LG Chem runs a diverse business portfolio with multiple fabrication processes in Scopes 1, 2 and 3 [29]. Based on that, LG Chem has included such elements as material procurement and in/outbound transportation in its life cycle assessment of carbon footprint by each value chain stage up to Scope 3, and is making plans to reduce the carbon emissions across all the scopes to achieve sustainability as a whole. This approach is crucial toward their major 2050 Net-Zero agenda, since it has been found that 65% greenhouse gasses are directly emitted during the supply and transport stages of Scope 3 [29]. Thus, the company's management is actively engaged in planning and actively executing the transition of LG Chem to environment-friendly raw materials and green supply chains to improve its environmental competitiveness in Scope 3, as well.

Finally, for the financing plan of the sustainability agenda in LG Chem, an essential part of the proceedings is invested via corporate ordinary, ESG and specifically green debt financing based on the proprietary LG Chem's Green Financing framework. Having issued the largest local bond offering estimated at 1.2 trillion won in 2021, followed by a USD 1 billion global green bond issuance the same year, the manufacturer has managed to obtain a significant level of financing "to accelerate ESG management in all business sectors, and further solidify the company's position as the leader in the field of sustainability" [41,42]. Most of the monetary assets obtained were planned to be put into the development of sustainable materials and resources according to the defined hierarchical priority-based project selection procedure determined both internally and externally via a Second Party Opinion [43]. Such a framework allowed LG Chem to ensure balanced and unbiased allocation of financing according to the overall aim and objectives of the bond issuance. As a result, a total of 9 renewable energy, circular economy and clean and clear transportation projects were finished in a 1 year timeframe, the most prominent of which achieved an outstanding 100,000 ton production enhancement of LG Chem's proprietary Polyolefin Elastomer (POE) recyclable plastic material [44,45]. The point that needs to be remembered

is that the managerial efforts of LG Chem in forming clear-cut sustainable strategy and support systems provide a secure foundation for the entirety of the manufacturing network within the firm, and ensure that all its levels are able to adhere to the agenda through defined vision, guidelines and the necessary resources presented.

4.2. Sustainable Supply Chain

LG Chem has been actively progressing its supply chain sustainability, requiring external parties involved to "apply and manage the same strict… standards" [46]. This directly stems from the earlier discussed major LCA initiative established by the company to construct and maintain a supply chain that is non-harmful to the environment, economy and community. At the same time, it acknowledges certain limitations associated with attempting to exclusively control the entire chain of suppliers, and assessing their environmental and social impacts. One of such examples is the international labor standards and regulations in the field of raw mineral procurement, where LG Chem has admitted to finding it "difficult to solve" such complex issues as children's labor, work-place safety and health, and responsible mineral sourcing on their own [46]. This resulted in the formation of an international proactive network, the Responsible Minerals Initiative (RMI), aimed at collaborative effort in information spreading and preventative measures tightening within the partnership circle of manufacturers and suppliers. Since then, the company has conducted a total of 13 independent audits of cobalt, lithium and nickel mines of their suppliers, including those of the major ones of Huayou Cobalt and CDM, to verify the extent of social and environmental responsibility present, which revealed that the material procurement process still held "room for improvement" [47], and required "corrective actions" [48].

To tackle the problems related to the inability to constantly evaluate and recommend appropriate solutions to the suppliers, LG Chem added a preemptive measure by setting sustainability evaluation criteria for battery and other material suppliers in 2019 [49]. As of now, the sustainability criterion takes up 20% of the total evaluation score, which is equivalent to the weight of product quality and development capabilities. As the importance of sustainable supply chains including ethics in battery material purchases is on the rise globally, the company values sustainability as importantly as product quality. Since the year of enactment, LG Chem managed to completely cut down the number of "high-risk suppliers" from 33 companies in 2019 without negatively impacting the overall number of regular suppliers, while also continuously maintaining an average number of roughly 220 sustainability evaluations annually from 2019 to 2021 [33]. Alongside the evaluation criteria, the manufacturer has developed a designated framework called the Supplier Code of Conduct to manage its supply chain through a specific set of guidelines and self-assessment checklists, which include areas of human rights and labor, health and safety, environment, sourcing of materials, ethics and management system [50]. This decision has enhanced LG Chem's own, consumers' and partners' awareness of sustainability issues rising directly from the material procurement sector, and has allowed the supplying companies to report on the issues for LG Chem to track "consistent implementation of their [suppliers'] social responsibilities" [33]. Accordingly, over half of the total number of LG Chem's suppliers successfully completed the ESG self-assessment with 43% of all the key suppliers having conducted the self-evaluation, signifying the urgency and high-priority nature of the Policy.

