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Sustainability framework for manufacturing in the steel industry: emphasis on eco-centric and sociocentric dimensions

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Abstract
Global policies, legislation, and eco-friendly initiatives have induced the steel industry to integrate sustainable development approaches. Sustainability requires all phases from raw material sourcing to transportation to waste and carbon footprint elimination—yielding positive effects. This research employs a two-step approach in sustainability. The first phase entails conducting a systematic literature review to construct a framework identifying the sustainability key drivers, and afterwards, validating them with industry professionals. In this study, these criteria are weighted and ranked using the Best–Worst Method (BWM) within the bounds of the social and environmental aspects aimed at creating an industry tailored sustainability framework. Findings indicate that the primary ranked environmental concern is 'E6 (Top management commitment),' trailed by 'E2 (Procurement of environmentally friendly raw materials)' and 'E4 (Technology advancement).' Regarding social aspects, the top-ranked criteria observed as 'S7 (Employee satisfaction) followed by 'S6 (ISO 26000),' and 'S2 (Ethics).' These results aid steel makers and policymakers remain relevant in the market by assisting the planning process of their business operational efficiencies, sustainability policies, and compliance regulations. This sustainability framework allows the steel industry to improve its competitive position by deepening the integration of social and environmental practices for enduring performance.

Keywords Sustainability, Manufacturing firms, Social and environmental, Best–worst method

1 Introduction

Concerns regarding the environment, regulations, and stakeholders are now driving the industries towards adopting green and sustainable manufacturing practices [46]. Digital technologies are crucial in the modern world when it comes to advancing sustainable manufacturing policies. Narkhede et al. [67] explored its relationship with Industry 5.0 and proposed the triple bottom line model, which adds resilience in value creation, social welfare, and sustainability. Moreover, Agarwal et al. [5] highlighted that organizations tend to face challenges in achieving the optimal balance among the three spheres of social, economic, and environmental sustainability. As industrial activities are growing across the globe, they pose an increasingly important concern for manufacturing companies [102, 103]. The rapid growth of industries, especially within the developing economies, has increased resources and environmental damage, which poses serious threats to ecology [74]. The fast-growing depletion of natural resources provides a challenge for the industries as they need to reconcile the demands for production with the need to protect the environment. Businesses need to maintain a balance in fulfilling the needs of people and protecting the environment. As defined by Yuan and Zhang, [113], sustainability is a collaborative process requiring many different parties such as investors, employees, customers, suppliers, members of the community, and government bodies. Governments are of particular importance when it comes to formulating sustainability policies and regulations because they have the authority to compel industries to embrace sustainable practices. Industries can be motivated to use more environmentally friendly practices if policymakers outline clear frameworks as guidelines, encouraging a shift towards greener servicing systems for the long term [116]. Sustainability is often categorized into three dimensions: eco-centric, techno-centric, and socio-centric [73]. In the context of steel manufacturing sector, "*sustainability can be defined as the ability of steel production methods to minimize environmental damage and promote social well-being while meeting current production demands without endangering the ability of future generations to meet their own needs*". Whereas, Eco-centric sustainability, which aims to reduce environmental impacts like carbon emissions, resource depletion, and energy consumption, and sociocentric sustainability, which addresses human and social aspects like employee welfare, community development, organizational ethics, and inclusive labor practices, are the two main dimensions that capture this dual emphasis. This study aims to provide a comprehensive framework that is suited to the operational realities and sustainability objectives of the steel industry by defining sustainability along these dimensions [13, 64].

The steel manufacturing sector has been recognized as one of the industries with high energy consumption and associated greenhouse gas emissions, with steel accounting for roughly 7–9% of the world's CO_2 emissions [39]. Despite the enormous effort directed towards achieving sustainability goals in steel production, there remain gaps regarding the holistic systematic evaluation frameworks that in some way integrate or consider sustainability metrics. Recently, Sen Gupta et al. (2024d) discussed that there needs to be a lot of research in sustainability. Current studies have exhaustively analyzed the achievement of sustainability in manufacturing by pinpointing critical drivers of environmental, social, and economic performance. In the context of the steel industry, the impact of technology, regulatory frameworks, supply chain management, and CSR have been studied regarding their contributions to sustainability [46, 67]. The implementation of low carbon technologies, including hydrogen-based steelmaking, carbon capture and storage (CCS), and electric arc furnaces (EAFs), is recognized as instrumental in achieving carbon emission reduction and energy efficiency improvement [5]. The circular economy approach, particularly scrap metal recycling and waste reduction, is also recognized for bolstering the sector's sustainability. In addition, some studies stress the need for sustained employee engagement, employee health and safety, and leadership in steel manufacturing to achieve sustainability targets [102].

Nonetheless, literature still has several notable gaps. For example, almost all assessments of sustainability are generic without an applicable model for dire emission contributors such as the steel industry. Although MCDM techniques have been widely applied to evaluate the sustainability criteria, very few studies have utilized systematic expert-driven approaches like the Best–Worst Method (BWM) to prioritize sustainability criteria. Furthermore, the research often lacks a comprehensive multi-faceted approach, missing the social and environmental aspects, yielding fragmented and disjointed sustainability attempts. There is also a glaring absence of focus on emerging economies where the steel industry is burdened by policy inconsistencies, high operational costs, green technology, and regulatory obstacles.

The model intends to assess the eco-centric and sociocentric dimensions utilizing the Best–Worst Method (BWM), thus offering a systematic approach to aid in decision-making towards achieving manufacturing sustainability. Therefore, the present study seeks to address the following research questions:

RQ1: Which social and environmental criteria are the most pivotal in determining sustainability in steel manufacturing?

RQ2: To prioritize social and environmental criteria for strategic decision-making in the steel sector?

The rest of the paper is organized as follows. Section 2 presents a literature assessment on SMP dimensions. Section 3 details model development. Section 4 discusses case illustration followed by results and discussion in Sect. 5. Lastly Sect. 6 presents conclusion and future scope.

