

The Emergence of Digitalization to the Manufacturing Sector in the Sustainability Context: A Multi-stakeholder Perspective Analysis

Abstract: Sustainable digitalization in industry needs very high preplanning to integrate the business strategies with the digitalized sustainability concept. However, stakeholders often have different perspectives that make them harder to being aligned. Stakeholders of the digitalized sustainable manufacturing industry must be identified and prioritized for effective implementation. Therefore, the present study combines a Systematic Literature Review and Hybrid Multi-Criteria Decision Techniques which consist of Full Consistency Method and Fuzzy-Evaluation based on Distance from Average Solution method to prioritize the stakeholder's role to digitalized sustainable manufacturing and associate strategies. This study explores various ways of implementation regarding the methodology and their relation with the different stakeholders. It sorts the stakeholders, such as manufacturers, research and development, managers, mergers and acquisitions, education programs, the 6R strategy, and eco-efficiency, to illustrate the corresponding strategies. Overall, the study highlights the urgent requirement of meticulous planning to synchronize business strategies with the digitalized form of sustainability while recognizing the difficulty in harmonizing distinct stakeholder's assessments. In the context of the methodical positioning of stakeholders and strategies, the provided research findings contain appropriate implications for industry professionals striving to successfully navigate sustainable digitalization complexities.

Keywords: Digitalized sustainable manufacturing; Systematic literature review; Hybrid multi-criteria decision making methods; Stakeholder strategies.

1. Introduction

The extensive resource utilization, inefficient waste management, material inefficiency, and low economic and social conditions eventually lead to digitalized sustainable manufacturing as an imperative paradigm in the industrial sector (Majeed et al., 2021). The past industrial revolutions engendered high pollution rates, huge toxic emissions, enormous solid waste disposal, unsafe working conditions, and high energy consumption. Recovering from these plights requires a long time and triggered the adaptation of triple-bottom-line sustainability concepts worldwide (Dabić

et al., 2023). For achieving sustainable manufacturing, various strategies have been deployed in the industry and a prominent one among them is digital technologies. The accomplishment of sustainable manufacturing via digitalization is defined as digitalized sustainable manufacturing which encompasses various digital technologies like the Internet of things, Blockchain technology, Machine learning, Cloud computing, and Cyber-physical systems in the context of sustainability principles (Bhagat et al., 2022).

Despite the huge potential of digitalized sustainable manufacturing, the common barriers impeding the implementation of digitalized sustainable manufacturing are a lack of awareness and understanding of long-term benefits associated with sustainability, fear of consequences, conventional manufacturing systems thwarting the adaptation of innovative technologies, and incompetent employees (Testa et al., 2022). The accomplishment of digitalized sustainable manufacturing requires meticulous planning with the formulation of pertinent strategies and policies. The unique contribution of each stakeholder is imperative in the formulation of digital sustainability initiatives and policies (Haleem et al., 2022). Without the intervention of stakeholders, the accomplishment of digitalized sustainable manufacturing is like herding cats (Kahupi et al., 2021). The Australian Institute of Company Directors defines a stakeholder as “persons, groups, and entities with a specific interest in an organization. For a company, this typically includes shareholders, suppliers, customers, and employees” (Mok et al., 2015). Internal stakeholders have a vested interest in the company and their performance determines success or failure. External stakeholders don’t participate in the company's daily activities and work outside the company. Internal stakeholders include shareholders, employees, managers, and the board of directors, whereas external stakeholders include suppliers, customers, government regulations and bodies, and the local community (INTUIT, n.d.). Primary stakeholders directly influence the business; they can be internal and external. Secondary external stakeholders work outside the business but are still interested in the company’s success and own a significant share of the company (INTUIT, n.d.). Each stakeholder has a distinct perspective based on their occupational and professional backgrounds, eventually leading to the company's sluggish adoption of digitalized sustainable manufacturing concepts (Dabić et al., 2023). There is a diverse perception of sustainability by multiple stakeholders: customers and manufacturers. For example, manufacturers assign less weightage to social sustainability, whereas consumers demand products that are eco-friendly and have minimal resource utilization (Rasheed & Ion, 2022). This contradiction can

engender conflicts, impeding the implementation of digitalized sustainable manufacturing. So, the prioritization of stakeholder strategies and perspectives is inevitable in the accomplishment of digitalized sustainable manufacturing in any industry. The need for different strategies for the successful implementation of digitalized sustainable manufacturing and how different stakeholders are associated with these strategies led us to the formulation of research questions as follows:

RQ 1: What are the different strategies for implementing digitalized sustainable manufacturing practices?

RQ 2: What is the significant role of each stakeholder in enhancing digitalized sustainable manufacturing practices?