Nevertheless, this strategy has resulted in the increase in the number of suppliers "subject to sustainability assessment" by more than 1.5 times in 2 years since 2019 [33], and a prominent rise in the ratio of high-risk suppliers "subject to on-site audit" from 3.1% in 2020 to 11.8% in 2022 [29]. As such, apart from organizing check-ups and pinpointing specific areas of improvement concerning the environmental and social performance management of suppliers, LG Chem also intends to provide them with further education, monetary support and appropriate equipment to build a "decarbonized" and "safe" supply network [29]. The choice of appropriate strategy, support systems, tools and practices is rooted in the consideration of small and medium-sized enterprises being unable to efficiently and

sustainably innovate their procurement capabilities without significant financial burden. With the management tools in place and the aforementioned efforts to conduct product lifecycle analysis and create reverse logistics for circular resource utilization, LG Chem strives to produce tangible results for sustainable supply chain construction.

4.3. Sustainable Production

Since the sustainability agenda of the manufacturing industry should aim to first and foremost promote green and socially responsible production, LG Chem has been making a fast-paced transition to renewable energy for all of its manufacturing sites world-wide. Emissions created from the burning of fossil fuels during the manufacturing operations have been identified as the major industry pollutant [51,52], which has prompted global manufacturing leaders, such as LG Chem, to pursue renewable energy sources. As such, the company secured a power purchase agreement and a renewable energy procurement item through the domestic Green Premium Program to convert half of its energy usage to renewables by 2030 [53]. Consequently, in 2021, 344,528 MWh of renewable energy was used that enabled the reaching of RE100 in the Tech Center in Osan and Yeosu Complex, and in battery materials production in Leyou, China, which was estimated to be equal to "the amount that can be used by about 260,000 people" annually [54].

LG Chem's Cheongju plant, which produces a significant part of all the company's electronic, display and battery materials, began achieving almost 4% of energy saving in 2015 and 30% renewable energy by 2021 [33,55]. It has an energy-management system established to conform to ISO 50001, which consists of following the energy-management rules, improving the awareness of all employees and identifying actions for energy saving, and sharing of energy-management performance at the corporate level. For this, LG Chem operates a company-wide Energy committee to conduct annual energy and greenhouse gas performance reporting to set further goals and organize necessary investment planning. By setting a performance evaluation system built upon systemized statistical models to track and analyze key factors that influence energy consumption, the Cheongju plant has sped up LG Chem's long-term plans to power all its production through renewables or more sustainable methods. This can be seen with the overall renewable energy consumption of the manufacturer exponentially rising to 700 times its initial amount in 2022 with green procurement, and solar and wind power generation [29].

Furthermore, LG Chem has been witnessed to actively finance the construction of new advanced sustainable factories and appropriate stand-alone solutions that could respond to all the recent ESG standards and potentially more stringent regulations. One of such cases is the innovative addition to its already existing Daesan Industrial Complex in the form of 10 plants to produce and commercialize biodegradable raw materials, with projected production capacity of over 380,000 tons annually [56]. In the same vein, the manufacturing company has been actively utilizing LG CNS's smart factory platform called Factova that has been designed for the LG Group's production facilities to aid with processes and operations connectivity and automation, reducing production time from half a year to less than 3 months [57]. However, the major sustainability advancement in production for the manufacturer is the commenced construction plans for an eco-friendly EV batteries cathode plant, making LG Chem potentially the biggest cathode supplier in the US. The production site is forecast to maintain a production of over 10,000 tons based on solely renewable energy sources, and unlock numerous communal benefits by engaging the local workforce and small domestic power companies by 2027 [58]. As such, it can be concluded that LG Chem is displaying well-defined strategic investments, supports, tools and practices in regard to its production pillar and its sustainability advancement.