2 Literature review

The term 'Sustainability' is considered strategically essential for organizations to shape an environment-friendly brand in the global market that stakeholders can trust [103]. Another study by Gimenez-Escalante et al. [29] analyzed sustainable aspects in the food sector and concluded the strong role of distributed localized manufacturing. According to Rehman et al. [79], developing a sustainable framework is considered a difficult task involving an integrated approach within and outside the organization. Paul et al. [74] study revealed deep insight into sustainable manufacturing practices (SMP), and the authors said the adoption of a green approach not only benefits the organization in terms of the environment, but it also helps in overall cost reduction and provides a greener image with a competitive gain. Researchers such as Gupta and Khanna [31], Abdul-Rashid et al. [2], Lai and Wong [57] demonstrated the wider scope of SMP from product initiation to disposal, concentrating on minimization of carbon footprint, and manufacturing cost during the product life cycle, through incorporating eco-friendly practices which leads to improving the image of the organization in the global market. Olmez et al. [72] highlighted the processes of liquid steel making and hot rolling as the greatest contributors to environmental impact, specifically concerning respiratory inorganics and global warming. From the findings, it is clear that there is a need for effective dust control and CO_2 mitigation measures. This demonstrates the necessity of applying LCA-based policies that tackle environmental as well as social health consequences, which further urge the need for the integrated sustainability paradigm in the manufacturing sector. Seth et al. [87] emphasized that SMP has a deeper approach concerning the social, economic, and environmental dimensions, directly influencing the firm's overall performance. Similarly, Deif [21] clarified that the purpose of SMP is to cut down the environmental deterioration and can prompt lower raw material costs, raise productivity, and enhance the image by utilizing appropriate natural resources and advanced technology. Therefore, according to the literature, SMP proved as the foremost approach for the sustainable development of manufacturing firms. Mangla et al. [65] also explored the societal, environmental, organizational, and technological perspectives of Industry 4.0, highlighting the need for further interdisciplinary research to address gaps in understanding the societal impact, human interaction, and challenges in context of Industry 4.0. Scharmer et al. [85] gave an extensive literature review for the different frameworks to address sustainable manufacturing. Jellil et al. [41] highlighted the strong role of consumer behavior in minimizing food wastages and hence attain sustainability. Recently, Sen et al. [88] investigated potential energy saving in machining using alternative lubrication methods, examined the use of two cooling and lubrication methods, Liquid Nitrogen (LN2) and Minimum Quantity Lubrication (MQL) and established that the combination of the two was the best. Bhowmik et al. [11] performed an extensive tribological study on aluminum matrix composites reinforced with SiC and TiB_2, noting the distinct effects of parameters like load, sliding speed, and distance on wear behavior, the study reveals that reinforced aluminum composites offer relevant insights for steel manufacturing, especially in terms of improving wear resistance and supporting sustainable material revolutions. From an eco-centric perspective, the hybrid nano-MQL method put forth by Kumar et al. [54] has substantially lowered emissions, temperature, and tool wear in machining processes, showcasing its capability in reducing the ecological footprint of advanced manufacturing. Han et al. [34] highlighted the need to incorporate psycho-physiological data in evacuation planning, especially in intricate landscapes, ethnographic research in high-altitude villages demonstrated that psychological stress and a person's age greatly affect evacuation performance. These results point to the necessity for human-centered organizational frameworks, especially in critical industries like steel manufacturing, that urge the design of work systems as a blend of well-being, stress management, and responsive planning within the context of sustainability. These strategies can also be used to improve safety for industrial workers and preparedness for surrounding communities.

In Fig. 1, a word cloud was presented based on an analysis of the Scopus database from 2012 to 2025, focusing on sustainable manufacturing. Initially, the research presented explored over 3000 articles. To narrow the scope, our search limited to business

Fig. 1 The word cloud on sustainable development of manufacturing

management and accounting, resulting in a final selection of 449 articles related to sustainable manufacturing. Using RStudio, word cloud was generated, which represents the frequency of commonly used terms in past studies. The word cloud clearly demonstrates that sustainable manufacturing, sustainable development, and manufacture are the most frequently mentioned words in the analyzed studies. Additionally, terms such as sustainable development, manufacturer, environment, life cycle assessment, decision-making, and sustainable indicators have also been commonly used in literature. Research has contributed to a more comprehensive understanding of sustainable manufacturing by considering the social and environment sustainability dimensions within manufacturing firms.

Effective execution of SMP is a complex task. Since there are various dimensions of sustainable manufacturing and concentrating on all is difficult, focusing on critical dimensions provides organizations with a better and faster way to develop a sustainable approach. From this perspective, various studies have been carried out. Chuang and Yang [15] identified key success parameters based on a three-layer model, found that green design is considered the major parameter of SMP. Similarly, Govindan et al. [30] compared 12 critical parameters of SMP considering the social and environmental dimensions. The fuzzy approach was adopted to overcome biased judgments,the study found that critical parameters play a significant role in the execution of SMP. However, all said studies are limited to a certain area of manufacturing. To overcome this, the presented research tries to frame a generalized model integrating all dimensions of SMP. In this view, the presented study has identified a range of parameters from past studies and subsequently developed a generalized integrated model with ethical considerations. Table 1 shows the various essential criteria to achieve the SMP. Table 1 shows a total of 22 criteria from past studies.

3 Model development

In the current times, the manufacturing sector is steadily focusing on effectively incorporating sustainable measures in manufacturing [94]. Recent research suggests that incorporating sustainable measures can be accomplished by assessing and controlling the critical parameters [68], such as Sen et al. [89] utilized wire-cut EDM to optimize the machining parameters with particle swarm optimization (PSO) and genetic algorithm (GA), which improved cost efficiency and energy utilization, advancing eco-centric sustainability in manufacturing. This also supports the framework's E3 (Process Management and improvement) and E4 (Technology Advancement) by improvement of Efficiency through Advanced Modeling Techniques. Manufacturers need to be on their toes to adopt sustainable practices and conserve the environment. Given this, numerous manufacturing models have been deployed for a thorough assessment of various process configurations to determine the effective implementation of sustainable practices [27]. However, there is still a broad scope for the available models that can be extended with more sustainable criteria. Therefore, presented research developed an integrated sustainable manufacturing practices model in this research work, as shown in Fig. 2. The proposed model emphasizes two significant dimensions: environmental and social sustainability. In the environmentally sustainable dimension, the research considered nine criteria from the identified range of criteria using expert's opinion method. Similarly, for the social dimension, eight essential criteria are considered.

