

Developing a Structural Framework for Evaluating and Benchmarking the Greenness of Manufactured Products

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Abstract

This paper aims to develop a structural framework for evaluating and benchmarking the greenness of manufactured products that supports sustainability-oriented decision-making in industrial decisions and operations. A hierarchical structural framework is developed using graph theory and a matrix approach to develop a Product Greenness Index (PGI). Thirty key performance indicators (KPIs) that cover the environmental, economic, and social dimensions of greenness are assessed. Two matrices, namely, the PGI and the Product Greenness Index Ratio (PGIR), are developed for evaluating and benchmarking the greenness of products. A case example involving two automotive component manufacturers (Firm A and Firm B) illustrates the benchmarking capability of the model. The results indicate that both firms scored well below the ideal benchmark of 2.066 for aggregate weighted KPI scores, with Firm B attaining a score of 1.171 (56.7%) and Firm A achieving 0.752 (36.4%), indicating a substantial performance gap from the defined sustainability target. Building on these aggregated KPI scores, Firm B achieved a higher PGI of 6.254×10^{12} alongside a PGIR of 0.094, compared to a PGI of 4.845×10^{12} and a PGIR of 0.073 attained by Firm A. These findings demonstrate the model's benchmarking capability in quantifying product greenness and identifying meaningful improvement opportunities across manufacturing firms. The model provides industry practitioners with a decision support tool to benchmark the greenness of a product against competitors or internal targets. It enables design-stage interventions that align product development with corporate sustainability goals, and it is clear and regulated. This research work contributes to the sustainable operations literature by introducing a novel graph-theoretical framework to product-level sustainability assessment. The integration of benchmarking into product business valuation distinguishes this work from other models focused solely on environmental performance assessment.

Categories: Data Science and Analytics for Engineering, Design and Manufacturing, Environmental and Sustainable Engineering

Keywords: structural modeling, sustainability, green operations, digraph, product greenness index

Introduction

The global economy relies on manufacturing, which drives growth, innovation, employment, and infrastructure development. It also contributes to environmental pollution, accounting for 23% of anthropogenic CO₂ emissions and utilizing 54% of global energy resources [1]. Increased awareness and environmental concerns, legislation such as the European Green Deal, and customer demand for eco-friendly products put pressure on manufacturers to adopt green and sustainable manufacturing practices. Hence, product greenness refers to the extent to which a product reduces

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environmental, economic, and social impacts throughout its lifecycle, including resource extraction, manufacturing, usage, and end-of-life management. It reflects the integrated optimization of environmental performance, resource and cost efficiency, and social responsibility [2]. The global sustainable manufacturing market, worth USD 203,651.8 million in 2023, is expected to grow to USD 422,121.3 million by 2030, as reported by Grand View Research in 2024 [3]. This growth reflects the economic and environmental significance of green practices and underscores the need for robust methods to measure and enhance product greenness. Additionally, recent research has highlighted the strategic importance of benchmarking green practices for business excellence [4,5]. Nunes and Bennett [6] emphasized categorizing green operations across automotive firms through environmental reporting, highlighting the role of benchmarking as a strategic tool. Similarly, Govindan et al. [7] proposed a multi-criteria framework for benchmarking green supply chain practices, directing toward integrated greenness indices.

Consumer behaviour also plays a pivotal role in the inclusion of greenness in a product. Islam and Ali Khan [8] found that 80% of consumers care about the environmental impact of their purchases. Research shows that green features affect customer greenness ratings [9,10]. These observations highlight the necessity for a comprehensive product greenness framework [11]. The concept of greenness considers both environmental benefits and social and economic dimensions [12]. Economically, green practices may reduce costs through optimized resource use and waste minimization [13]. Additionally, socially sustainable products may also appeal to consumers, enhancing brand reputation and market competitiveness [14]. These trends emphasize the need for product greenness assessment methods, which can help firms in meeting customer expectations and regulatory requirements while saving money on resources. Lifecycle assessment (LCA) is a popular method for assessing a product's environmental impact from raw material extraction to disposal [15]. Using an inventory of energy and material inputs, LCAs evaluate environmental impacts and aid decision-making [16]. However, LCAs are time-consuming and expensive because they involve considerable data collection and processing [17]. The complex interdependencies among greenness indices are also commonly missed [18]. For example, optimization of energy utilization may increase material consumption, causing trade-offs that conventional LCAs cannot fully model [19]. Manufacturers struggle to measure product greenness due to these limitations. In today's business world, benchmarking is a strategic tool that helps industries find best practices and improve performance by comparing goods or companies in a structured manner. Benchmarking for environmental sustainability, especially at the product level, is still not well studied, even though it is widely used in areas like quality and productivity. Many existing sustainability indicators do not make it easy to benchmark and standardize. Graph theory and matrix method, which are structural modeling tools, can be successfully used in the greenness assessment of products as well as benchmarking. A recent study demonstrates their application in sustainable manufacturing, particularly in Industry 4.0 [20].

The present study offers novel contributions toward product-level sustainability assessment. Primarily, it introduces the application of the Graph Theory and Matrix Approach (GTMA) for evaluating product greenness through the proposed Product Greenness Assessment Function (PGAF), enabling simultaneous consideration of key performance indicator (KPI) magnitudes and their interrelationships. Existing methodologies include multi-criteria decision-making methods and composite sustainability indices, which generally evaluate indicators independently or employ linear aggregation techniques. The proposed GTMA-based framework captures both the individual significance and interactive influence of KPIs within a comprehensive network structure. In addition, the study proposes two new benchmarking measures, namely the Product Greenness Index (PGI) and the Product Greenness Index Ratio (PGIR), to facilitate both intra-firm and inter-firm comparison against the Ideal Product Greenness Index (IPGI). Furthermore, the framework incorporates a systematically developed set of 30 KPIs encompassing environmental, economic, and social sustainability dimensions, identified through an extensive literature review, established sustainability standards, and expert validation from academia and industry.

The present work is structured as follows. The Materials and Methods section defines the KPIs associated with product greenness, outlines the proposed greenness assessment methodology, and presents the developed models and frameworks for evaluating and benchmarking manufactured products. The Results and Discussion section evaluates the greenness of products and demonstrates the applicability of the proposed framework through a case study.

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Materials And Methods

Based on the definition of product greenness provided earlier, the proposed framework systematically identifies indicators spanning environmental, economic, and social sustainability dimensions. The overall methodology adopted for product greenness assessment and benchmarking is illustrated in Figure 1.