To address the research questions mentioned above, with the help of a literature review and brainstorming between the authors, we have identified the different stakeholders and determined their significance in promoting digitalized sustainable manufacturing. Further, with the use of Hybrid Multi-Criteria Decision-Making techniques (HMCDM): Full Consistency Method (FUCOM) and Fuzzy-Evaluation based on Distance from Average Solution (F-EDAS), we have analyzed and prioritized the different strategies for implementing digitalized sustainable manufacturing.

This research represents a significant contribution to the understanding and promotion of sustainable manufacturing within the industrial sector. The study highlights the urgent issues of extensive use of resources, ineffective waste management, and poor financial and social situation. In such a way, the importance of shifting toward digitalized sustainable manufacturing is underlined, while the last can hardly be overestimated referring to the industrial revolutions of the past, which resulted in environmental and social degradation, as well as challenging socioeconomic conditions. As such, reviewing a system that ties together such modern technologies as Internet of Things, Blockchain, Machine Learning, Cloud Computing, Smart Sensors, and Cyber-Physical Systems is novel, to say the least, and does contribute to the exclusive and original information contained in this study. The present research also provides detailed information on the definition of digitalized sustainable manufacturing, which features various digital technologies, adhering to the basic principles of sustainability and providing the necessary codifications. Thus, through the identification of common barriers to digitalized sustainable

manufacturing implementation, such as simple unawareness or resistance to non-conventional systems, the study indicates the possible challenges organizations will face. Concerning this, the necessity to focus on stakeholder implications to develop digital sustainability policies is underlined, and the information regarding the complexity of such interaction and its influence on the manufacturing practice. This study can offer a new perspective on opportunities for the transformation of the industry cannot be denied. The analysis of the barriers typical of digitalized sustainable manufacturing shows that stakeholders should be involved, and the corresponding strategies and policies must be designed. Thus, this research is a valuable contribution not only in a theoretical sense but also from a practical point of view. Industry professionals might find it particularly useful if they are considering the adoption of sustainable manufacturing practices in the digital era.

Furthermore, this paper is organized as follows: Section 2 provides a literature background on the role of stakeholders in sustainable manufacturing and digital technologies. Section 3 outlines the methodology followed by Section 4, which presents a case application. Furthermore, Section 5 presents the results and discussion of the study. Finally, Section 6 discusses implications followed by Section 7 provides conclusions.

2. Literature Review

2.1. Digitalized sustainable manufacturing

In recent years, the implementation of digital technologies, such as process automation, 3D printing, the Internet of Things, and robotics, has transformed the operations of international firms. As such, the use of emerging technologies has significantly supported international firms to secure their long-run viability, persistence, and expansion in the global market. Hence, the concept of sustainability has gained significance in the context of digital transformation, having a considerable effect on many economic sectors, including the agricultural sector (Di Vaio et al., 2023). While becoming more focused on the issue of environmental sustainability, agricultural organizations recognize the utmost importance of effective waste management, sustainable production techniques, and pollution management in internal and external processes and activities (Xu et al., 2023). Therefore, sustainable digital transformation is a significant change with profound implications for the capacities, achievements, and orientations of organizations

(Bartolacci et al., 2020). Furthermore, this event has complex and varied facets of sustainability accomplished through digital transformation in any economic setting and proved to be beneficial simultaneously on many levels (Rupeika-Apoga et al., 2022). This digital change will have a systematic effect on any organization with the use of information and communication technology or the onset of novel sustainable procedures that are sufficient for corporate organizations. The shift will significantly affect processes and outputs aimed at a waste reduction, reuse, and recycling policy. This will essentially secure the profit margins of firms and keep corporate costs down. Furthermore, new methods through which information and communication technology are utilized will allow firms to bring tangible gains to the organization, such as the ability of any enterprise to streamline its processes (Hervé et al., 2021). In other words, it will facilitate the development and implementation of new and inventive corporate procedures in which information and communication technology can support providing long-term advantages to the whole organization and enhance the total quality of work of the workers (Kim, 2015).

2.2. Stakeholder's role

The stakeholder's role in accomplishing digitalized sustainable manufacturing is very critical (Leesakul et al., 2022). In an organization's context, stakeholders are any group or individual who is capable of influencing or being influenced by the organization's goals and objectives (Dwivedi & Momaya, 2023). Several papers in the literature are focused on the analysis of the significance of stakeholders for corporations and the need to align corporate policies with their interests (Nejati et al., 2014; Donaldson & Preston, 1995). Both facts accentuate the fact that stakeholders can play a pivotal role in companies' success and long-term viability (Donaldson & Preston, 1995). To this end, an understanding of stakeholders' preferences and fostering productive relationships is paramount for organizations wishing to operate in a socially responsible and financially viable manner (Mitchell et al., 1997). According to Freeman and Reed (1983), interested stakeholders can be defined as "any group or individual who can affect or is affected by the achievement of the organization's purpose". These stakeholders include "citizens, customers, employees, governments, intergovernmental organizations, NGOs, policymakers, and suppliers" (Freeman & Reed (1983). The contribution of these stakeholders is critical for the organization's long-term viability.