Table 1 Past studies considered sustainability parameters in global firms

S. No	Parameter	Source	Description
1	Top Management Commitment	[20, 32, 79, 87]	Top management commitment is one of the most crucial criteria responsible for sustainable manufacturing. It was found to be among the top five criteria affecting green manufacturing
2	Environmental Compliance and Regulations	[7, 20, 30, 79, 87, 111]	The unsustainable pattern of consumption and production is the main factor contributing to the continuous deterioration of the global environment. Environmental compliances and regulations make facility operators more aware of the need for resources and energy efficiency over the whole life cycle while meeting standards and compliances [12]
3	Procurement of Environmentally friendly raw Materials	[16, 79, 87, 98, 99]	Buying eco-friendly raw materials is a key step toward greener production and a stronger circular economy [44]. When firms weave these green inputs into their supply chains, they cut harm to the planet and boost long-term efficiency. Research shows that such green purchasing lifts performance on all three pillars of the triple bottom line-environmental, social, and economic [47]. In addition, early collaboration with suppliers' steers product design in a sustainable direction and opens doors to eco-aware options, thus driving responsible sourcing and technological innovation [111]
4	Green design, and Innovation	[16, 30, 40, 49, 87]	Green design and innovation are essential because they focus on stopping harm to the planet upfront and cutting down waste in materials, function, technology, and quality [49]. Sustainable development works even better when each individual knows about, and takes part in, recycling and zero-waste efforts. Among the five major elements that shape sustainability, business strategy, technological innovation, and organizational culture are the strongest drivers of both environmental and social gains. A supportive culture and high innovation ability help firms craft products and processes that meet green goals [4]
5	Organizational culture and capabilities	[4, 20, 30, 87, 111]	Business strategy, technological prowess, and organizational culture are proven to significantly improve the environmental and social sustainability performance of businesses among the five critical components. It is also revealed that organizational culture and capabilities have a favorable impact on the organizations' sustainable manufacturing
6	Process Management and Improvement	[16, 75, 79, 87, 108]	Process innovation is crucial for achieving competitiveness and sustainable performance. Processes that are optimized and continuously improved would have the least possible negative environmental effects are becoming more and more crucial for modern production
7	Technology advancement	[16, 69, 71, 87]	It is defined as the uses of digital technology such as the Internet of Things, Cyber Systems, Data Analytics, Artificial intelligence, Cloud Computing, and Virtual Reality to improve the firm's performance. Technical considerations must be considered because the leather industry can move to a sustainable manufacturing process while using cleaner technologies to reduce and prevent pollution problems
8	Eco-Product Innovation	[42, 86]	Corporate sustainability is greatly enhanced by eco-process innovation. Eco-innovation is characterized as fresh concepts for enhancing procedures while lessening environmental strain
9	Competitive Advantages with Green Image	[20, 30, 36, 101]	Competitive advantages and green brand image are positively correlated. Companies implement sustainable production to improve their image. Customers nowadays must select products that are eco-friendly and sustainable
10	Water Consumption management	[6, 28, 51, 97]	Analyzing the present water management to maximize water use would help reduce water consumption during the manufacturing process and lead to more sustainably produced goods. One of the sustainable and renewable processes for turning brackish or salty water into fresh water is solar desalination. Utilizing solar desalination helps achieve the Sustainable Development Goals by reducing carbon emissions, reducing CO_2 levels, and mitigating other harmful effects of global warming

Table 1 (continued)

S. No	Parameter	Source	Description
11	Material Consumption	[18, 23, 28, 79, 96]	Efficient material use lies at the heart of sustainable manufacturing, mainly because it cuts the volume of raw resources needed. Relying on recycled and reused inputs further shrinks a firm's environmental footprint and preserves vital natural stock. When reverse logistics is woven into the supply chain, it completes the circular model by collecting materials for recycling, remanufacturing, repair, or reuse. Collectively, these approaches empower producers to lengthen product life and limit waste, bringing daily operations into line with broader sustainability goals
12	Government Incentives	[20, 38, 43, 48, 60, 82, 112]	The highest-ranking factor encouraging SMEs to implement sustainable manufacturing was "Financial assistance/support from the government". Government promotes sustainable manufacturing by providing incentives in terms of discounts in tax slab, certifications, subsidies and so forth. This Financial incentive programs encourage environmentally friendly manufacturing and investment
13	Internal Environment Management	[76]	Adopting green supply chain strategies is positively and substantially correlated with internal environmental management and green information systems. The internal environment of any organization consists of its structure, process control, culture, incentive schemes, policies, and more. If these things are not conducive with respect to employees and workers, it will negatively impact on the firm's performance
14	Collaborations	[8, 20, 25, 30, 37, 80, 111]	Sustainable manufacturing relies on active teamwork among a wide range of external partners, from suppliers to regulators. Within Industry 4.0, effective operations depend on the seamless integration of machines, and smart devices. Achieving that link requires collaborative platforms that facilitate production tasks and data streams together using advanced digital tools and services. Only through this seamless integration firms can operate both efficiently and sustainably in a cooperative setting. Well-crafted industrial policies, however, depend not just on design but on committed, ongoing input from all stakeholders. By adopting fresh approaches and nurturing strong alliances, these partners can create the conditions needed to speed up and broaden sustainable manufacturing efforts
15	Gender ratio	[9, 115]	Maintaining gender ratio helps in making effective and equitable decision making. A balanced gender ratio facilitates long term sustainable development
16	Ethics	[23, 63, 105]	More consumers who care about ethics are prepared to buy eco-friendly goods, which promotes sustainable manufacturing. The following is a succinct definition of ethics: "A society's individual members are encouraged to engage in positive-sum interactions and to avoid negative-sum interactions by a system of beliefs"
17	Health, welfare, and safety	[23, 104, 106]	There is a positive effect of sustainable manufacturing on health and welfare. Occupational health and safety have become a global problem in the workplace. It is not a new concept to link sustainability and safety. Numerous studies have shown the significance of safety in promoting sustainable development
18	Human Rights	[24, 70, 81]	To ensure sustainable manufacturing, manufacturers should uphold human rights in their internal operations and check that their supply chain partners are acting in accordance with the law. Human rights hold a unique place among all the various criteria considered in sustainable manufacturing, including biodiversity, natural resources, sustainable urbanization, access to equal opportunity, security, and social cohesion
19	Philanthropy	[3, 23]	The performance of philanthropy and sustainable production are strongly correlated. CSR is a type of philanthropic activity that producers voluntarily engage in to create a sustainable production system at work
20	Employee and Community Development	[33, 55]	The development of communities and the safety of the workforce and goods can all be considerably enhanced by sustainable production. Along with employee and community development, sustainable manufacturing has been identified as a strategy for enhancing organizational business and market performance

