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The Development of an Efficiency-Based Global Green Manufacturing Innovation Index: An Input-Oriented DEA Approach

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Abstract: Innovation-based economic growth is considered to be a vital strategic aim for all economies, but environmentally friendly concepts and sustainable development (SD) must also be considered. The literature on the Global Innovation Index (GII) shows various investigations relevant to innovation, yet the lack of comprehensive consideration within the GII of environmental concerns represents a critical challenge. This paper aims to provide a holistic-perspective evaluation model for the top 15 manufacturing countries worldwide in order to resolve this. The efficiency-based Global Green Manufacturing Innovation Index (GGMII) was developed by formulating an input-oriented data envelopment analysis model. Criteria such as the value added to the gross domestic product (GDP), corresponding CO_2 emissions, and unemployment rates were examined in order to represent the economic, environmental, and social dimensions of SD, respectively. Other scientific and technological dimensions were also considered. The data corresponding to all ten of the criteria were collected from World Bank Open Data. The results show a mismatch between the original GII and the proposed GGMII for the top eight manufacturing countries (the United States, the United Kingdom, Germany, Korea, France, China, Japan, and Canada), while the remaining countries (Italy, Spain, Russia, India, Mexico, Brazil, and Indonesia) occupied the same rank in both indices, but showed a sizable diminution in their original GII scores. The proposed GGMII might be utilized as a benchmarking instrument for all countries worldwide in the future.

Keywords: green manufacturing innovation index; global index; green innovation index; sustainability; data envelopment analysis; multiple criteria decision making; World Bank; United States; China; efficiency

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Citation: Alidrisi, H. The Development of an Efficiency-Based Global Green Manufacturing Innovation Index: An Input-Oriented DEA Approach. *Sustainability* **2021**, *13*, 12697. https://doi.org/10.3390/su132212697

Academic Editor: Antonella Petrillo

Received: 26 October 2021
Accepted: 15 November 2021
Published: 17 November 2021

1. Introduction

Innovation-based economic growth is considered a vital strategy for attaining economic success in employment and overall prosperity. The environmental degradation associated with such advancements has resulted in the appearance of several environmentally friendly concepts, such as green/sustainable development (SD) [1]. The rapid development of green innovation worldwide is contributing significantly to almost all kinds of industries [2]. However, attempts to research such promising concepts are still in need of unbounded and continued support [3]. Even though the recent literature on the Green Innovation Index (GII) has provided various investigations relevant to different aspects of innovation, some key technological and/or practical issues have not yet been handled appropriately.

The dilemma of creating a comprehensive GII that considers environmental concerns represents one such critical issue. Even when the latest version of the GII (Figure 1), published in 2020, employed data envelopment analysis (DEA) as a benchmarking tool to measure economies' multi-dimensional performances with respect to innovation [4], the sustainability dimensions (in particular, the environmental measures) were not explicitly included either as inputs or as outputs. Moreover, the structural relationships among the

GII inputs and outputs have been ignored in the recent utilization of DEA in the GII [5]. The potential capability to measure a degree of innovation is more complex than what is being considered and practiced in the current GII [6,7]. For these reasons, this paper aims to develop an efficiency-based Global Green Manufacturing Innovation Index (GGMII) for the top 15 manufacturing countries worldwide.