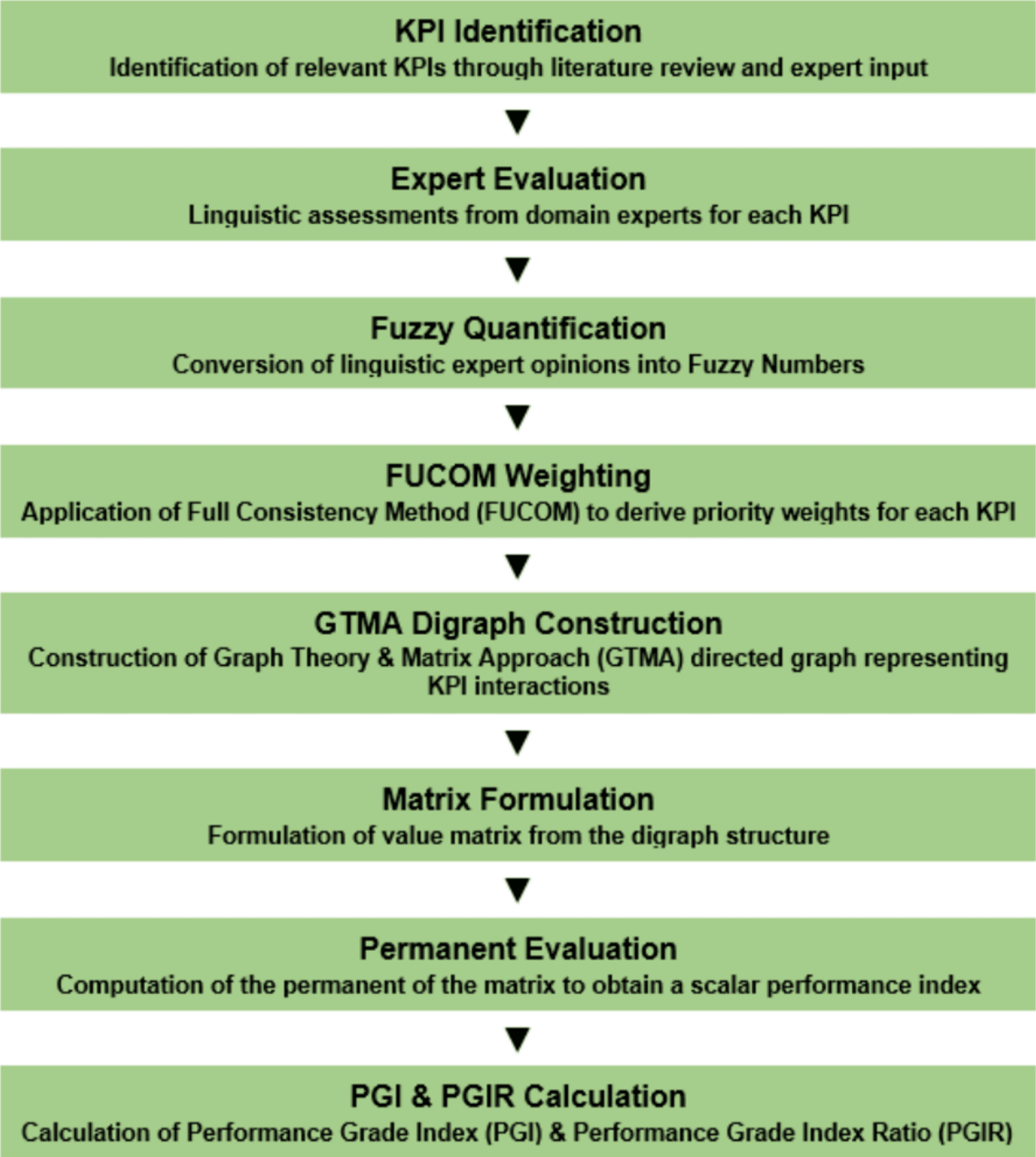


FIGURE 1: Flowchart of the proposed KPI evaluation framework

KPI, Key Performance Indicator

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KPIs for product greenness

Ho et al. [21] emphasized that KPIs help in making fair comparisons within and across different firms. Additionally, KPIs also support managers and decision-makers in monitoring performance and taking corrective actions [22,23]. Yuan et al. [24] opined that measuring true performance is possible only after key KPIs are selected, agreed upon, and consistently tracked. Researchers have also provided guidelines for the selection of indicators. Govindan et al. [7] opined that all three dimensions of sustainability (social, economic, and environmental), with multiple metrics, should be considered to achieve a comprehensive evaluation of product greenness performance. Nardo et al. [25] reminded that indicators need to be observable and quantifiable to fit the application. As per OECD Publishing (2008), indicators should encompass all aspects of greenness assessment to identify a product's strengths, shortcomings, and opportunities for improvement in becoming more environmentally friendly [26].

After a careful review of the literature, industrial reports, and regulatory requirements, a list of 52 comprehensive greenness indicators was identified, of which 30 were considered vital for the present work. Each of these KPIs can be broken down into more specific sub-criteria, hereafter called 'Trackers', to provide a detailed evaluation. These trackers are listed in Table 7 with their respective references.

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KPI Symbol	Indicators	Tracker Symbol	Trackers/Sub-Indicators	References
GI ₁	Raw Material Consumption	GI _{1.1}	Total Non-Renewable & Renewable Material Consumption per unit of Product	Schandl et al. [27]; Kovanda [28]
		GI _{1.2}	Virgin Material Intensity	
		GI _{1.3}	Total Virgin Material cost per unit of Product	
GI ₂	Recycled Material Share	GI _{2.1}	Percentage of Non-Renewable & Renewable Recycled Material Consumption per unit of Product	Kumar and Mani [29]; Azapagic et al. [30]
		GI _{2.2}	Percentage of Recycled Material cost per unit of product	
GI ₃	Waste Management	GI _{3.1}	Total Quantity of Solid Waste Generated Per Unit of Product	Schmidt and Laner [31]; Voukkali et al. [32]
		GI _{3.2}	Quantity of Recycled Solid Waste Per Unit of Product	
		GI _{3.3}	Cost Recovered from Recycling	
GI ₄	Emissions into Ground	GI _{4.1}	Quantity of Material Sent to Landfill per unit of product	Huijbregts et al. [33]; Xin et al. [34]
		GI _{4.2}	Metal Emissions, Hazardous Solid Waste Disposal, Pesticides, Fertilizers & other Chemical Emissions to Land	
GI ₅	Material Eco-Efficiency	GI _{5.1}	Reduction in Consumption of Total Mass of Material Per Unit of Product from	Huijbregts et al. [33]; Vogiantzi and Tserpes [35]

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			last Comparative Version	
		Gl _{5.2}	Total Savings on Account of Concerned Sub Indicators	
Gl ₆	Fresh Water Consumption	Gl _{6.1}	Quantity of Fresh Water used per unit of Product	Huijbregts et al. [33]; Mir et al. [36]
		Gl _{6.2}	Total Water cost per unit of Product	
Gl ₇	Wastewater Management	Gl _{7.1}	Total Volume of Liquid Waste Generated per unit of Product	Shamshad and Rehman [37]; Bellver-Domingo et al. [38]
		Gl _{7.2}	Percentage of Water Recycled Internally	
		Gl _{7.3}	Total cost for Wastewater Management per unit of Product	
Gl ₈	Emissions into Water	Gl _{8.1}	Quantity of Specific Material Discharged to Water per unit of Product	Huijbregts et al. [33]; Xu et al. [39]
		Gl _{8.2}	Eutrophication Mass Fraction	
		Gl _{8.3}	Pollution Mass Concentration in Liquid Waste	
Gl ₉	Non-Renewable Energy Consumption	Gl _{9.1}	Quantity of each type of Non-Renewable Energy used per Product	Azapagic et al. [30]; International Organization for Standardization [40]
		Gl _{9.2}	Quantity of Electricity from Non-Renewable Source used Per product	
Gl ₁₀	Renewable Energy Share	Gl _{10.1}	Percentage of total Renewable Energy Consumption used per Product	Nardo et al. [25]; Hao and Dragomir [41]

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		GI _{10.2}	Total Renewable Energy cost Fraction used per Product	
GI ₁₁	Energy Eco-Efficiency	GI _{11.1}	Quantity of Energy units saved due to Energy Conservation Programs	Campos et al. [42]; Tsai et al. [43]
		GI _{11.2}	Savings achieved through Resource conservation (here, Energy) usage.	
GI ₁₂	Greenhouse Gas Emissions	GI _{12.1}	Global Warming Potential (GWP)	Huijbregts et al. [33]; International Organization for Standardization [40]
		GI _{12.2}	Costs of Purifying Air from Greenhouse Gas Emissions	
GI ₁₃	Emission of Pollutants	GI _{13.1}	Acidification Potential (to Air) Tons (Or Kilograms) of SO ₂ /SO _x Equivalents.	Huijbregts et al. [33]; Yan et al. [44]
		GI _{13.2}	Costs of Purifying Air from Pollutants	
GI ₁₄	Particulate Matter Emission	GI _{14.1}	Photochemical Ozone Burden Per Unit Product	Huijbregts et al. [33]; Hwang et al. [45]
		GI _{14.2}	Costs of Purifying Air from Particulate Matter Emission	
GI ₁₅	Workplace Safety	GI _{15.1}	Time of Lost Workdays due to Injuries and Illnesses	Teodoro and Giambò [46]; Rahman et al. [47]
		GI _{15.2}	Total Costs of Health Protection of Employees	
GI ₁₆	Noise Pollution	GI _{16.1}	Level of noise Pollution at The Working Stations & around Plant	Salim and Saravanan [48]; Raj and Patil [49]
		GI _{16.2}	Expenditure to Reduce Noise Pollution levels	

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GI ₁₇	Accidents & Cataclysm	GI _{17.1}	Reduction in Accidents & Cataclysm count and impact	Huijbregts et al. [33]; Taneja et al. [50]
		GI _{17.2}	Cost Spent on Environment Liabilities	
GI ₁₈	Management Commitment	GI _{18.1}	Composite Management Performance Indicators for Measuring Implementation of Policies and Programs	Shabbir et al. [51]; Shaikh et al. [52]
		GI _{18.2}	Management Ethical Indicator	
		GI _{18.3}	Cost spent on Environmental Compliances & Recognitions	
GI ₁₉	Manufacturing Plant & Processes Impact	GI _{19.1}	Total Land Occupied, used for Operations & Affected due to Operations around Plant	Swarnakar et al. [53]; Jayawickrama et al. [54]
		GI _{19.2}	Operational Performance Indicators for Quantifying Physical Facilities, Equipment, Processes, Supply & Delivery segment of the Plant	
GI ₂₀	Environmental Compliances & Recognitions	GI _{20.1}	Management Performance Indicators for Measuring Environmental Conformity	Nardo et al. [25]; ISO 14001 [55]
		GI _{20.2}	Costs Associated With EHS Compliance	
GI ₂₁	Supply Chain Management	GI _{21.1}	Total Suppliers Assessment on EHS Scale	Qu and Ji [56]; Kamra et al. [57]
		GI _{21.2}	Percentage Value of Product Acquired from	