Table 1 (continued)

S. No	Parameter	Source	Description
21	ISO 26000	[50]	A ranking of the ISO 26000 practices is used to help managers choose the best course of action for enhancing the social responsibility of the Indian freight transport sector. The ISO 26000 standard is being used by even small freight transportation companies to enhance sustainable performance
22	Employee satisfaction	[61, 114]	Based on the linkages between sustainable manufacturing enablers and organizational performance outcomes, it can be said that incentives, commissions, benefits, ergonomics, and work flexibility all promote employee satisfaction

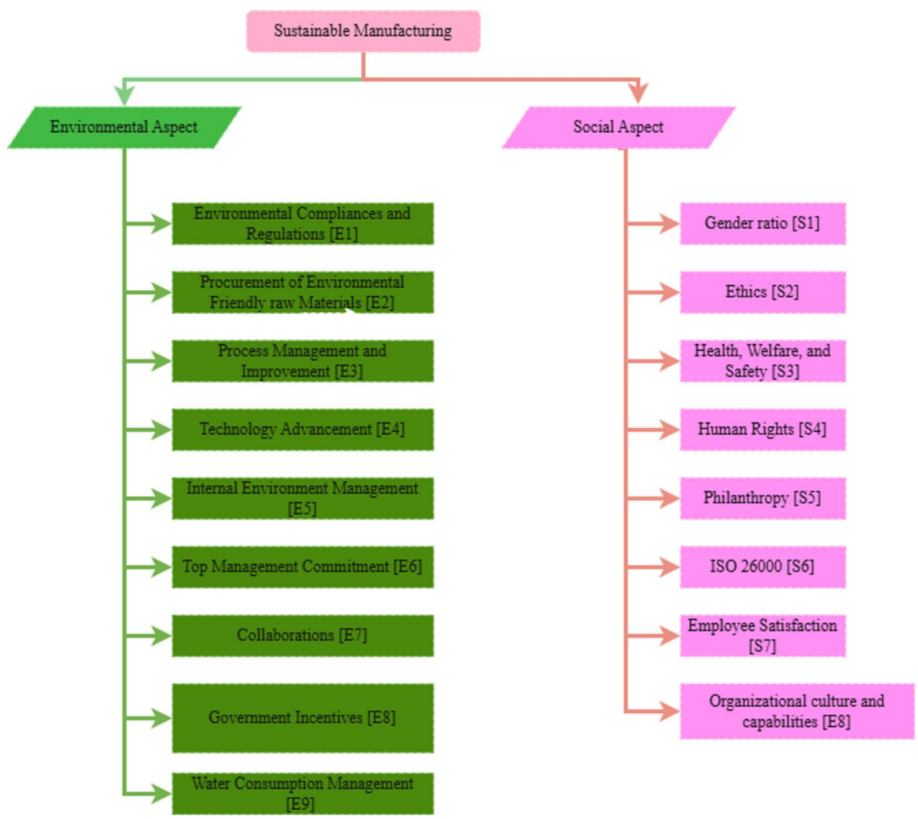

Fig. 2 Sustainable manufacturing practices

4 Research methodology

The study has applied two-stage methodologies. In the first stage, the study applied the qualitative approach to identify the criteria associated with environmental and social sustainability. In this study, the authors have considered the Scopus and Science Direct databases to achieve the first objective. The study identified a total of 22 criteria related to sustainable manufacturing from literature. These identified criteria are shown in Table 1. Further, in the second stage, experts' opinions were used to shortlist the key criteria, finally 9 criteria of environmental and 8 social criteria were selected, followed by computation of weights by Best Worst Method. There is a wide range of techniques available in literature for the assessment of criteria. Among such techniques, multicriteria decision-making techniques are the preferable approaches [14, 84]. Some of the techniques include AHP [83], VIKOR [109], ELECTRE [17], TOPSIS [56], and Best–Worst method [77]. For example, Sen et al. [92] applied the TOPSIS method to assess and rank differing blended bio-lubricants used under Minimum Quantity Lubrication (MQL) conditions for sustainable machining. Their research illustrated the potential of MCDM approaches in aiding green manufacturing decisions by showing the most competitive environmentally favorable alternatives based on several eco-performance metrics.

All the approaches are efficient for decision-making. However, among the available methods, the Best–Worst method is one of the finest techniques for evaluating key criteria in decision-making. Rezaei [77] developed the Best–Worst Method, which works on the principle of pairwise comparison using a scale of 1 to 9. To be more exact, this method's computation is based on two vectors: best and worst,and worst to others. A decision-maker must do pairwise comparisons based on the Best–Worst considerations. The BWM offers various advantages over the AHP, a common technique in management studies. The AHP approach requires n(n-1)/2 pairwise comparisons, but BWM only needs (2n – 3) pairwise comparisons. BWM uses less data and achieves more consistency [58].