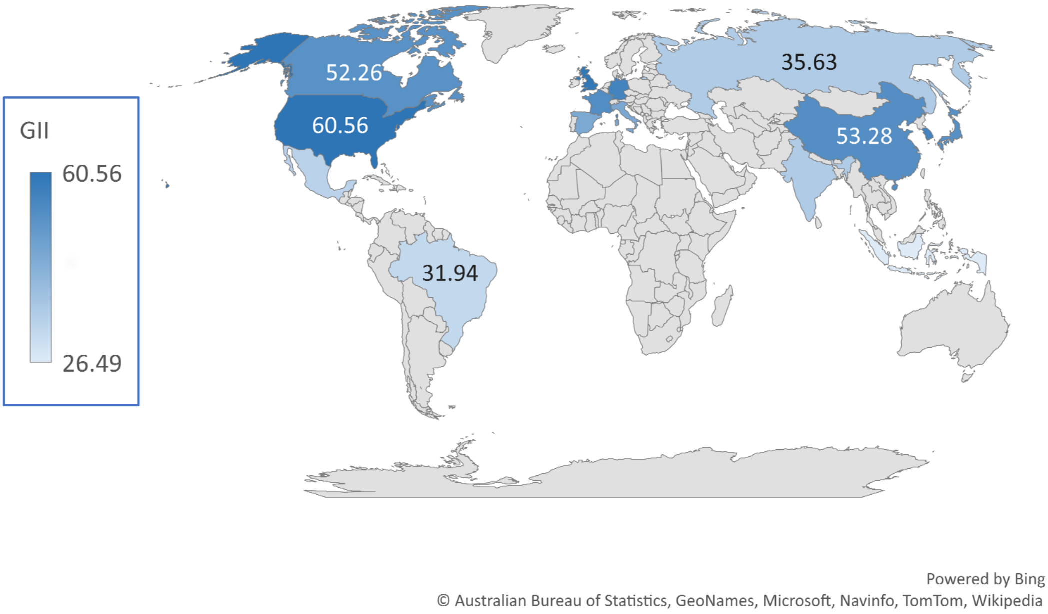

Figure 1. Global Innovation Index (GII) for the top 15 manufacturing countries worldwide, based on the manufacturing net value added to the GDP. (Source: data corresponding to each country were collected by the author from the Global Innovation Index report [4]; a licensed Microsoft Excel copy from King Abdulaziz University was then utilized to develop the figure; which is automatically labeled by the following statement: "Powered by Bing © Australian Bureau of Statistics, GeoNames, Microsoft, Navinfo, TomTom, Wikipedia").

An input-oriented DEA approach was formulated using ten criteria, three of which represented SD in its three generic dimensions, which consider aspects of manufacturing. These three criteria were selected to represent economic, environmental, and social factors: (1) manufacturing in terms of the net value added to the country's gross domestic product (GDP) measured in US dollars, (2) the CO_2 emissions from all manufacturing industries, including construction, as a percentage of the total fuel combustion, and (3) the level of unemployment measured as a percentage of the total labor force. The remaining seven criteria represent the maturity of the manufacturing practices, as all relevant/appropriate scientific and technological World Bank indicators were considered. The extent to which the GII scores had been influenced by the final efficiency scores of these 15 countries was then identified in order to obtain the final GGMII scores for each country. The remaining sections of this paper are organized as follows: Section 2 introduces the innovative practices already present in the top 15 manufacturing countries by briefly presenting some recent discussions from the literature; Section 3 presents the DEA method and its application; Section 4 illustrates the results and the discussion; and Section 5 summarizes the paper.

2. Relevant Literature

The different aspects of innovation are presented briefly in this section, in order to highlight the nature of the innovative practices being utilized in the top manufacturing countries. In the United States, innovation in Massachusetts has been investigated for "ecosystems dynamics," and it has been concluded that the state has great manufacturing capabilities that are providing effective contributions to its leading industries [8], including complex industries such as the automotive industry [9]. The UK Innovation Index has shown that the UK's intangible investments such as investment in R&D, software, design, training, and organizational capital were key contributors to economic growth. Furthermore, it was concluded that the UK information/communications industry represented the most intangible industry in terms of the value it added to the UK's economy [10]. In Germany, it has been stressed that organizational characteristics play a significant role in determining the extent to which firms attain innovation [11]. Similarly, in France, numerous innovation-focused studies have been conducted. For instance, innovation has been studied in relation to the influence of the company directors' characteristics, and it was found that highly educated and independent executives contribute positively to complex decision making, in turn fostering the innovation process and increasing the number of patents that are registered [12].