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			Suppliers in Regard to EHS Scale	
GI ₂₂	Employment Practices	GI _{22.1}	Human Capital Composite Score	Sultan and Hussain [58]; Koman et al. [59]
		GI _{22.2}	Capital Spent on Employee Welfare & Trainings	
GI ₂₃	Societal Compliances	GI _{23.1}	Social Ethical Composite Indicator	Schmiedeknecht [60]; Annarelli et al. [61]
		GI _{23.2}	Capital Spent on External Stakeholders	
GI ₂₄	Ecosystem & Biodiversity Conservation	GI _{24.1}	Ecosystem & Biodiversity Impact Score	Dalton et al. [62]; El Geneidy et al. [63]
		GI _{24.2}	Capital Spent on Ecosystem & Biodiversity Conservation	
GI ₂₅	User Impact	GI _{25.1}	Product Safety and Health Impact on user	Dow Jones Sustainability Indices [60]; Arvidsson et al. [64]
		GI _{25.2}	Net Environment Impact of Product for the Whole Life Cycle with user	
GI ₂₆	Product Durability	GI _{26.1}	Potential Life of Product	Englhardt et al. [65]; Jerome and Ljunggren [66]
		GI _{26.2}	Product Reliability	
GI ₂₇	Economic Output	GI _{27.1}	Total Revenue & Value Indicator	Schmiedeknecht [60]; Dong et al. [67]
		GI _{27.2}	Value of Investments in Sustainable Development Investments in Sustainable R&D as a Fraction of the Expenses of the Company	

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GI ₂₈	Economic Inputs	GI _{28.1}	Average Capital Employed	Kumar et al. [68]; Mohamed Abdul Ghani et al. [69]
		GI _{28.2}	Debt Indicators	
GI ₂₉	Product & Service Policies	GI _{29.1}	Service Intensity	Da Silva et al. [70]; Ries et al. [71]
		GI _{29.2}	Reuse, Recycle, Repair, Exchange, Recall & Related Policies	
GI ₃₀	Training & Education	GI _{30.1}	Training & Education Composite Indicator	Da Silva et al. [70]; Khatib and AlAmosh [72]
		GI _{30.2}	Capital Spent on Trainings & Related Programs	

TABLE 1: Greenness KPIs and associated trackers

KPIs, Key Performance Indicators

Modelling for greenness in manufactured products

Modelling greenness in manufactured products includes assessing both individual and interconnected greenness indicators. The 30 KPIs in the previous section are essential for measuring product greenness. GTMA is used to model these KPIs. Nodes represent indicators, and edges demonstrate their influence in a digraph. A digraph representing the key performance indicators for a manufactured product can be expressed as Equation (1).

$$G_d = (GI_i, g_{(i-j)}) \quad (1)$$

where $GI_j = \{GI_1, GI_2, \dots, GI_N\}$ denotes the set of nodes representing KPIs, and $g_{i,j} = \{g_{ij}, \dots, g_{NN}\}$ denotes the set of edges showing the influence between them, where $i, j = 1, 2, \dots, N$. In the digraph, each node stands for a KPI, e.g., GI_2 is 'Recycled Material Share', and each edge shows how one KPI affects another, e.g., g_{1-2} represents the influence of GI_1 on GI_2 .

A panel of 12 experts comprising sustainability analysts, design engineers, manufacturing managers, and academic researchers from the automotive and discrete manufacturing sectors participated in developing and validating the benchmarking system. They were responsible for developing the digraph model, establishing the interrelationships among KPIs, and determining the weights of the KPIs. With 8 to 25 years of experience, their broad perspectives ensured that the proposed greenness index is both practical and academically rigorous. The experts, whose overview is presented in Table 2, were recruited through professional networks and institutional collaborations, and their participation was voluntary. Their role was to validate and refine the interrelationships among the 30 KPIs in the digraph model and to assign relative weights to each KPI using structured pairwise comparisons informed by fuzzy linguistic scales. The results are shown in a digraph (Figure 2), highlighting how the 30 KPIs influence each other.

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Expert No.	Designation	Experience (Years)	Category	Expertise
Expert 1	Senior Sustainability Analyst	14	Sustainability Analyst	Green product lifecycle assessment & environmental compliance
Expert 2	Sustainability Consultant	10	Sustainability Analyst	Carbon footprint analysis & sustainability reporting (GRI/ISO 14001)
Expert 3	EHS Manager	17	Sustainability Analyst	Environmental, health & safety auditing in automotive supply chains
Expert 4	Senior Design Engineer	12	Design Engineer	Eco-design & design for disassembly in automotive components
Expert 5	Product Development Engineer	9	Design Engineer	Material selection, lightweight design & DFM for green manufacturing
Expert 6	R&D Engineer	15	Design Engineer	Clean manufacturing processes & energy-efficient product development
Expert 7	General Manager – Manufacturing	20	Manufacturing Manager	Lean & green manufacturing operations in discrete production systems
Expert 8	Production Manager	13	Manufacturing Manager	Waste minimization, process optimization & Industry 4.0 adoption
Expert 9	Plant Manager	18	Manufacturing Manager	Sustainable plant operations & environmental compliance management
Expert 10	Associate Professor	11	Academic Researcher	Sustainable manufacturing & multi-

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				criteria decision-making (MCDM)
Expert 11	Professor	25	Academic Researcher	Industrial sustainability, green supply chain & benchmarking systems
Expert 12	Assistant Professor	8	Academic Researcher	Operations management & quantitative sustainability assessment