4.1 Proposed hybrid solution approach

The current study proposes a two-stage problem to identify and rank the potential sustainable manufacturing criteria. The details of the proposed solution methodology are shown in Fig. 3.

4.2 Case illustration

To test the proposed sustainability assessment framework, the presented study have considered two steel-makers companies in India, and labelled Company X and Company Y. These firms were selected for their size and position in the market, and for the fact that they have already flagged a willingness to adopt greener practices in their operations. The selection of the two cases line-up with [66] forecast that says Indian steel sector demand will hit 260 million tons by 2035. Because steel production adds roughly 12 per cent to the country's industrial pollution, which shows clear pressure to adopt sustainable practices into everyday operations. Company X and Company Y are therefore

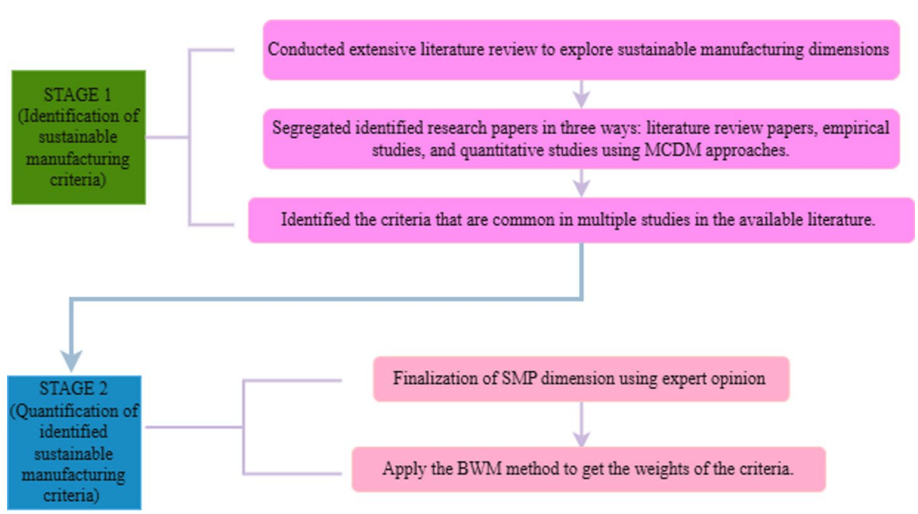

Fig. 3 Research flow chart

considering boosting their environmental and social sustainability image in response to shareholders, new rules and regulations, and global customers.

4.2.1 Company X

Company X is a major steel maker with more than 1,500 staff and annual revenue exceeding INR 500 crore. Operating for over twenty years, it mainly turns out flat and long steel products for the automotive, infrastructure, and consumer goods sectors. Although the firm holds numerous quality and environmental badges-including ISO 9001 and ISO 14001-its leaders are now rethinking the overall sustainability plan so that it keeps pace with global norms and rising customer demands. During the review, management noted that no formal tool exists to rank which green actions should come first. While projects to cut raw material waste, switch to greener inputs, and upgrade emission controls have started, there is no single yardstick to decide which move delivers the biggest gain for the organization and society. Amid mounting pressure to boost staff welfare and safety, the executive team has therefore agreed to trial the Best–Worst Method (BWM) model, believing it will clarify and sequence the most vital sustainability goals for future planning.

4.2.2 Company Y

Company Y is a mid-sized maker of alloy steel parts for the automotive and heavy-equipment industries. It employs almost 900 people and reports yearly sales close to INR 200 Crores. Although the firm holds ISO 9001 for quality and ISO 45001 for workplace safety, it has yet to roll out a full sustainability plan. Lately, managers have begun exploring how to adapt sustainable thinking into purchasing, production, and HR. Their main pain points are excessive scrap, climbing emissions, and uneven employee ratings of job satisfaction. By joining this study, they seek guidance on which social and environmental goals matter most over the long haul. Findings from the BWM-based ranking should steer investment choices, compliance rules, and training for staff at all levels.

4.3 Data collection

At the outset, a carefully designed questionnaire was circulated to capture both social and environmental aspects of sustainable manufacturing. Responses were gathered from ten industry experts, each holding between ten to twenty years of front-line experience in operations, supply chain, safety, technology, or quality management. All participants occupy senior positions in steel manufacturing firms and deeply understand the sectors pressing sustainability hurdles and strategic goals. Before collecting responses, the authors briefed each expert on the purpose of study and context to make sure the clarity and significance. Their responses were then used to calculate factor weights via the Best–Worst Method (BWM). Table 2 provides a detailed profile of the experts.

5 Results and discussion

To determine the potential criteria for sustainable manufacturing, the research have proposed the SMP model, showing two significant aspects of sustainability: environmental and economic. Previous studies focused more on economic and environmental sustainability and paid less attention to social sustainability. Therefore, this model tries to capture environmental and social sustainability dimensions separately. Further, these two

Table 2 Experts profile

SN	Position	Area of expertise	Gender	Experience (Years)
1	Manager	Sustainability	Male	> 15 years
2	Operations Manager	Operations	Male	> 17 years
3	General Manager	Manufacturing	Male	> 10 years
4	Assistant General Manager	Operations	Male	> 11 years
5	Senior Engineer	Engineering	Female	> 16 years
6	Operations Manager	Operations	Male	> 13 years
7	Quality Control Manager	Quality	Female	> 12 years
8	Process Engineer	Process design	Male	> 16 years
9	Deputy Manager	Supply chain	Male	> 18 years
10	Deputy Manager	Manufacturing	Female	> 19 years

Table 3 Expert preferences of best (B) environmental Criterion over other (O) criteria with respect to eco-centric dimension