4.4. Sustainable Materials

As for the materials pillars, in 2021 LG Chem started their own subsidiary environment-friendly material brand called LETZero under the initiative of producing non-harmful substances without contribution to net carbon emissions [59]. The product line includes

post-consumer recycled (PCR) ABS, and plant-based renewables and biodegradables, with the environmental benefits having reached 40% reduction in CO_2 emission and 30% less water consumption and cumulative energy demand [60]. Heavily involving the mechanical recycling of discarded products that has proven to engage less energy than creating new materials from scratch, the manufacturer has been able to directly reduce waste volumes, while also cutting down on greenhouse gas emissions and diversifying its portfolio by actively engaging in the biodegradables and renewables market segment [60]. Specifically, the main manufacturing line includes developing eco-friendly products, such as PCR plastics and other bio balanced materials based on renewable oils and decomposable components, which enhances the corporation's resource circulation capabilities. As a result, it supplies environment-friendly materials made of 60% PCR polycarbonate to global IT companies, with plans to expand this product line, and has announced a prominent range of partnerships with global leaders in cosmetics, electronics and IT sectors, such as LG Electronics, Mura Technology, Innerbottle, CJ Logistics and Coupang in 2021 to further enhance "a closed-loop system from material procurement to recycling" [33]. It is specifically the collaborative efforts with the Korean e-commerce platform Coupang that allowed LG Chem to apply the post-consumer recycling technology to produce polyethylene (PE) film, as well as pellets to re-develop future delivery packages from remains put to waste. Furthermore, LG Chem's materials closed loop lifecycle is not limited to private firms' involvement, but also reaches the public sphere through a waste repurposing initiative between the manufacturer and one of the South Korean city administrations to procure "clean resources" via a new recycling facility [61].

In addition to the attainments related to LETZero, LG Chem directly pursued a partnership with a food processing company, Archer Daniels Midland (ADM), to set up two joint ventures, GreenWise Lactic and LG Chem Illinois Biochem, for the commercial production of pure lactic acid to manufacturer polylactic acid (PLA) used for the development of various high value-added biomaterials [62]. The joint venture is considered a highly beneficial strategy for "solving environmental issues such as climate change and waste plastics", by bringing innovative sustainable solutions, as well as advancing the companies' competitive stance in the market [63]. In the same vein, LG Chem has also partnered with Neste, the largest diesel producer, to produce synthetic resins from bio materials, which is expected to cut as much as half of the greenhouse gas emissions related to their manufacturing processes [64]. Instead of relying on non-degradable raw materials, LG Chem initiated the production of resins based on the vegetable oils materials supplied by Neste, the effectiveness of which material is identical to synthetic resins [65]. Consequently, the manufacturer has been able to obtain a special certification of quality for "Eco-Friendly Bio-Balanced Products", essentially becoming the first South Korean company to achieve a global industry standard in sustainability [66]. Such accessible achievements displayed by the corporation significantly uplift consumer confidence in the brand and competitive advantage in the external market, while markedly highlighting the linkage between the managerial sustainability strategy, supports, tools and practices aligned to fulfill the green objectives.