TABLE 2: Characteristics of experts

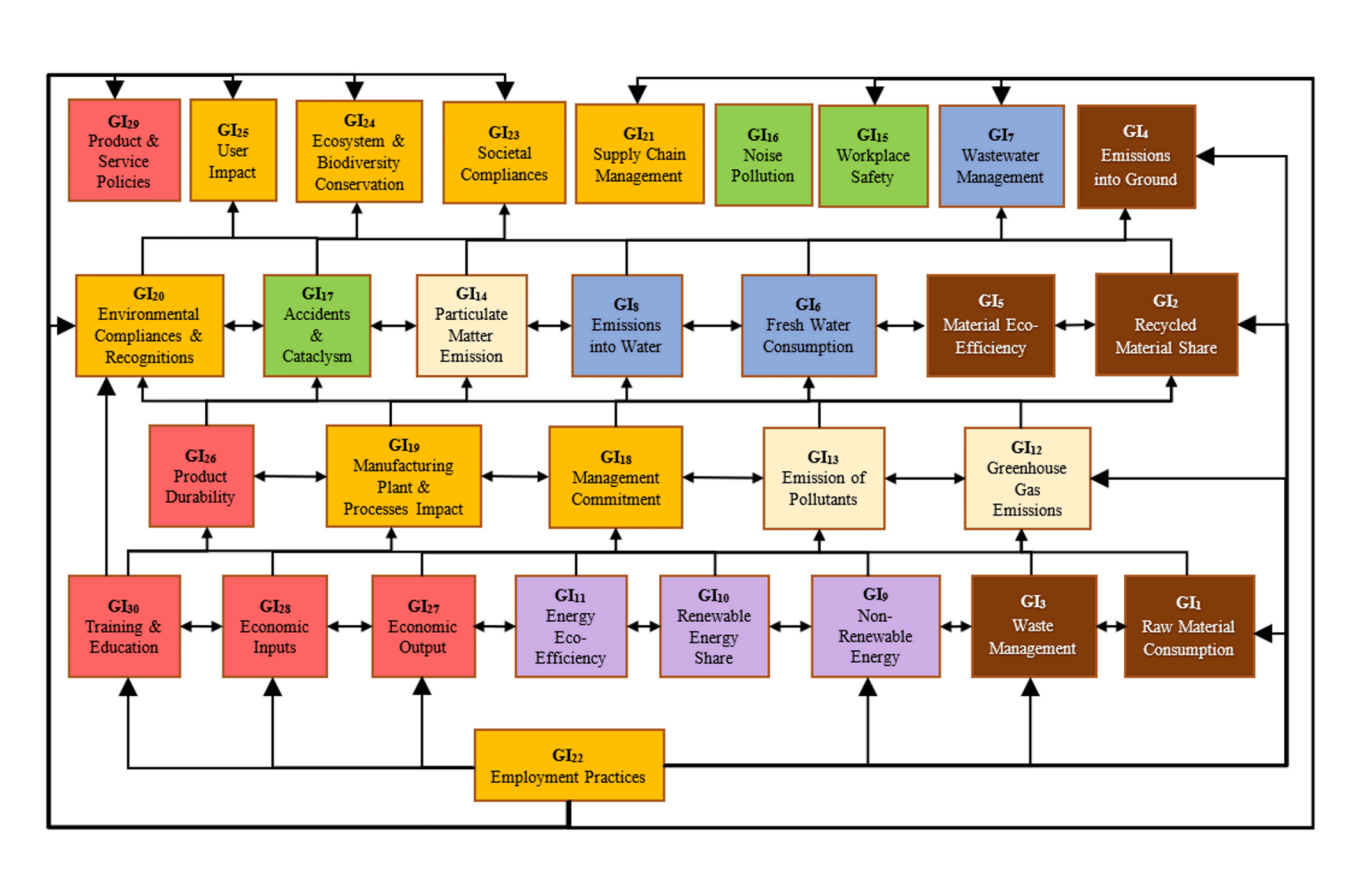


FIGURE 2: Greenness digraph of manufactured products

Representation of model using equivalent matrix

In this part, a matrix is created from the product greenness digraph to capture all interrelationships among KPIs. The digraph is converted into a matrix (Equation 2), where diagonal elements represent KPIs and off-diagonal elements show their interdependence.

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$$GI_f = \begin{bmatrix} GI_1 & g_{i1-2} & \cdots & \cdots & g_{i1-n} \\ g_{i2-1} & GI_2 & \cdots & \cdots & g_{i2-n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ g_{ij-1} & g_{ij-k} & \cdots & \cdots & g_{ij-n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ g_{iN-1} & g_{N2} & \cdots & \cdots & GI_N \end{bmatrix} \quad (2)$$

In Equation (2), 'GI₁' denotes the numerical value of the i^{th} greenness indicator and 'g_{ij}' is the degree of interrelationships among indicators. The permanent of the matrix (GI_f) written as per(GI_f) is used to define the PGAF. Combinatorial mathematics defines the Permanent function as a conventional matrix function, whereby all its terms are positive. It is useful for capturing the positive nullity of a digraph - an important concept in graph theory [73,74]. This function captures all green KPIs and their interdependencies. Equation (3) gives the general form of PGAF for a system with 'N' indicators.

$$\begin{aligned} \text{Per}(GI_{f1}) &= \prod_{i=1}^N GI_i \\ &+ \sum_i \sum_j \sum_k \sum_l \sum_m \cdots \sum_N (g_{ij}g_{ji}) GI_k GI_l GI_m \cdots GI_N \\ &+ \sum_i \sum_j \sum_k \sum_l \sum_m \cdots \sum_N (g_{ij}g_{jk}g_{ki} + g_{ik}g_{kj}g_{ji}) GI_l GI_m \cdots GI_N \\ &+ \left\{ \sum_i \sum_j \sum_k \sum_l \sum_m \cdots \sum_N (g_{ij}g_{ji})(g_{kl}g_{lk}) GI_l GI_m \cdots GI_N \right. \\ &\quad \left. + \sum_i \sum_j \sum_k \sum_l \sum_m \cdots \sum_N (g_{ij}g_{jk}g_{kl}g_{li} + g_{il}g_{lk}g_{kj}g_{ji}) GI_m \cdots GI_N \right\} \\ &+ \left[\sum_i \sum_j \sum_k \sum_l \sum_m \cdots \sum_N (g_{ij}g_{ji})(g_{kl}g_{lm}g_{mk} + g_{km}g_{ml}g_{lk}) GI_n \cdots GI_N \right. \\ &\quad \left. + \sum_i \sum_j \sum_k \sum_l \sum_m \cdots \sum_N (g_{ij}g_{jk}g_{kl}g_{lm}g_{mi} + g_{im}g_{ml}g_{lk}g_{kj}g_{ji}) GI_n \cdots GI_N \right] \\ &+ \cdots \end{aligned} \quad (3)$$

From Equation (3), it is evident that the PGAF captures all the attainable terms from a combinatorial perspective. This includes Greenness assessment KPIs, i.e., 'GI₁', and the interdependent influence term 'g_{ij}' including their degree of influence or interdependence and their potential combination. Using the fundamental concept of PGAF, an equivalent matrix is developed and presented in Equation (4). It can be observed from the matrix 'GI_f' in Equation (4) that several of the off-diagonal elements are zero. This represents that there is no interdependent relationship among the KPIs. Consequently, these zero-valued elements will be excluded from the generalized PGAF Equation (3). The evaluation of the PGAF is elaborated in the next section.

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$$GI_{f1} = \begin{bmatrix}
 GI_1 & gi_{1-2} & gi_{1-3} & 0 & 0 & 0 & 0 & gi_{1-8} & gi_{1-9} & 0 \\
 0 & gi_{1-12} & gi_{1-13} & gi_{1-14} & gi_{1-15} & 0 & gi_{1-17} & \cdots & gi_{1-30} & \\
 0 & GI_2 & gi_{2-3} & 0 & 0 & 0 & gi_{2-7} & 0 & 0 & 0 \\
 0 & gi_{2-12} & gi_{2-13} & 0 & 0 & 0 & 0 & \cdots & 0 & \\
 gi_{3-1} & gi_{3-2} & GI_3 & gi_{3-4} & 0 & gi_{3-6} & gi_{3-7} & gi_{3-8} & gi_{3-9} & 0 \\
 0 & gi_{3-12} & gi_{3-13} & gi_{3-14} & gi_{3-15} & 0 & gi_{3-17} & \cdots & gi_{3-30} & \\
 0 & 0 & 0 & GI_4 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
 0 & 0 & gi_{5-3} & 0 & GI_5 & 0 & gi_{5-7} & 0 & 0 & 0 \\
 0 & gi_{5-12} & gi_{5-13} & 0 & 0 & 0 & 0 & \cdots & 0 & \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \\
 gi_{30-1} & gi_{30-2} & gi_{30-3} & gi_{30-4} & 0 & gi_{30-6} & gi_{30-7} & gi_{30-8} & gi_{30-9} & 0 \\
 0 & gi_{30-12} & gi_{30-13} & gi_{30-14} & gi_{30-15} & 0 & gi_{30-17} & \cdots & GI_{30} &
 \end{bmatrix} \quad (4)$$

Results And Discussion

Evaluating greenness of products

Evaluation of the greenness of products is carried out by computing the PGAF first, then populating it with relevant diagonal (GI_i) and off-diagonal elements (gi_{ij}), and finally calculating the permanent of this matrix, as represented in Equation (5).

$$\text{Permanent (PGAF Matrix)} = \text{per}(GI_f) \quad (5)$$

Quantification of diagonal elements

Each KPI consists of its sub-indicators GI_{ij} where $i = 1, 2, 3, \dots, 30$ and $j = 1, 2, \dots, m$ (refer to Table 1). These trackers fall into two categories: beneficial or non-beneficial. Table 1 outlines the expectations associated with these trackers that are related to increasing greenness in a relevant way. These trackers can vary across different sectors depending upon the materials and processes involved and the required environmental standards. Individual scores for these trackers need to be derived from their qualitative attributes, as direct deduction of these trackers is often not feasible. Hence, fuzzy logic-based ranking using linguistic evaluations is employed, as established by Rao and Davim [75]. Linguistic inputs from experts are mapped to 11-point fuzzy scale numbers, which are then defuzzified into crisp values, as detailed in Table 3 below, proposed by Rao and Davim [75]. These experts are from the field of manufacturing sustainability and greenness assessments and have valuable experience. To ensure more accurate and consistent evaluations, the values are normalized within a scale ranging from 0 to 1.

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Qualitative description of linguistic variables	Assigned Values (X_{ij})
Exceptionally high	0.95
Extremely high	0.865
Very High	0.754
High	0.665
Above Average	0.59
Average	0.5
Below Average	0.41
Low	0.335
Very Low	0.225
Extremely Low	0.135
Exceptionally low	0.045

TABLE 3: Fuzzy scale for sub-indicators assessment

Refer to Rao and Davim [75].