According to several studies, China also needs to work on creating a kind of growth that collectively and implicitly considers all of the aspects of green economic growth (i.e., the economic and the environmental dimensions) in order to attain better utilization of its resources [13]. In Spain, knowledge-intensive business services (KIBS) have been investigated in order to study the relationships between various sources of knowledge and innovation authenticity, and it was concluded that R&D was negatively linked with innovation, indicating that the definition of R&D should be clarified in order to ensure better linkages with innovation [14]. In the Korean manufacturing sector, the innovation capabilities of small and medium-sized enterprises (SMEs) have been empirically investigated in order to identify the strategic directions necessary for policymakers to be able to enhance sustainable innovation practices, considering the positive linkage between technological innovation performance and firms' innovation capabilities [15].

Several aspects of green innovation have been studied in Japan, the United States, and a set of European firms, and one of the conclusions was that R&D efforts focusing on clean production processes strongly affect firms' maturity levels in terms of their strategic decisions on green investments [16]. Indeed, the positive effect of digitalization on Japanese manufacturing SMEs resulted in better levels of attainment in satisfying customer needs, sales, and profits [17]. In the Italian manufacturing sector, several innovation issues have been discussed in the recent literature, such as the significance of R&D in product innovation within SMEs [18], the relationship between open innovation and human resources [19], the challenges for craft companies relating to digital manufacturing and open innovation [20], the funding of SMEs and their associated innovation strategies [21], and the learning processes that are taking place during the implementation of innovation practices [22].

With the aid of a robust data set, innovation was recently analyzed using two direct measures, R&D spending and the total number of innovations, in order to investigate the case of a Canadian manufacturing company [23]. In Mexico, large amounts of data were collected from 6378 companies in order to understand and interpret the nature of Mexico's competition with China to penetrate US markets, in particular, the analysis explored the extent to which such competition has enhanced innovation in the Mexican manufacturing sector [24]. The market competition among Mexican companies showed a negative linear relationship with the firms' innovation capabilities, due to the gaps between leader and follower companies [25]. In Indonesia, innovation was found to represent a critical dilemma, and it needed to be treated promptly in order to resolve issues such as substandard innovation performance indicators, the absence of creativity culture, limited R&D spending, and the absence of a comprehensive national innovation plan [26]. Hence, recent barriers to innovation for Indonesian manufacturing companies have been classified into four categories: markets and institutional situations; human resources and organizational relationships; risks associated with financial issues; and knowledge sharing and collaboration [27]. In order to enhance Russian manufacturing companies' performance in innovation, science-based collaboration strategies have been discussed in an effort to link academia with industries [28]. Local Indian companies have attained better green innovation practices compared to foreign direct investment (FDI) companies due to a lack of enforcement of regulations on foreign companies in India [29].

3. Method

The DEA approach belongs to the linear programming family of optimization techniques and represents one of the most commonly practiced multi-criteria decision-making (MCDM) methods [30]. It is well known as an efficiency measurement and benchmarking tool for comparing different decision-making units (DMUs) [31]. It can be applied to measure any set of DMUs in the service sector, manufacturing sector, or global context, where a set of countries needs to be compared on parameters such as health care systems [32], SD [33], or innovation [34]. Various forms of DEA formulations can be conducted to address a number of purposes. The input-oriented constant returns to scale (CRS) DEA model can be formulated as follows [35]:

$$Min\ \theta + \varepsilon\,(\sum_{i=1}^{m} S_i^- + \sum_{r=1}^{s} S_r^+) \tag{1}$$