Experts	B to O	E1	E2	E3	E4	E5	E6	E7	E8	E9
1	E6	4	2	3	1	4	1	2	3	6
2	E2	3	1	2	4	3	1	4	7	5
3	E4	1	2	5	1	3	4	7	3	9
4	E6	6	3	4	6	8	1	5	4	5
5	E5	5	2	5	4	1	2	4	3	6
6	E6	7	1	4	3	7	1	2	8	1
7	E5	4	3	5	6	1	7	2	8	9
8	E4	6	2	5	1	6	3	4	7	8
9	E6	7	1	2	4	6	1	3	8	9
10	E5	5	6	1	8	1	4	3	2	9

Table 4 Expert preference of other (O) criteria over Worst (W) criterion with respect to eco-centric dimension

Experts	1	2	3	4	5	6	7	8	9	10
Other to worst	**E7**	**E3**	**E3**	**E7**	**E1**	**E9**	**E3**	**E7**	**E9**	**E7**
E1	7	3	5	1	1	6	7	4	1	2
E2	4	5	8	2	2	2	6	5	3	4
E3	2	1	1	3	4	1	1	3	5	6
E4	8	4	7	5	6	4	8	6	9	9
E5	3	1	2	4	5	6	2	2	6	3
E6	4	2	6	3	4	7	4	7	4	5
E7	1	1	2	1	2	1	3	1	2	1
E8	1	3	6	4	5	1	5	8	8	7
E9	2	4	2	4	6	1	9	9	1	8

influential criteria help achieve the primary objective of attaining the SMP in manufacturing firms. The research shortlisted nine environmental and eight economic criteria, and then computing weights using BWM, the different steps involved are mentioned in Appendix A. Excel solver was used to evaluate the weights. Table 3, 4, 5, and 6 shows the pairwise comparison for environmental and socially sustainable manufacturing criteria. The final weights of environment and economic sustainable manufacturing criteria are represented in Tables 7 and 8 respectively.

The presented research considered equal importance for each expert, and based on that, final optimal weights were evaluated by doing an arithmetic average of obtained weights by 10 experts. It has been observed that E6 (Top management commitment) scores highest, followed by E2 (Procurement of environmentally friendly raw materials)

Table 5 Expert preferences of best (B) social criterion over other (O) criteria with respect to sociocentric dimension

Experts	B to O	S1	S2	S3	S4	S5	S6	S7	S8
1	S6	7	1	3	8	9	1	2	3
2	S7	9	5	6	4	3	4	1	3
3	S6	4	1	4	7	5	1	3	4
4	S7	7	3	5	3	2	8	1	6
5	S7	5	4	6	4	8	3	1	2
6	S7	4	5	5	7	1	4	1	7
7	S8	2	4	3	5	6	7	8	1
8	S6	3	7	8	6	4	1	5	3
9	S6	2	1	7	6	4	1	5	4
10	S7	4	4	6	7	5	2	1	6

Table 6 Expert preference of other (O) social criteria over Worst social (W) criterion with respect to sociocentric dimension

Experts	1	2	3	4	5	6	7	8	9	10
Other to worst	**S1**	**S5**	**S5**	**S1**	**S5**	**S4**	**S4**	**S5**	**S1**	**S1**
S1	1	4	5	1	6	2	6	8	1	1
S2	9	6	4	5	6	3	7	5	2	4
S3	7	6	5	6	4	4	5	7	4	2
S4	2	3	4	4	3	1	1	2	5	3
S5	1	1	1	2	1	5	4	1	3	5
S6	6	5	8	1	6	6	8	5	6	7
S7	5	7	9	2	7	8	5	6	7	8
S8	4	5	7	3	5	5	9	8	4	6

and E4 (Technology advancement). These ranking highlights how crucial active leadership is for building a workplace culture that prioritizes sustainability and for making long-term investments in greener and sustainable practices. Agarwal et al. [5] noted that strong leadership serves as a vital link between a firm's everyday objectives and broader eco-centric principles. The high position of sustainable procurement also ties to a rising awareness, noted by Karuppiah et al. [46], that sourcing low-emission materials can greatly cut a products total carbon footprint. Also, experts rated criteria E9 (water consumption) as lowest,this finding suggests that, within steel making, concerns over air emissions and energy use still overshadow worries about water use. Further, while evaluating social sustainability, the highest-rated criteria were S7 (Employee satisfaction), followed by S6 (ISO 26000) Compliance, and S2 (Ethics). Maniendaran et al. [62] show that clear conflict-resolution plans in small and medium-sized enterprises lift morale, and that improved morale, in turn, raises output and strengthens retention. The high place given to ISO 26000 also suggests organizations want their day-to-day actions to match widely accepted global norms on social responsibility. Ethics, sitting third, remains the backbone of a firm's public standing and the trust stakeholders extend over the years. By comparison, Human Rights (S4) and Philanthropy (S5) fell lower in the ranking, perhaps because managers still find them harder to measure or adopt into routine steel-making work. The obtained results from the study align closely with prior studies in the field of sustainable manufacturing. For example, Jilcha [45] noted that robust leadership commitment drives safety and performance when initiatives such as Vision Zero are adopted in metal manufacturing. Likewise, Olmez et al. [72] found that water use receives little attention because firms regard emissions and energy consumption as far weightier issues

Table 7 Final scores for environmental criteria

Experts	1	2	3	4	5	6	7	8	9	10	Average Value	Rank
(ε^*)	0.123	0.123	0.083	0.152	0.104	0.119	0.195	0.168	0.143	0.159	0.137	
E1	0.076	0.114	0.213	0.045	0.027	0.042	0.111	0.072	0.023	0.077	0.080	8
E2	0.151	0.218	0.148	0.146	0.157	0.173	0.148	0.217	0.213	0.064	0.164	2
E3	0.101	0.048	0.026	0.110	0.068	0.027	0.027	0.087	0.178	0.227	0.090	5
E4	0.180	0.085	0.266	0.073	0.085	0.097	0.074	0.266	0.089	0.048	0.126	3
E5	0.076	0.114	0.099	0.055	0.237	0.042	0.249	0.072	0.059	0.227	0.123	4
E6	0.237	0.218	0.074	0.287	0.170	0.292	0.063	0.145	0.236	0.096	0.182	1
E7	0.028	0.085	0.042	0.088	0.085	0.146	0.222	0.025	0.118	0.023	0.086	7
E8	0.101	0.049	0.099	0.110	0.114	0.036	0.056	0.062	0.044	0.193	0.086	6
E9	0.050	0.068	0.033	0.088	0.057	0.146	0.049	0.054	0.039	0.043	0.063	9

across the steel-making life cycle. On the social side, research by Fernando et al. [24] and Kumar [50] shows that companies that prioritize employee well-being and uphold ethical norms usually earn a stronger social image.