To evaluate product greenness, this fuzzy logic approach is utilized, as shown in Table 3, taking GI_1 as a sample KPI and providing a structured method to assess greenness under uncertainty. Improved greenness of the product will be reflected when the tracker shows a reduction in raw material consumption and an increase in renewable material consumption. For example, for raw material consumption, three sub-indicators/trackers were identified ($GI_{1,1}$, $GI_{1,2}$, $GI_{1,3}$), as presented in Table 4. Thus, if the ratio of total renewable to total non-renewable material consumption per unit of product is found to be high, this will show an increasing trend towards renewable raw material consumption, and hence a higher fuzzy score will be assigned, as presented in the form of a scale in Table 3. This procedure is repeated for all other 29 KPIs.

Greenness evaluation also requires weighting each indicator (W_i). The Full Consistency Method was used to weight diagonal items (greenness indicators) according to Gautam et al. [76]. Consequently, the numerical evaluation of greenness indicators is expressed by Equation (6).

$$GI_i = W_i \left(\sum_{j=1}^N GI_{ij} \right) \quad (6)$$

where $i = 1, 2, \dots, 30$ and $j = 1, 2, \dots, m$.

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Fuzzy Scale	Tracker/Sub-Indicators		
	GI _{1.1}	GI _{1.2}	GI _{1.3}
	Total non-renewable & renewable material consumption per unit of product	Virgin material intensity	Total virgin material cost per unit of product
Exceptionally high (0.95)	A significantly large decrease in non-renewable & renewable material consumption per unit of product is attained	A significantly large decrease in virgin material intensity is achieved	A significantly large decrease in total virgin material cost per unit of product is attained
Extremely high (0.865)	An exceptionally high reduction in total non-renewable & renewable material consumption per unit of product is attained	An exceptionally high reduction in virgin material intensity is attained	An exceptionally high reduction in total virgin material cost per unit of product is attained
Very High (0.754)	A substantial reduction in total non-renewable & renewable material consumption per unit of product is attained	A substantial reduction in virgin material intensity is attained	A substantial reduction in total virgin material cost per unit of product is attained
High (0.665)	A significant reduction in total non-renewable & renewable material consumption per unit of product is attained	A significant reduction in virgin material intensity is attained	A significant reduction in total virgin material cost per unit of product is attained
Above Average (0.590)	A moderate to high reduction in total non-renewable & renewable material consumption per unit of product is attained	A moderate to high reduction in virgin material intensity is attained	A moderate to high reduction in total virgin material cost per unit of product is attained
Average (0.500)	A moderate reduction in total non-renewable & renewable material consumption per unit of product is attained	A moderate reduction in virgin material intensity is attained	A moderate reduction in total virgin material cost per unit of product is attained
Below Average (0.410)	A modest reduction in total non-renewable & renewable material consumption per unit of product is attained	A modest reduction in virgin material intensity is attained	A modest reduction in total virgin material cost per unit of product is attained

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Low (0.335)	A slight reduction in total non-renewable & renewable material consumption per unit of product is attained	A slight reduction in virgin material intensity is attained	A slight reduction in total virgin material cost per unit of product is attained
Very Low (0.225)	A negligible reduction in total non-renewable & renewable material consumption per unit of product is attained	A negligible reduction in virgin material intensity is attained	A negligible reduction in total virgin material cost per unit of product is attained
Extremely Low (0.135)	An extremely minimal reduction in total non-renewable & renewable material consumption per unit of product is attained	An extremely minimal reduction in virgin material intensity is attained	An extremely minimal reduction in total virgin material cost per unit of product is attained
Exceptionally low (0.045)	An insignificant or no reduction in total non-renewable & renewable material consumption per unit of product is attained	An insignificant or no reduction in virgin material intensity is attained	An insignificant or no reduction in total virgin material cost per unit of product is attained

TABLE 4: Fuzzy scale for assessing tracker/sub-indicators of Raw Material Consumption (GI1)

Quantification of off-diagonal elements

The degree of influence exerted by one KPI on another is indicated by the off-diagonal elements (gi_{ij}). A simple scale from 0 to 4 is used to showcase this degree of influence, where '0' means no influence at all, '1' means minor influence, '2' means moderate influence, '3' means fairly strong influence, and '4' means the strongest influence.

For example, Raw Material Consumption (GI_1) has a high influence on Recycled Material Share (GI_2), Waste Management (GI_3), Emissions into Ground (GI_4), Material Eco-Efficiency (GI_5), Fresh Water Consumption (GI_6), and Greenhouse Gas Emissions (GI_{12}); an above-average influence on Wastewater Management (GI_7), Emissions into Water (GI_8), Non-Renewable Energy Consumption (GI_9), Emission of Pollutants (GI_{13}), Particulate Matter Emission (GI_{14}), and Management Commitment (GI_{18}); and an average influence on Manufacturing Plant & Processes Impact (GI_{19}), Environmental Compliances & Recognitions (GI_{20}), Supply Chain Management (GI_{21}), Employment Practices (GI_{22}), and Economic Output (GI_{27}). Raw Material Consumption (GI_1) has a minor influence on Workplace Safety (GI_{15}), Accidents & Cataclysm (GI_{17}), Societal Compliances (GI_{23}), User Impact (GI_{25}), Product Durability (GI_{26}), Economic Inputs (GI_{28}), Product & Service Policies (GI_{29}), and Training & Education (GI_{30}). Similarly, Raw Material Consumption (GI_1) has no impact on other KPIs, such as Renewable Energy Share (GI_{10}), Energy Eco-Efficiency (GI_{11}), and Noise Pollution (GI_{16}). Likewise, the influence of the other indicators is evaluated and displayed in Figure 3.

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KPI	GI ₁	GI ₂	GI ₃	GI ₄	GI ₅	GI ₆	GI ₇	GI ₈	GI ₉	GI ₁₀	GI ₁₁	GI ₁₂	GI ₁₃	GI ₁₄	GI ₁₅	GI ₁₆	GI ₁₇	GI ₁₈	GI ₁₉	GI ₂₀	GI ₂₁	GI ₂₂	GI ₂₃	GI ₂₄	GI ₂₅	GI ₂₆	GI ₂₇	GI ₂₈	GI ₂₉	GI ₃₀	
GI ₁	GI ₁	4	4	4	4	4	3	3	3	0	0	4	3	3	1	0	1	3	2	2	2	1	1	2	1	1	2	1	1	1	
GI ₂	0	GI ₂	4	0	0	0	3	0	0	0	0	3	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	
GI ₃	1	4	GI ₃	1	0	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
GI ₄	0	0	0	GI ₄	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
GI ₅	0	0	4	0	GI ₅	0	2	0	0	0	0	3	1	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	
GI ₆	0	0	2	0	0	GI ₆	4	0	0	0	0	2	2	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	
GI ₇	0	0	3	0	0	0	GI ₇	0	0	0	0	1	3	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	
GI ₈	0	0	0	0	0	0	4	GI ₈	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	
GI ₉	2	2	2	2	0	1	2	2	GI ₉	0	0	4	3	4	1	0	1	1	2	3	2	1	2	2	2	2	2	4	4	2	2
GI ₁₀	2	1	1	1	0	1	1	1	4	GI ₁₀	0	4	4	3	1	0	1	1	2	3	2	1	3	3	2	2	3	4	3	2	
GI ₁₁	1	1	1	1	0	1	1	1	4	0	GI ₁₁	3	4	3	1	0	1	2	3	4	2	1	3	3	4	3	4	3	3	2	
GI ₁₂	2	1	2	1	0	1	2	2	3	0	0	GI ₁₂	3	4	2	0	1	2	2	4	1	2	4	4	3	4	3	3	4	2	
GI ₁₃	1	1	2	1	0	1	1	2	3	0	0	3	GI ₁₃	4	2	0	1	1	2	3	1	1	4	4	3	3	3	3	4	2	
GI ₁₄	0	0	1	0	0	0	2	0	0	0	0	4	3	GI ₁₄	0	0	0	1	2	3	0	0	3	3	3	0	0	0	0	0	
GI ₁₅	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GI ₁₅	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
GI ₁₆	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GI ₁₆	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
GI ₁₇	0	0	1	0	0	0	1	0	0	0	0	2	1	0	0	0	GI ₁₇	0	0	3	0	0	0	0	0	0	0	0	0	0	
GI ₁₈	4	4	4	3	0	4	3	3	3	0	0	3	3	2	3	0	3	GI ₁₈	3	3	3	3	3	2	2	2	4	4	2	4	
GI ₁₉	2	3	3	3	0	3	3	4	3	0	0	4	3	2	3	0	3	3	GI ₁₉	3	2	3	3	3	2	2	4	4	2	4	
GI ₂₀	2	0	3	0	0	4	3	0	0	0	0	3	3	0	0	0	0	3	3	GI ₂₀	0	0	3	3	3	3	0	0	0	0	
GI ₂₁	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GI ₂₁	0	0	0	0	0	0	0	0	0	
GI ₂₂	1	1	3	2	0	2	2	1	1	0	0	1	1	1	4	0	4	3	3	1	1	GI ₂₂	2	1	1	1	3	4	3	4	
GI ₂₃	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GI ₂₃	0	0	0	0	0	0	0	0	
GI ₂₄	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GI ₂₄	0	0	0	0	0	0	0	
GI ₂₅	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GI ₂₅	0	0	0	0	0	
GI ₂₆	0	0	0	0	0	2	0	0	0	0	0	2	2	0	0	0	2	1	2	0	0	2	2	4	GI ₂₆	0	0	0	0	0	
GI ₂₇	1	1	2	1	0	2	2	2	3	0	0	3	2	1	2	0	2	3	2	2	3	3	2	2	1	1	GI ₂₇	4	3	3	
GI ₂₈	1	1	1	1	0	2	3	2	3	0	0	3	3	2	2	0	1	4	3	2	3	3	1	2	1	1	2	GI ₂₈	3	3	0
GI ₂₉	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GI ₂₉	0	0
GI ₃₀	1	1	2	2	0	2	2	2	2	0	0	2	1	1	3	0	3	2	2	2	1	3	2	2	1	1	2	3	2	GI ₃₀	