The interplay of stakeholders differs between public and private organizational structures (Roxas et al., 2020). The public organization's relationship largely constitutes a partnership structure, while for private companies, this play is typically seen as a contract structure between private owners and employees or other organizations (Falqueto et al., 2020). Thus, it is essential for government leaders, the committed personnel of the department responsible for the initiative's implementation, the internal IT departments, and the IT service providers to interact with each other. A key benefit of such interaction is that once the establishment of such an optimal partnership occurs, all concerned parties will be extensively involved, freeing up resources to digitalize the organization effectively (Magni et al., 2022). Hence, government leadership will provide a forward-thinking direction while the department staff will provide the needed perspective and dedication. The technical pieces will be effectively organized since IT service providers will use their core competencies, and the internal IT know-how will function as support. The establishment of this optimum partnership among concerned stakeholders will be the basis of the effective implementation of sustainable digitalization (Goel et al., 2022). Stakeholders play an essential role in generating, applying, and assessing ideas, including policies, products, services, and strategies irrespective of an organization's size (Whetten et al., 2006). Stakeholders collaborate to actively scrutinize organizations' efforts, which allows well-informed decision-making and optimal use of resources (Kant, 2020). The professional teams are required to ensure that the needs of key stakeholders are taken into account when decisions are made or initiatives are realized, as this will improve the speed of an organization's recovery in situations of crisis (Freeman & Reed, 1983). The impact of stakeholders is becoming increasingly important as they pertain to organizations ensuring their important stakeholders are environmentally sustainable (Nejati et al., 2014). In the context of new global environmental issues and the growing environmentalism of stakeholders, it is assumed that this trend will dictate the priority of these stakeholders for businesses in terms of their environmental conduct (Roxas et al., 2020). Stakeholders may go beyond their legal responsibilities and use pressure, incentives, and other means to force the organization to engage in environmentally friendly activities, which can have a significant impact on companies' efforts in this area (Kant, 2020). In addition, stakeholders often disclose their expectations by asking for environmental reporting. Companies make environmental reports to show their commitment to being green stakeholders. Stakeholder theory emphasizes that

customers, suppliers, shareholders, and staff contribute trade value and influence the company (Pinheiro et al., 2022).

3. Methodology

This section entails the research methodology adopted in the current study to analyze the stakeholder's role through different strategies in sustainable digitalized manufacturing, using systematic literature review (SLR) and Hybrid MCDM methods. The used methodology is shown in Figure 1.