S. T:

$$\sum_{j=1}^{n} \lambda_j\, x_{ij} + S_i^- = \theta x_{io}\ ;\ i = 1,\ 2,\ \ldots\ ,\ m \tag{2}$$

$$\sum_{j=1}^{n} \lambda_j\, y_{rj} - S_r^+ = y_{ro}\ ;\ r = 1,\ 2,\ \ldots\ ,\ s \tag{3}$$

$$\lambda_j\ ,\ S_i^-\ ,S_r^+\ \geq 0 \tag{4}$$

where the total number of DMUs (i.e., alternatives) is represented by n, which equals 15 in the current application, representing the top 15 manufacturing countries worldwide. For each country j, j = 1, 2, 3, . . . , n; the outputs are represented by s, such that, r = 1, 2, 3, . . . , s; and the inputs are represented by m, such that, i = 1, 2, 3, . . . , m. The amount of input i utilized by country j is represented by x_{ij}. The amount of input i utilized by country j_o is represented by x_{io}, where j_o represents the country under assessment. The amount of output r produced by country j is represented by y_{rj}. The amount of output r produced by country j_o is represented by y_{ro}. The weight to be computed for each country j is represented by λ_j. For country j_o, slack for input i is represented by S_i^-, while for output r, S_r^+ represents the surplus. A very small positive number *(ε)* is usually utilized, as shown herein, to ensure that there is appropriate employment of all slack and surplus values within the model. Technically, the efficiency score of country j can be attained if: (1) all S_i^-, i = 1, 2, 3, . . . , m; and S_r^+, r = 1, 2, 3, . . . , s; = 0; and (2) the efficiency score θ = 1.

Ten criteria were utilized in order to conduct the input-oriented CRS–DEA model. The first three criteria represented the three pillars of SD in the manufacturing context: (1) manufacturing as measured in terms of the net value added to a country's GDP, measured in US dollars (MVA); (2) the CO_2 emissions from all manufacturing industries, including construction, as a percentage of total fuel combustion (CO_2); and (3) the level of unemployment as a percentage of the total labor force (UER). In other words, these three criteria (MVA, CO_2, and UER) represented the economic, environmental, and social dimensions (pillars) of SD, respectively. The remaining seven criteria were selected from World Bank Open Data. According to the World Bank's categorization for its huge global data set, the remaining seven criteria were chosen to represent the category of science and technology sector indicators: (4) charges for the use of intellectual property in terms of payments in US dollars (IPP); (5) charges for the use of intellectual property in terms of receipts in US dollars (IPR); (6) the value of high-technology exports in US dollars (HTE); (7) the number of researchers in R&D per million people (RRD); (8) the number of scientific and technical journal articles published (STJ); (9) the number of patent applications filed (PAP; residents and non-residents); and (10) the number of trademark applications filed (TAP; direct residents and direct non-residents). Data corresponding to the redundant criteria were excluded (e.g., when the data were provided in the form of the total number and in a percentage as well for the same criterion). The data corresponding to all 10 of the criteria for the 15 countries (Table 1) were extracted from World Bank Open Data [36].

Table 1. Input measures, output measures, and GII for each investigated country.