FIGURE 3: Influence level across greenness KPIs

KPIs, Key Performance Indicators

Evaluation of PGI and benchmarking

The PGI is a numerical evaluation that captures the effect of adopting product-level sustainability practices within the manufacturing sector. It is assessed through the PGAF, which assigns a score to GI_{ij} and GI_{ij} based on these practices. For benchmarking the greenness of products by different manufacturers, two other important metrics, such as IPGI and PGIR, are proposed. IPGI reflects the best possible PGI a manufacturer can achieve, setting a target for sustainability efforts. In this ideal case, all sub-indicators (GI_{ij}) get the top fuzzy score of 0.95, while gi_{ij} values follow the earlier 0-4 scale. The benchmark product, i.e., the product with the highest PGI, serves as the reference point. The PGIR is the ratio of the PGI of a product manufactured by the firm to the PGI of an ideal product manufactured with all ideal conditions possible and expressed as Equation (7).

$$PGIR = \frac{\text{PGI of product by particular firm}}{\text{PGI of ideal manufactured product}} \quad (7)$$

PGIR ranges from 0 to 1, where 1 is ideal and 0 means no sustainability effort. A low PGIR highlights the need for improvement, and efforts should aim to raise it closer to the Ideal Value of 1. Both IPGI and PGIR collectively facilitate structured and data-driven benchmarking to identify best-in-class products from a sustainability perspective.

Case example

A case study of two automotive component manufacturers producing the Universal Joint Cross is presented to demonstrate the framework's applicability and evaluate the PGI. Both firms are similar-sized small and medium-sized enterprises. Inputs for the quantification of KPIs were collected directly through site visits, discussions with personnel,

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and observation of production process metrics, with the voluntary participation and cooperation of the concerned organizations. To maintain anonymity, the firms are referred to as Firm A and Firm B throughout the manuscript, following common practice in industrial case study research.

As per the procedure explained earlier, each product's greenness KPI was rated using the linguistic fuzzy scale shown in Table 5. Using this scale, Table 6 was prepared. It includes the qualitative evaluation scores for different indicators for both manufacturing firms 'A' and 'B'. The evaluation process for the greenness trackers/sub-indicators is explained for every KPI of Firm A and Firm B. The case study responses for each tracker/sub-indicator are also presented in Table 6.

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S. No.	KPI Symbol	Weight of KPIs (W_i)
1	GI ₁	0.02957
2	GI ₂	0.02910
3	GI ₃	0.03249
4	GI ₄	0.02851
5	GI ₅	0.02758
6	GI ₆	0.05389
7	GI ₇	0.05396
8	GI ₈	0.04519
9	GI ₉	0.04985
10	GI ₁₀	0.04379
11	GI ₁₁	0.04666
12	GI ₁₂	0.05481
13	GI ₁₃	0.05128
14	GI ₁₄	0.04548
15	GI ₁₅	0.05866
16	GI ₁₆	0.05260
17	GI ₁₇	0.05320
18	GI ₁₈	0.01495
19	GI ₁₉	0.01212
20	GI ₂₀	0.01346
21	GI ₂₁	0.01211

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22	GI ₂₂	0.01819
23	GI ₂₃	0.01688
24	GI ₂₄	0.01218
25	GI ₂₅	0.01763
26	GI ₂₆	0.02372
27	GI ₂₇	0.02754
28	GI ₂₈	0.02597
29	GI ₂₉	0.02478
30	GI ₃₀	0.02384

TABLE 5: Weight of individual KPI from FUCOM analysis

FUCOM, Full Consistency Method; KPI, Key Performance Indicator

Utilizing Equation (5), KPI values of manufacturing Firms A and B are calculated. For example, the value of Raw Material Consumption (GI₁) for Firm A was calculated as follows:

$$(GI_1)_A = W_i \sum (G_{ij})_A = W_1 \sum (GI_{1.1} + GI_{1.2} + GI_{1.3})_A$$

From Table 5, $W_1 = 0.02957$, and from Table 6, $\sum (GI_{1.1} + GI_{1.2} + GI_{1.3})_A = 0.135 + 0.135 + 0.410 = 0.680$.

Hence, $(GI_1)_A = 0.02957 \times 0.680 = 0.0201$.

In a similar way, the values of the other greenness KPIs were evaluated for both manufacturing firms (Table 7). These values are presented as the diagonal elements of the matrices for Firms A and B in Equations (8) and (9), respectively. Using the data from Tables 5 and 6, the product greenness PGAF matrices were constructed for both firms. To ensure consistency, the diagonal values were rounded and then normalized using a scale factor of 100x. The greenness matrices of Firms A and B and for the Ideal PGI, i.e., GI_{fA} , GI_{fB} , and GI_{fideal} , respectively, are derived as shown in the matrices in Equations (8), (9), and (10).

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KPI Symbol	Tracker Symbol	Firm A		Firm B	
		Evaluation	Score (G_{ij}) _A	Evaluation	Score (G_{ij}) _B
GI ₁	GI _{1,1}	Extremely Low	0.135	Above Average	0.59
	GI _{1,2}	Extremely Low	0.135	Above Average	0.59
	GI _{1,3}	Below Average	0.41	Low	0.335
GI ₂	GI _{2,1}	Below Average	0.41	Above Average	0.59
	GI _{2,2}	Above Average	0.59	Above Average	0.59
GI ₃	GI _{3,1}	Low	0.335	Average	0.5
	GI _{3,2}	Below Average	0.41	Average	0.5
	GI _{3,3}	Extremely Low	0.135	Above Average	0.59
GI ₄	GI _{4,1}	Low	0.335	Low	0.335
	GI _{4,2}	Average	0.5	Below Average	0.41
GI ₅	GI _{5,1}	Average	0.5	Above Average	0.59
	GI _{5,2}	Exceptionally Low	0.045	Below Average	0.41
GI ₆	GI _{6,1}	Below Average	0.41	Below Average	0.41
	GI _{6,2}	Exceptionally Low	0.045	Average	0.5
GI ₇	GI _{7,1}	Below Average	0.41	Low	0.335
	GI _{7,2}	Low	0.335	Above Average	0.59
	GI _{7,3}	Exceptionally Low	0.045	Average	0.5
GI ₈	GI _{8,1}	Extremely Low	0.135	Average	0.5
	GI _{8,2}	Above Average	0.59	Exceptionally low	0.045