4.5. Overall Assessment and Implications

In the sustainable manufacturing-assessment framework developed, the evaluation criteria are strategy with a concrete sustainability vision and plan, organizational and structural supports, tools to enable green production and supply chains and practice in key areas leading to substantial achievements. From the goal of Net-Zero 2050 and sustainability policy to material, plant and reduce/recycle technologies and progress made toward net-zero, a wide range of sustainable manufacturing components have been assessed in this paper. To determine the scores (low, medium, high), a qualitative assessment was performed with the framework in Table 2. High means two thirds of the detailed indices indicate a high level of advancement whereas low is given when most of the indices still demonstrate an early stage in that category. For example, LG Chem's strategy is evaluated

to be high because its vision and investment as well as concrete planning for sustainable manufacturing are highly advanced. But practices are only medium as the company's global value chain management and production site upgrade are still limited. Note that qualitative yet objective evaluations have been made on the company's performance based on its published corporate reports and media/research articles. A more quantitative assessment is possible with additional data and research from sustainable manufacturing cases and outcomes.

Table 2. Assessment Results of Sustainable Manufacturing from this Case Study.

Category	Level	Analysis
Overall	High	The sustainable manufacturing level of the firm can be said to be high because of its first-mover initiatives, continuous efforts and tangible outcomes. It was comparatively higher in strategy and support due to the strong leadership of top management. More advanced tools and practices are to be implemented in the near future, while they are still in the development stage. The company needs to lead sustainable manufacturing among global manufacturers to be in the top category, and showcase the best practices for other firms in traditional maker industries.
Strategy	High	The investment plan is quite active, as the firm pledged billions of dollars in research, development, open innovation and other initiatives. Their Energy and emissions reduction plan is also aggressive, as it is the first chemical company to declare net-zero by 2050. Processes for reusing internal resources are in place, and efforts are highly encouraged to reduce waste generation and increase the efficient use of energy and materials. Corporate social responsibility has been the enterprise-wide philosophy, as it leads to creating positive social impacts throughout the value chain.
Supports	High	The company has separate organizations in ESG and sustainability. Rules and policy guidelines clearly exist as they apply to the firm's wide spectrum of business operations that include supplier relations. The sustainability documents elaborate green production policy and processes related to the purchase of eco-friendly, socially desirable materials and equipment, and their recycling and reuse. Most of all, the CEO is the champion of sustainable management who spreads the corporate culture and mindset to become a manufacturer leading in sustainability.
Tools	Med	While digital transformation and smart factories are the key trend, the petrochemical industry is still catching up with the latest production technologies. Although the level of digitalization of work processes is quite high, and good progress has been made in terms of the construction of a future plant environment, actual improvement in processes appears rather slow. Data requirement of raw materials and plant processes is immense, so that big data analysis is required. For a circular economy, a reverse logistics network should be constructed, and be fully functional. Even though the firm has a sustainability monitoring system in place, the level of infrastructure optimization and its usage for greater impact remains generally not high.
Practices	Med	To make the value chain sustainable, the company has been working with suppliers, and assessing its products' lifecycle. However, managing the wide range of issues and stakeholders is a task that needs collaboration with international organizations and other companies. In terms of production aspects, RE100 has been achieved in some initial factory sites. Energy saving schemes are in use in the plant and office space, but not all sites are actively tapping their potential to make the best practices, and to spread them.
Achievements for the Environment	Med	To cut carbon emissions by 30 million tons a year, aggressive measures should be implemented over the next decades. The company already benefits from sustainable manufacturing in many cases where 40% emissions reduction and 30% less energy and resource use have been possible. Also, an 85% recycling rate is seen in post-consumer recycled products. All these achievements are significant in indicating that the company is on the right track to become the first mover to reach net-zero by 2050.
Achievements for Socioeconomic Value	Med	Higher safety standards are in place to comply with South Korea's recent law on industrial accidents. Partnership has been established with a number of domestic and international organizations, and efforts to increase public awareness of ESG issues are continuously being made.Human rights improvement and other social innovation outcomes should be monitored, and continuously be upgraded.