The low ε^* value indicates tight dispersion and strong consensus [78]. To present the reliability of results, radar charts were prepared for both environmental and social dimensions, Figs. 4 and 5 show the same. In the eco-centric dimension, the expert panel clearly agreed on the importance of top management support, intelligent procurement, and enabling technology, whereas employee well-being and ISO standards surfaced as primary concerns in the sociocentric domain.

A few strategies were used by top steel producers to increase the relevance of our suggested sustainability framework. For example, in accordance with our eco and sociocentric standards, Tata Steel has implemented programs for community development, ISO 26000 compliance, and the responsible sourcing of raw materials [110]. Similarly, the use of electric arc furnaces, waste heat recovery, and high rates of scrap steel recycling are further examples of ArcelorMittal's eco-centric strategies that support our stated priorities (E6, E2, and E4) [53]. From the sociocentric viewpoint, the steel industry's use of sustainable manufacturing improves both operational results and overall socioeconomic growth. Case studies from domestic and international steel operations show how programs like skill development, health outreach, inclusive hiring, and vocational training help create jobs, build local capacity, and strengthen communities [35, 100]. These initiatives, which have their roots in organized corporate social responsibility, promote social inclusion, ethical labor practices, and adherence to global norms such as ISO 26000. All things considered, these initiatives support the legitimacy and long-term viability of manufacturing activities [95]. From the results, it has been observed that "Technological Advancement" surfaced as a prominent concern, manufacturing firms could implement the optimization methods to achieve these objectives. Sen et al. [90] utilize evolutionary algorithms to refine machining processes, reducing energy costs and improving overall efficiency, this supports the determination made in the study regarding the use of smart optimization methods for balancing environmental considerations and operational demands. These instances demonstrate the suggested framework's applicability and practical viability in the context of contemporary steel production processes.

The current framework additionally assists environmental regulators in assessing various manufacturing firms relative to their sustainability performance, as illustrated in Fig. 2. Such assessments promote competition on a global scale towards sustainable development. These findings are corroborated by recent studies within predictive modeling by Sen et al. [93], where energy consumption and machining processes were enhanced using optimization methods such as NSGA-II and TLBO, demonstrating how firms can achieve better compliance and sustainability results.

From a managerial standpoint, the proposed framework enables environmental regulators and decision-makers to benchmark and assess the sustainability performance of manufacturing firms, thereby promoting global competitiveness and sustainable development. These implications are supported by predictive modeling studies. For example, Sen et al. [93] demonstrated that optimization techniques like NSGA-II and TLBO can significantly enhance energy efficiency and sustainability outcomes in machining. In the same way, Debnath et al. [22] applied advanced predictive approaches such as Gene Expression Programming (GEP) to forecast key machining metrics like material

Table 8 Final scores for social criteria

Experts	1	2	3	4	5	6	7	8	9	10	Average value	Rank
(ε^{*})	0.075	0.180	0.120	0.170	0.096	0.102	0.155	0.180	0.157	0.153	0.139	
S1	0.027	0.055	0.086	0.042	0.079	0.089	0.224	0.166	0.033	0.038	0.084	7
S2	0.263	0.098	0.224	0.141	0.099	0.071	0.112	0.071	0.224	0.115	0.142	3
S3	0.113	0.082	0.086	0.085	0.066	0.071	0.149	0.062	0.054	0.077	0.085	6
S4	0.042	0.123	0.049	0.141	0.099	0.030	0.027	0.083	0.064	0.066	0.072	8
S5	0.038	0.044	0.026	0.212	0.029	0.254	0.075	0.035	0.095	0.092	0.090	5
S6	0.236	0.123	0.328	0.053	0.132	0.089	0.064	0.318	0.358	0.230	0.193	2
S7	0.169	0.311	0.115	0.254	0.299	0.345	0.056	0.100	0.076	0.306	0.203	1
S8	0.113	0.164	0.086	0.071	0.198	0.051	0.293	0.166	0.095	0.077	0.131	4

removal rate (MRR), tool wear rate (TWR), and surface roughness. Their findings underscore how intelligent modeling tools can drive both environmental and technological improvements, aligning with our model's eco-centric and technological advancement dimensions. In the steel manufacturing sector, the implementation of circular strategies such as material recycling can greatly enhance sustainability. For example, Dasgupta et al. [19], conducted study to synthesize a novel high-performance polymer composite using waste plastics and ground tire rubber. In the steel sector, practices like reclaiming scrap steel or slag recycling can result in waste minimization and material recovery, thereby advancing ecologically oriented sustainability goals.