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	Gl _{8,3}	Below Average	0.41	Exceptionally low	0.045
Gl ₉	Gl _{9,1}	Low	0.335	Average	0.5
	Gl _{9,2}	Below Average	0.41	Low	0.335
Gl ₁₀	Gl _{10,1}	Extremely Low	0.135	Average	0.5
	Gl _{10,2}	Average	0.5	Above Average	0.59
Gl ₁₁	Gl _{11,1}	Low	0.335	Below Average	0.41
	Gl _{11,2}	Below Average	0.41	Exceptionally low	0.045
Gl ₁₂	Gl _{12,1}	Average	0.5	High	0.665
	Gl _{12,2}	Low	0.335	High	0.665
Gl ₁₃	Gl _{13,1}	Below Average	0.41	High	0.665
	Gl _{13,2}	Low	0.335	Above Average	0.59
Gl ₁₄	Gl _{14,1}	Low	0.335	High	0.665
	Gl _{14,2}	Below Average	0.41	Extremely high	0.865
Gl ₁₅	Gl _{15,1}	Exceptionally Low	0.045	High	0.665
	Gl _{15,2}	Low	0.335	Exceptionally high	0.95
Gl ₁₆	Gl _{16,1}	Average	0.5	Above Average	0.59
	Gl _{16,2}	Exceptionally low	0.045	High	0.665
Gl ₁₇	Gl _{17,1}	Extremely Low	0.135	High	0.665
	Gl _{17,2}	Below Average	0.41	Extremely high	0.865
Gl ₁₈	Gl _{18,1}	Average	0.5	High	0.665
	Gl _{18,2}	Low	0.335	Extremely high	0.865
	Gl _{18,3}	Low	0.335	Above Average	0.59

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Gl ₁₉	Gl _{19.1}	Exceptionally low	0.045	Exceptionally high	0.95
	Gl _{19.2}	Low	0.335	Average	0.5
Gl ₂₀	Gl _{20.1}	Average	0.5	Very High	0.754
	Gl _{20.2}	Below Average	0.41	Very High	0.754
Gl ₂₁	Gl _{21.1}	Average	0.5	Very High	0.754
	Gl _{21.2}	Exceptionally low	0.045	Below Average	0.41
Gl ₂₂	Gl _{22.1}	Average	0.5	High	0.665
	Gl _{22.2}	Low	0.335	Low	0.335
Gl ₂₃	Gl _{23.1}	Above Average	0.59	Low	0.335
	Gl _{23.2}	Average	0.5	Below Average	0.41
Gl ₂₄	Gl _{24.1}	Extremely Low	0.135	Average	0.5
	Gl _{24.2}	Extremely high	0.865	High	0.665
Gl ₂₅	Gl _{25.1}	Extremely Low	0.135	Extremely Low	0.135
	Gl _{25.2}	Above Average	0.59	High	0.665
Gl ₂₆	Gl _{26.1}	Below Average	0.41	Extremely high	0.865
	Gl _{26.2}	Extremely Low	0.135	High	0.665
Gl ₂₇	Gl _{27.1}	Below Average	0.41	Very High	0.754
	Gl _{27.2}	Very High	0.754	Low	0.335
Gl ₂₈	Gl _{28.1}	Average	0.5	Extremely Low	0.135
	Gl _{28.2}	Exceptionally low	0.045	Low	0.335
Gl ₂₉	Gl _{29.1}	Below Average	0.41	Extremely Low	0.135
	Gl _{29.2}	Average	0.5	Above Average	0.59

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GI ₃₀	GI _{30.1}	Exceptionally high	0.95	Exceptionally high	0.95
	GI _{30.2}	High	0.665	High	0.665

TABLE 6: Tracker/sub-indicator-wise quantification of all greenness KPIs using the linguistic fuzzy scale

KPI, Key Performance Indicator

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KPI Symbol	Firm A $\Sigma(GI_{ij})_A$	Firm B $\Sigma(GI_{ij})_B$	Ideal Value $\Sigma(GI_{ij})_{Ideal}$
GI ₁	0.680	1.515	2.850
GI ₂	1.000	1.180	1.900
GI ₃	0.880	1.590	2.850
GI ₄	0.835	0.745	1.900
GI ₅	0.545	1.000	1.900
GI ₆	0.455	0.910	1.900
GI ₇	0.790	1.425	2.850
GI ₈	1.135	0.590	2.850
GI ₉	0.745	0.835	1.900
GI ₁₀	0.635	1.090	1.900
GI ₁₁	0.745	0.455	1.900
GI ₁₂	0.835	1.330	1.900
GI ₁₃	0.745	1.255	1.900
GI ₁₄	0.745	1.530	1.900
GI ₁₅	0.380	1.615	1.900
GI ₁₆	0.545	1.255	1.900
GI ₁₇	0.545	1.530	1.900
GI ₁₈	1.170	2.120	2.850
GI ₁₉	0.380	1.450	1.900
GI ₂₀	0.910	1.508	1.900
GI ₂₁	0.545	1.164	1.900

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GI ₂₂	0.835	1.000	1.900
GI ₂₃	1.090	0.745	1.900
GI ₂₄	1.000	1.165	1.900
GI ₂₅	0.725	0.800	1.900
GI ₂₆	0.545	1.530	1.900
GI ₂₇	1.164	1.089	1.900
GI ₂₈	0.545	0.470	1.900
GI ₂₉	0.910	0.725	1.900
GI ₃₀	1.615	1.615	1.900

TABLE 7: Quantification of greenness KPIs for firms A, B, and Ideal

KPI, Key Performance Indicator

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KPI Symbol	Weight of KPI (W_i)	Firm A KPI Value $GI_{iA} = W_i(\sum GI_{ij})_A$	Firm B KPI Value $GI_{iB} = W_i(\sum GI_{ij})_B$	Ideal KPI Value $GI_{i\text{ideal}} = W_i(\sum GI_{ij})_{\text{ideal}}$
GI ₁	0.02957	0.0201	0.045	0.084
GI ₂	0.02910	0.0291	0.034	0.055
GI ₃	0.03249	0.0286	0.052	0.093
GI ₄	0.02851	0.0238	0.021	0.054
GI ₅	0.02758	0.0150	0.028	0.052
GI ₆	0.05389	0.0245	0.049	0.102
GI ₇	0.05396	0.0426	0.077	0.154
GI ₈	0.04519	0.0513	0.027	0.129
GI ₉	0.04985	0.0371	0.042	0.095
GI ₁₀	0.04379	0.0278	0.048	0.083
GI ₁₁	0.04666	0.0348	0.021	0.089
GI ₁₂	0.05481	0.0458	0.073	0.104
GI ₁₃	0.05128	0.0382	0.064	0.097
GI ₁₄	0.04548	0.0339	0.070	0.086
GI ₁₅	0.05866	0.0223	0.095	0.111
GI ₁₆	0.05260	0.0287	0.066	0.100
GI ₁₇	0.05320	0.0290	0.081	0.101
GI ₁₈	0.01495	0.0175	0.032	0.043
GI ₁₉	0.01212	0.0046	0.018	0.023
GI ₂₀	0.01346	0.0122	0.020	0.026

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GI ₂₁	0.01211	0.0066	0.014	0.023
GI ₂₂	0.01819	0.0152	0.018	0.035
GI ₂₃	0.01688	0.0184	0.013	0.032
GI ₂₄	0.01218	0.0122	0.014	0.023
GI ₂₅	0.01763	0.0128	0.014	0.034
GI ₂₆	0.02372	0.0129	0.036	0.045
GI ₂₇	0.02754	0.0321	0.030	0.052
GI ₂₈	0.02597	0.0142	0.012	0.049
GI ₂₉	0.02478	0.0226	0.018	0.047
GI ₃₀	0.02384	0.0385	0.039	0.045
Sum	0.9999	0.7524	1.171	2.066

TABLE 8: KPI value for firms A, B, and Ideal

KPI, Key Performance Indicator

Table 8 presents KPI-wise evaluation for both firms (GI_{IA} and GI_{IB}) alongside the corresponding ideal benchmark value (GI_{ideal}). The aggregate weighted KPI scores, computed as the summation of all 30 indicators, provide overall performance scores of 0.7524 for Firm A and 1.171 for Firm B, against an ideal benchmark of 2.066. The findings indicate that Firm B achieves approximately 56.7% of the ideal benchmark, while Firm A obtains only 36.4%, highlighting a relatively stronger performance of Firm B while also revealing a substantial gap from the ideal in both firms.

$$GI_{IA} = \begin{bmatrix} 2.00 & 4 & 4 & 4 & 4 & 4 & 3 & 3 & 3 & 0 \\ \dots & 1 & & & & & & & & \\ 0 & 2.91 & 4 & 0 & 0 & 0 & 3 & 0 & 0 & 0 \\ \dots & 0 & & & & & & & & \\ 1 & 4 & 2.86 & 1 & 0 & 1 & 1 & 1 & 1 & 0 \\ \dots & 1 & & & & & & & & \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & & & & & & & & \\ 1 & 1 & 2 & 2 & 0 & 2 & 2 & 2 & 2 & 0 \\ \dots & 3.85 & & & & & & & & \end{bmatrix} \quad (8)$$