Overall, LG Chem's status is high in the areas of sustainability strategy, organizational support and leadership, and environmental accomplishments, including renewable energy use, eco-friendly material technologies and water conservation, with a well-defined system of monitoring performance through smart technologies. In the other areas of tools, practices and accomplishments for social value creation, while procedures, measures, software programs and hardware equipment are in place, more tangible outcomes require longer-term operations and continuous improvements. In creating social value, the company has been actively pursuing initiatives, including communal partnerships, local employment, workplace justice and safety for sustainability. Indeed, the corporate governance of LG Chem has been making decisive and beneficial strategies, as well as defining and organizing appropriate for these support systems, tools and practices to ensure the achievement of short-term objectives, such as a swift transition to renewable energy and reduction of power consumption, and the larger scope agenda of Net-Zero 2050 and social responsibility across the entirety of the network.

5. Discussion and Implications

As an essential implication for manufacturing firms, sustainability should be adopted as part of a business strategy by top management, as well as an operational practice by all the layers of the value chain, including production sites and external suppliers. The strength of corporate sustainable management policies is determined by the degree of corporate governance support and extent to which the sustainability agenda is spread through clear-cut vision, planning and decision-making. It can be seen from the case of LG Chem that targets should be established at a reasonable level, raising awareness of consumers, employees and management, encouraging the entire manufacturing network toward the goal, acknowledging areas in need of improvement and highlighting interim attainments as a part of sustainability as an evolving, work-in-progress agenda. It is important to emphasize that LG Chem, despite its major efforts in exclusively controlling its entire supply chain level of greenness and societal stance, has been able to reflect on the limitations directly linked to this, and instead opted for the formation of more beneficial partnerships and networks to collectively build sustainability at all levels.

Active development, the raising of necessary funds, and information spreading, which stem from a defined higher strategy, could be emphasized as a prerequisite to the formulation of the support systems and technological tools and practices necessary to actively transition to sustainable manufacturing via sustainable materials, production and supply chain that result in desired quantifiable outcomes. Moreover, LG Chem's sustainability initiatives have led to an increased corporate value that is visible through the valuation of its ESG and ordinary corporate bonds, as well as the strengthening of consumer satisfaction from 66.1 in 2019 to 84 points in 2022 [29]. As such, it can be noted that defining and raising awareness of a corporate long-term sustainability agenda provides a significant payoff in the form of long-term investor and customer trust, hence, competitive advantage in the market.

Having qualitatively evaluated the level of sustainability of such a manufacturer as LG Chem through the analysis of the four pillars of management, supply chain, production and materials and the application of the proposed assessment framework, it can also be concluded that the indices within the framework could be reasonably modified, depending on the company size to be reviewed. That is because, as has been identified in the case study, large corporations have a limited ability to control and manage the entirety of their supply chain sustainability, whilst small and medium enterprises might not extend past Scopes 1 and 2 together, or have no capability to adequately audit and select solely low-risk ESG procurers. Thus, it is essential to moderately adjust the detailed indices within the proper framework to assess the level of sustainability in smaller sized corporations within reasonable regulatory and voluntary standards. Another limitation of the present study is that quantitative evaluation cannot yet be made, and as more detailed results and data become available, scores in the assessment factors can be determined.

6. Conclusions

Given the need to advance sustainability in the manufacturing sector, it is essential for companies to have an assessment framework to measure the maturity of their sustainable production practice and to make an innovation plan. Such initiatives should originate directly from top management and be implemented through the entirety of the value chain. In this sustainable manufacturing-assessment framework, production and operation-related achievements are evaluated as well as green, socially and economically responsible strategies, support systems, tools and practices. The application of the framework to the case of a leading chemical manufacturer revealed that the governance-centered initiative is highly effective in a global manufacturing corporation when sustainability measures need to be adopted and spread widely to the organization. New product development can be aligned with creating business opportunities and pursuing excellence in sustainable manufacturing at the same time. To achieve a meaningful ESG impact, the manufacturer should provide higher-risk value chain participants with necessary support systems and tools to further advance their stance in sustainability together.

Author Contributions: Conceptualization, methodology, resources, supervision, writing: J.L.; analysis, writing, visualization: E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Soonchunhyang University's research project #2024-0910.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

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