Country	MVA (USD)	CO_2 (%)	UEM (%)	IPP (USD)	IPR (USD)	HTE (USD)	RRD	STJ	PAP	TAP
China	3,823,413,525,563.08	31.715	5	37,781,733,950	8,554,460,470	757,723,684	1307	528,263	1,400,661	2,104,414
United States	2,341,847,481,000.00	8.656	8.3	40,682,000,000	114,045,000,000	143,489,383	4412	422,808	621,453	492,729
Japan	1,027,967,141,295.59	19.181	3	28,218,283,570	43,038,454,714	102,966,232	5331	98,793	307,969	188,374
Germany	737,937,446,321.57	12.442	4.3	16,026,253,188	35,863,331,279	180,663,903	5212	104,396	67,434	78,304
Korea, Rep.	416,992,725,408.30	13.656	4.1	9,889,600,000	6,855,400,000	163,988,798	7980	66,376	218,975	218,564
India	382,564,765,196.94	26.408	7.1	7,241,107,557	1,253,654,725	21,662,006	253	135,788	53,627	348,912
Italy	298,426,716,137.25	11.195	9.3	4,096,757,343	4,243,284,776	34,865,443	2307	71,240	10,127	42,899
France	266,634,199,796.08	15.696	8.6	12,423,182,138	14,660,286,102	87,649,839	4715	66,352	15,869	102,513
United Kingdom	245,753,017,715.65	9.597	4.3	16,853,200,293	22,426,905,155	64,038,019	4603	97,681	19,250	105,674
Indonesia	220,502,279,972.38	18.395	4.1	1,640,504,467	83,574,615	6,415,055	216	26,948	11,481	62,021
Mexico	219,880,228,825.35	13.448	4.7	329,131,627	7,648,358	69,544,185	315	16,346	15,941	145,916
Russia	219,222,070,424.19	12.321	5.7	6,809,070,000	116,3920,000	10,864,830	2784	81,579	35,511	85,040
Brazil	190,428,838,205.10	20.602	13.7	4,029,140,415	634,291,803	5,969,585	888	60,148	25,396	247,157
Canada	159,724,381,266.89	12.044	9.5	12,704,911,612	6,016,672,959	26,040,619	4326	59,968	36,488	68,277
Spain	155,493,889,937.26	14.272	15.7	5,063,616,548	2,949,863,121	15,731,961	3001	54,537	1447	53,701

4. Results and Discussion

4.1. Results

The results of this newly developed input-oriented DEA model show that five of the fifteen top manufacturing countries score 1 in "efficiency" (Table 2). Such results confirm that there is no evidence that, relatively (i.e., when compared to the remaining 10 top manufacturing countries), these countries are inefficient in terms of their utilization of inputs in the pursuit of achieving maximum outputs. These five countries attain the maximum outputs (MVA, IPP, IPR, HTE, RRD, STJ, PAP, and TAP) with the best utilization of the two inputs (CO_2 and UEM). In other words, each of these five countries achieves the best output level in all of the output measures collectively (MVA, IPP, RRD, etc.), when considering the minimum CO_2 emissions criterion as well as minimum UER level. Consequently, these countries' adjusted GII scores remain the same as their scores in the original GII; this is a result of multiplying the original GII by the country's maximum efficiency score (i.e., multiplied by one).

Table 2. DEA results.

Country	Efficiency Score	GII	Adjusted GII
China	1	53.28	53.28
United States	1	60.56	60.56
Japan	1	52.7	52.70
Germany	1	56.55	56.55
Korea, Rep.	1	56.11	56.11
India	0.243	35.59	8.65
Italy	0.366	45.74	16.74
France	0.527	53.66	28.28
United Kingdom	0.933	59.78	55.77
Indonesia	0.098	26.49	2.60
Mexico	0.226	33.6	7.59
Russia	0.409	35.63	14.57
Brazil	0.191	31.94	6.10
Canada	0.634	52.26	33.13
Spain	0.366	45.6	16.69

Note that although the United Kingdom scores 0.933, which is slightly lower than all five of the most efficient countries, its final (adjusted) ranking is still better than two of those five countries: China and Japan. This is due to the fact that its original GII is very high (it is second best, according to the GII ranking). The remaining nine countries can be categorized into four levels according to their final adjusted GII: (1) moderate performance, Canada (33.13) and France (28.28); (2) low performance, Italy (16.74), Spain (16.69), and Russia (14.57); (3) very low performance, India (8.65), Mexico (7.60), and Brazil (6.10); and (4) extremely low performance, Indonesia (2.6). It is important to mention that these performance description levels are identified considering relative performance among only these 15 selected countries, and as such, these descriptive levels should not be used to label these top manufacturing countries outside of this assessment. In other words, these nine countries perform moderately, low, very low, and extremely low compared to the top six manufacturing countries, but these performance assessments are not absolute with respect to the rest of the world.