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$$GI_{fB} = \begin{bmatrix} 4.480 & 4 & 4 & 4 & 4 & 4 & 3 & 3 & 3 & 0 \\ \dots & 1 & & & & & & & & \\ 0 & 3.434 & 4 & 0 & 0 & 0 & 3 & 0 & 0 & 0 \\ \dots & 0 & & & & & & & & \\ 1 & 4 & 5.166 & 1 & 0 & 1 & 1 & 1 & 1 & 0 \\ \dots & 1 & & & & & & & & \\ 0 & 0 & 0 & 2.124 & 0 & 0 & 0 & 0 & 0 & 0 \\ \dots & 0 & & & & & & & & \\ 0 & 0 & 4 & 0 & 2.758 & 0 & 2 & 0 & 0 & 0 \\ \dots & 0 & & & & & & & & \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \ddots & \vdots & & & & & & & & \\ 1 & 1 & 2 & 2 & 0 & 2 & 2 & 2 & 2 & 0 \\ \dots & 3.850 & & & & & & & & \end{bmatrix} \quad (9)$$

$$GI_{fIdeal} = \begin{bmatrix} 8.427 & 4 & 4 & 4 & 4 & 4 & 3 & 3 & 3 & 0 \\ \dots & 1 & & & & & & & & \\ 0 & 5.529 & 4 & 0 & 0 & 0 & 3 & 0 & 0 & 0 \\ \dots & 0 & & & & & & & & \\ 1 & 4 & 9.261 & 1 & 0 & 1 & 1 & 1 & 1 & 0 \\ \dots & 1 & & & & & & & & \\ 0 & 0 & 0 & 5.416 & 0 & 0 & 0 & 0 & 0 & 0 \\ \dots & 0 & & & & & & & & \\ 0 & 0 & 4 & 0 & 5.240 & 0 & 2 & 0 & 0 & 0 \\ \dots & 0 & & & & & & & & \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \ddots & \vdots & & & & & & & & \\ 1 & 1 & 2 & 2 & 0 & 2 & 2 & 2 & 2 & 0 \\ \dots & 4.530 & & & & & & & & \end{bmatrix} \quad (10)$$

The permanents of the matrices shown in Equations (8), (9), and (10) were then evaluated. Since Figure 3 depicts several off-diagonal elements as zero, reflecting the absence of interdependence between certain KPI pairs as determined from the digraph, this sparsity allows the permanent to be decomposed into contributions from non-interacting subgraphs, significantly reducing the effective computational order. Zero-valued off-diagonal elements were excluded a priori, reducing the effective computational order [77,78]. This permanent represents the PGI of both firms. For Firm A, $(PGI)_A = 4.845 \times 10^{12}$, and for Firm B, $(PGI)_B = 6.254 \times 10^{12}$ were obtained. For obtaining the ideal PGI, the permanent of the ideal PGI matrix presented in Equation (10) was calculated. This provides the ideal value of the Product Greenness Index, i.e., $(PGI)_{Ideal} = 6.597 \times 10^{13}$. In order to better understand the greenness adoption by the firms, the PGIR of both manufacturing firms is calculated as per Equation (7).

PGIRs of both firms were obtained using Equations (11) and (12).

$$PGIR_A = \frac{\text{PGI of manufacturing firm A}}{\text{PGI of ideal manufacturing firm}} \quad (11)$$

$$PGIR_B = \frac{\text{PGI of manufacturing firm B}}{\text{PGI of ideal manufacturing firm}} \quad (12)$$

From the equations, $PGIR_A$ and $PGIR_B$ come out to be 0.073 and 0.094, respectively.

As can be observed, Firm B has a higher PGI and PGIR compared with Firm A. However, when compared to the ideal PGI value, i.e., $(PGI)_{Ideal} = 6.597 \times 10^{13}$, both firms show extremely low scores. This indicates that both companies need to make greater efforts to improve the greenness of their products. Comparing the case study matrices with the ideal matrix highlights the need to identify which indicators most influence the PGI values.

How to cite this article:

Comparative analysis and discussion of PGI assessment

The proposed PGI framework has been applied to two Indian automotive component manufacturers. Using 30 KPIs across environmental, economic, and social dimensions, PGI values were computed based on a matrix permanent. Firm B achieved a PGI of 6.254×10^{12} and a PGIR of 0.094, outperforming Firm A, which had a PGI of 4.845×10^{12} and a PGIR of 0.073. However, both firms scored considerably lower than the ideal PGI, revealing significant greenness gaps. Key deficiencies were observed in raw material consumption, recycled material usage, and emissions. Firm B performed better in workplace safety, biodiversity conservation, and renewable energy usage. The results validate the model's capability to capture interdependent relationships among greenness indicators and provide actionable insights. This benchmarking enables manufacturers to strategically identify and improve weak areas towards cleaner production goals.

Although the proposed framework performed effectively for the 30-KPI system considered in this study, its computational complexity may increase as the number of KPIs grows. The greenness index is calculated using the permanent of an $N \times N$ matrix, and the computation becomes more complex for larger systems. However, for practical industrial applications, KPI sets are generally limited by the scope of assessment, organizational boundaries, and data availability. Future studies may further improve the scalability of the framework by dividing the KPI system into smaller functional groups, using sparse matrix structures, and applying efficient approximation methods for permanent calculation.

Despite its practical applicability, the proposed framework has certain limitations. The determination of KPI weights, fuzzy scores, and interdependency values primarily depends on expert judgment, which may introduce subjectivity into the assessment process. Furthermore, validation through a single automotive case study limits the immediate generalizability of the findings across broader industrial sectors. The fixed interdependency scale adopted in the framework may also not fully represent the dynamic relationships among KPIs under changing technological and regulatory environments.

Conclusions

This study presents a comprehensive framework for evaluating product-level sustainability using graph theory and a matrix-based PGI. The framework also offers an opportunity for inter-firm benchmarking in line with green operation strategies, aligning with emerging trends in sustainability benchmarking literature. By accounting for the performance and interdependence among 30 multidimensional KPIs, the PGI provides a structured quantification of product greenness. The comparative analysis of two manufacturing firms (A and B) using the PGIR illustrates the utility of the framework, revealing that even relatively mature firms significantly underperform when benchmarked against ideal sustainability standards. The results indicate that Firm B achieved a higher PGI value of 6.254×10^{12} with a corresponding PGIR of 0.094, whereas Firm A attained a lower PGI of 4.845×10^{12} with a corresponding PGIR of 0.073. Despite Firm B outperforming Firm A, both firms fall substantially short of the ideal PGI benchmark of 6.597×10^{13} , exposing greenness gaps that inter-firm comparison alone would not have brought to light. Furthermore, the aggregate weighted KPI scores of both firms also substantiate this, with Firm B achieving only 1.171 ($\approx 56.7\%$) of the ideal benchmark value (2.066), while Firm A reaches only 0.752 ($\approx 36.4\%$).

From a managerial perspective, the PGI framework serves as a powerful diagnostic tool for operations and sustainability managers to identify priority improvement areas, balance trade-offs, and enhance compliance with sustainability standards. The framework enables firms to quantify greenness not only in terms of individual KPIs but also their network influence - an aspect typically overlooked in traditional LCA-based tools. By identifying top-performing products in terms of greenness, manufacturers can benchmark their designs, isolate improvement opportunities, and promote the diffusion of environmentally superior practices across the sector. The proposed framework's primary limitations include reliance on expert judgment for KPI weights and interdependency values and validation within a single automotive case study. Computational scalability, data intensity, and the static nature of the framework further present challenges for large-scale industrial implementation. Robustness analysis, including sensitivity and uncertainty analyses, represents an important direction for future research to assess the stability of the PGI and PGIR under variations in expert-derived parameters.

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Future work should also focus on multi-sector validation and dynamic, data-driven weighting approaches to enhance scalability and objectivity. Enhancing the model's adaptability by incorporating fuzzy weights for sector-specific regulations and stakeholder priorities would further improve its practical relevance.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue.

Animal subjects: All authors have confirmed that this study did not involve animal subjects or tissue.

Conflicts of interest: In compliance with [the ICMJE uniform disclosure form](#), all authors declare the following:

- **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work.
- **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work.
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Data Availability Statements

Data sharing is not applicable. This work is theoretical; no datasets were generated or analyzed.

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