5.1 Managerial implications

The managerial implications of this proposed model are significant for manufacturing firms. The following practical insights can be helpful for managers for the successful adoption of sustainable manufacturing:

a. Establishing a specialized team for compliance is necessary for tracking regulatory activities, monitoring adherence to environmental and labor standards, and aligning business practices with policies on sustainability at the national level and within industry. Such a compliance structure not only mitigating legal risks but also enhances environmental and social responsibility [107].
b. Strategic partnership with green suppliers can help to manufacture eco-friendly products and achieve sustainable practices.
c. An effective lifecycle assessment (LCA) allows industrial manufacturers to pinpoint and address the inefficient areas of the entire production stream, thus providing practical opportunities for cutting down carbon emissions as well as incurring environmental costs. In the steel sector, LCA demonstrates that total environmental costs can be greatly decreased by the use of renewable electricity and a shift towards greater scrap usage [10].
d. Investing in advanced and digital technologies helps in optimum utilization of resources, reducing wastages, and improving organizational performance [59].
e. Steel manufacturing firms ought to focus on community initiatives and improving working conditions, which include offering vocational training and contributing to health and educational programs. European studies on steel mills indicate that such initiatives enhance community trust and retention [26, 52].
f. Critical social issues such as wage fairness, employment opportunities, and diversity should be included in the managers' KPIs. These social indicators align firms with ESG objectives and regulatory requirements. Businesses that track social KPIs are more prepared for sustainability shifts and inter stakeholder accountability [1].

6 Conclusion and scope for future work

Sustainable development in developing nations involves three key strategies (monetary, ethical practices, and Eco-socio policies). It handles two key goals together: consistent economic and Eco-socio development. Sustainable practices proved to be the initial and foremost step to developing a sustainable manufacturing environment to encounter ongoing issues such as global warming, scarce resources, and social distress. Therefore, the present study provides support for the firms to implement sustainable practices efficiently by focusing on the critical parameters. This study also delineates the importance

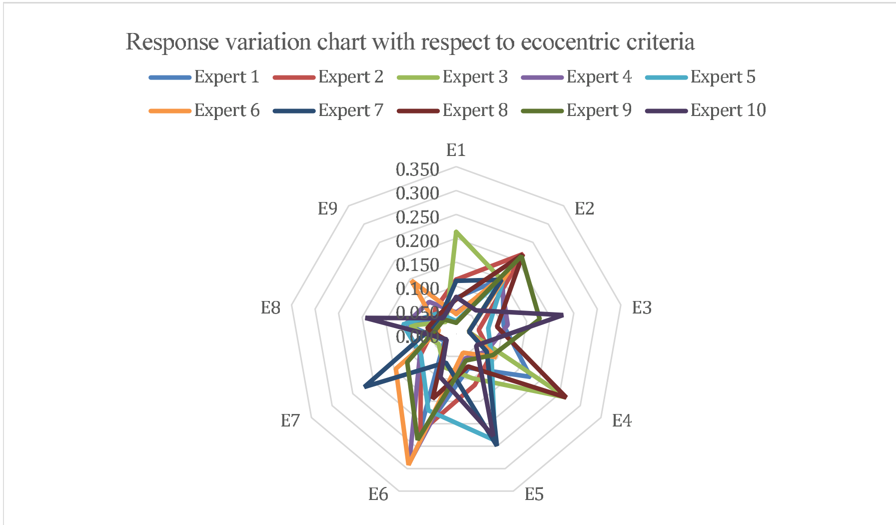

Fig. 4 Variation of responses of experts concerning nine eco-centric Criteria

Fig. 5 Variations of responses of experts concerning eight sociocentric Criteria

of ethical practices in developing SMP across global manufacturing firms. The generalized conceptual model proposed in this study helps in focusing on the key criteria of sustainable manufacturing. Apart from these, ethical practices criteria induced in the model will develop determination in industries to implement SMP successfully across the manufacturing process. The obtained weights for the identified criteria will strongly impact the achievement of sustainable goals in the manufacturing practices of the firms.

In the future, the computed results can be verified using other mathematical approaches such as Analytical network process, TOPSIS etc. Using the fuzzy approach in the work can also reduce the possible biases by the experts. Further study can be conducted in other industry types like automobile, leather, construction, and healthcare. The proposed work can also be extended to the ranking of the various manufacturing firms with respect to the criteria proposed in the models.

Appendix A: Steps associated with the BWM analysis

Step 1: Identify a set of SMP criteria $\{F_1, F_2, \ldots F_m\}$ through literature review.

Step 2: Among the identified SMP criteria (F_m), fix the best (F_B) and the worst (F_W) SMP criterion.

Step 3: Rating the best SMP criteria with respect to others on 1–9 scale, $A_B = (\alpha_{B1}, \alpha_{B2}, \ldots \alpha_{Bm})_,$ and $(\alpha_{BB} = 1)$.

Likewise, likewise develop Others-to-Worst (OW) table for criteria such as: $A_W = (\alpha_{1W}, \alpha_{2W}, \ldots \alpha_{mW})^T{}_,$ and $(\alpha_{WW} = 1)$.

Whereas α_{Bm} specify the preference of the BO and α_{mW} specify the preference OW.

Step 4: Compute optimal weights $(F_1^*, F_2^*, F_3^* \ldots F_m^*)$ using minmax model

$$max_m = \left\{ \left| \frac{F_B}{F_m} - \alpha_{Bm} \right|, \left| \frac{F_m}{F_W} - \alpha_{mW} \right| \right\} \quad s.t. \sum_m^M F_m = 1 F_m \geq 0, \quad for\, all\, m \tag{1}$$

The Minmax Model (1) can be solved using linear programming problems

$$\begin{aligned} &\varphi^* s.t. \left| F_B - \alpha_{Bm} F_m \right| \leq \varphi^*, \quad for\, all\, m \left| F_m - \alpha_{mW} F_W \right| \\ &\leq \varphi^*, \quad for\, all\, m \sum_m^M F_m = 1 F_m \geq 0, \quad for\, all\, m \end{aligned} \tag{2}$$

(φ^*) reveals the reliability of the pairwise assessment.

Step 5: Optimal weights can be computed of SMP criteria, according to [78], the value of (φ^*) must be close to zero.

Author contributions

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

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Data availability

The datasets generated and/or analyzed during the current study are available from the authors at reasonable request.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the Amrita Vishwa Vidyapeetham, India. The research was conducted in accordance with the institution's ethical guidelines.

Informed consent

Informed consent was obtained from all participants involved in the study. No participants were below the age of 18 years. Consents to participate and to publish were documented for each participant.

Consent for publication

Not applicable.

Competing interest

The authors declare no competing interests.

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