Table 3 presents further clarification and interpretation of the data. The first and second columns adjacent to the listed countries present the rankings of the 15 countries according to their GII and GGMII scores, respectively. All changes in ranking are presented in the third and fourth columns. Among the top eight manufacturing countries, the US remains first in both the GII and GGMII, while for the remaining countries, five out of seven rise one position in the GGMII as a consequence of the distinct drops of the UK (−2) and France (−3), including Canada, which shows 36.6% diminution in its original GII score.

Note that the 6.7% diminution in the UK's original GII score results in lowering its final GGMII rank by two positions, while the relatively sizable drop in France's ranking results from a 47.3% diminution in its original GII, placing it three positions lower (now ranking eighth) in the GGMII list, which is lower than its original GII ranking of fifth. The rest of the 15 countries (i.e., those ranked nine to fifteen) remain at the same rank in both GII and GGMII, though they show substantial diminution in their original GII scores.

Table 3. Final rank based on the proposed GGMII.

Country	Rank (GII)	Adjusted Rank (GGMII)	Change in Ranking		Change in GII (in %)
United States	1	1	–	–	0
United Kingdom	2	4	↓	−2	−6.7
Germany	3	2	↑	1	0
Korea, Rep.	4	3	↑	1	0
France	5	8	↓	−3	−47.3
China	6	5	↑	1	0
Japan	7	6	↑	1	0
Canada	8	7	↑	1	−36.6
Italy	9	9	–	–	−63.4
Spain	10	10	–	–	−63.4
Russia	11	11	–	–	−59.1
India	12	12	–	–	−75.7
Mexico	13	13	–	–	−77.4
Brazil	14	14	–	–	−80.9
Indonesia	15	15	–	–	−90.2

4.2. Discussion and Implications

The resulting GGMII ranking list is significantly mismatched with the original GII ranking list for the top eight manufacturing countries. Even for the remaining seven countries, the substantial diminution in their original GII scores indicates the need to expand such a developed and innovative index to cover all global manufacturing contributors, including the group of twenty (G20) [37] and the European Union [38]. This may also eventually be applicable to all, or any subset of, United Nations (UN) countries [39] for the purpose of benchmarking best practices. Regardless of the final GGMII scores, the overall results corresponding to the eight top-ranked manufacturing countries confirm their industrial leadership and dominance globally. Such outputs are confirmed practically, through their global leadership and dominance, contributions, and the representation of six out of eight members of the group of eight (G8) countries [40], as well as empirically, through the results of many sustainability-focused studies [41]. The results clearly confirm the significant innovative green manufacturing contributions of Korea and China when compared with other G8 countries (particularly Russia and Italy), although neither Korea nor China are members of the G8. Thus, the group of 13 (also known as the G8+5) may provide a relatively more appropriate representation of the top manufacturing nations [42], except in the case of South Africa. Even with its extremely low GGMII score (when compared with the top 14 manufacturing countries), Indonesia shows potential, considering that it is neither a member of the G8 nor the G8+5, and particularly when it is compared to South Africa. The outcomes of several recent studies may also provide justifications for the diminution in GII scores for Indonesia [26,27], France [43], and Brazil [44].

The United States and China are the largest contributors to CO_2 emissions. However, they are still the most powerful countries in terms of GDP (including manufacturing-based GDP), which is one of the three pillars of sustainability (i.e., the economic aspect). Although some countries have relatively low GGMII scores, their national green initiatives, such as green practices in Brazilian logistics systems [45] and the production of high-complexity products in Mexico [46], hold promise for innovative green manufacturing in the future. Using the top eight countries as benchmarks, manufacturing countries could accelerate the successful implementation of global green initiatives through collaboration. However, international communities should be aware of the political–economic decisions and practices enacted by their nations, such as Germany's support for the Nord Stream 2 pipeline between Russia and Germany, that are in conflict with green strategic thinking. Thus, such issues should be discussed and carefully managed globally to ensure the use of clean and innovative manufacturing practices worldwide.

The analytic model presented in this study is novel because it is a refinement of the current edition of the Global Innovation Index (GII). It synergizes the current GII scores with sustainable development data and technological indicators from the top manufacturing countries. The application of DEA, which is superior to other MCDM methods in developing such an index particularly, is also novel. To clarify, DEA can be formulated to address an unlimited number of quantitative criteria (inputs and outputs) and alternatives (e.g., the countries in the current study). In contrast, subjective MCDM methods, such AHP and ANP, use a limited number of qualitative criteria and alternatives because of the consistency issues associated with subjective inputs (e.g., expert opinions). Other classic outranking MCDM methods, such as TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje), and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations), can address unlimited numbers of quantitative and/or qualitative criteria and alternatives. However, they provide an effectiveness-based, rather than an efficiency-based, final score for each alternative. DEA generates efficiency scores for all of the alternatives by considering the proportion of all of the output criteria to all of the input criteria collectively. In addition, the DEA formulation setup allows for certain features of the developed linear programming model suggested in the present study to facilitate the formulation of an input-oriented DEA model to examine each country's ability to produce output measures that give preference (i.e., top priority) to the minimum input measures (i.e., minimum CO_2 emissions and unemployment rate). Such linear programming formulation features only apply to DEA. They are inapplicable in other MCDM methods. In this regard, further formulations for different innovative DEA models can be found in [47–52].

5. Conclusions

This paper argues that the current GII lacks a comprehensive perspective through which green manufacturing dimensions can be considered. Consequently, this study provides a holistic-perspective evaluation model proposed for application to the top 15 manufacturing countries worldwide to resolve such a dilemma. In order to assess aspects of sustainability, the manufacturing-based GDP values, CO_2 emissions, and unemployment rates for the investigated countries were considered to address the green criteria. A set of scientific and technological indicators were utilized as an additional set of criteria to address the innovative manufacturing concerns corresponding to this dilemma.

All corresponding criteria (two inputs and eight outputs) were utilized to develop the input-oriented CRS–DEA model. The results from the DEA-based efficiency scores of the 15 countries were embedded in the GII scores (i.e., the GII was multiplied by the DEA-based efficiency score for each country) to obtain the proposed GGMII. The results show a mismatch between the original GII and the proposed GGMII for the top eight manufacturing countries, while the remaining countries (ranked from nine to fifteen) occupied the same rank in both indices, although they all showed a sizable diminution in their original GII scores. These results provide a potential incitement for other countries not included in the current study in terms of their prospective GGMII scores. It is apparent that the current GII is not capable of appropriately reflecting the issues that are relevant to sustainability as well as measures of scientific and technological advancement. This calls for further investigation in the future considering additional countries. Hence, the proposed GGMII might be utilized as a benchmarking instrument for an extended set of countries worldwide, such as G20, EU, or UN countries, in the future.

Finally, the present study has limitations stemming from the differences between developed and developing countries. It was limited to the top manufacturing countries because of their shared characteristics, which facilitated the development of a unified index. In the development of such an index, the consideration of countries with low CO_2 emissions is challenging because of their poor manufacturing practices (as evidenced by GDP). This leads to another limitation: the extent to which the criteria accurately reflect green dimensions. For example, indicators related to recycling activities may (or may not) represent the environmental dimension more appropriately than the indicator, CO_2 emissions, used in the index presented in this study. Thus, international communities and organizations, including the World Bank, universities, and research centers, should dedicate their future research efforts to the identification of the criteria needed to provide a fair assessment of global green manufacturing practices in all countries.

Funding: This research received no external funding.

Acknowledgments: The author would like to acknowledge with thanks the KAU's technical support.

Conflicts of Interest: The author declares no conflict of interest.

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