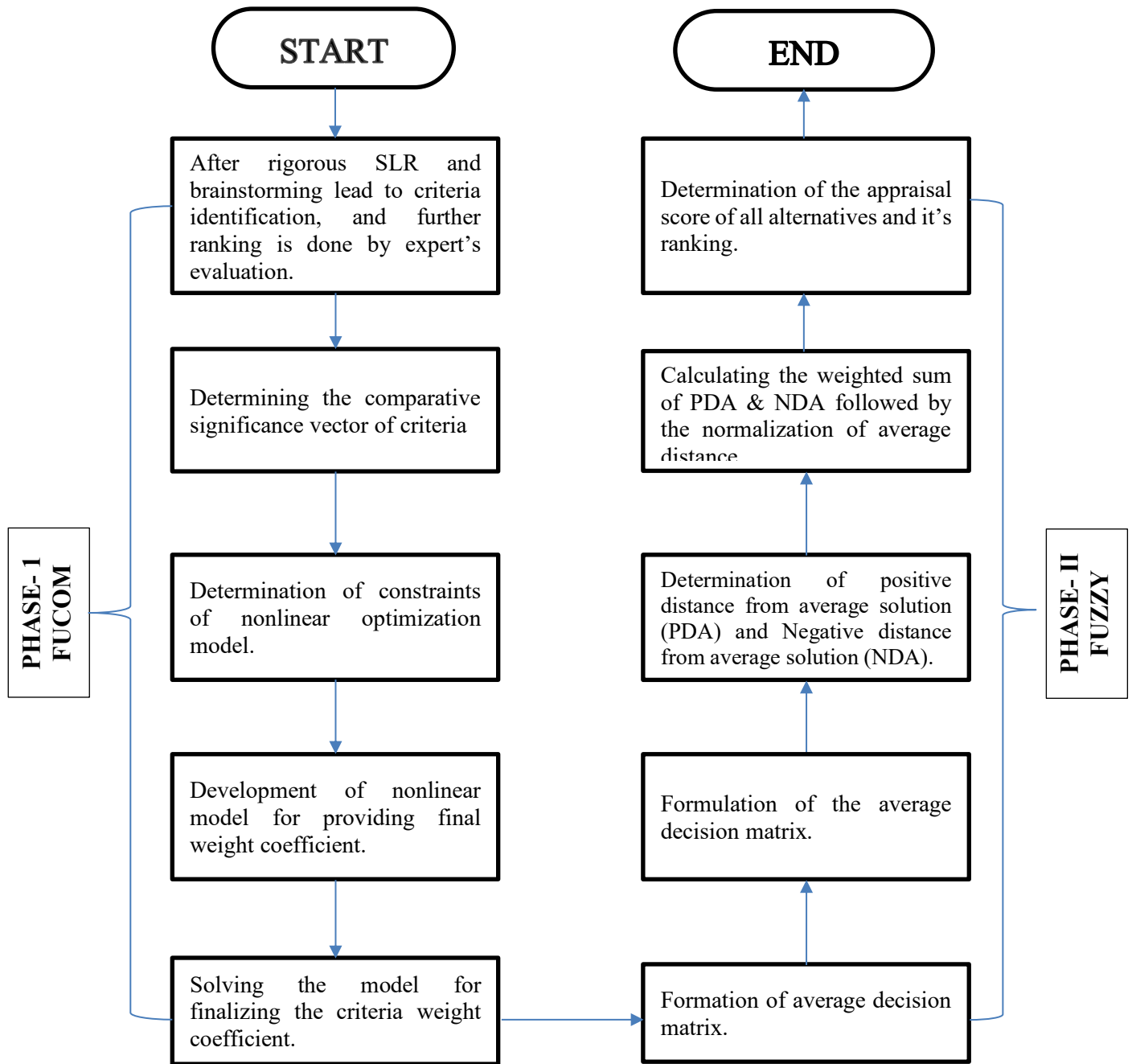


Figure 1: Research methodology

The literature review encompasses explicit, transparent, unambiguous, and systematic SALSA methodology (Search, Appraisal, Synthesis, and Analysis), which is used to collect, synthesize, and analyze to acknowledge research gaps (Mengist et al., 2020). In addition to these four basic steps, Mengist et al. (2020) extended it to PSALSAR by including research protocol and reporting results. Here, the PSALSAR methodology is adopted to oversee the SLR process. In Stage 1, the

paper identifies and prioritizes stakeholders' roles in implementing digitalized sustainable manufacturing. The study's time frame is from 2012 to 2022, considering the evolution of sustainable development goals by the UN Sustainable Summit in September 2015 for the 2030 agenda. Stage 2 involves the search for strategies, which involves database selection to identify relevant and updated data from appropriate source engines. For the research study, Web of Science and Science Direct databases were chosen, as they contain a vast collection of articles irrespective of the specialized area (Singh et al., 2021).

Furthermore, these databases are indexed and encompass a wide range of relevant articles, using a systematic and well-defined selection process for publication inclusion (Powell & Peterson, 2017). The search string “((ALL=(stakeholders OR "role of stakeholders" OR "Analysis of stakeholders" OR "Impact of stakeholders" OR "Identification of stakeholders")) AND ALL=("innovative technologies" OR "digital manufacturing" OR "digital innovation techniques" OR "Digitalized sustainable manufacturing" OR "Industry 4.0" OR "Industry 4.0 technologies")) AND ALL=("sustainable manufacturing" OR "Sustainable development" OR sustainability)” had been utilized in Web of Science databases yielding 126 articles and " Significance of stakeholders" OR "prioritization of stakeholders" AND "digitalized sustainable manufacturing" OR "Smart sustainable manufacturing" OR "innovative sustainable manufacturing" used in Science direct resulting in 119 articles.

The next stage (Appraisal) involves evaluating selected articles to identify the most relevant papers that meet specific objectives. This stage includes 1) evaluating articles based on inclusion criteria and 2) conducting quality assessments (Mengist et al., 2020). The final synthesis stage entails extracting and classifying relevant data from the selected papers (Verma et al., 2022). Variables of interest are identified and mapped with specified objectives to achieve the research objective. The selected papers are evaluated based on their contribution to the research theme's intensity, analysis of proposed methodologies for digitalized sustainable manufacturing implementation, and the role of stakeholders in fostering digitalized sustainable manufacturing adaptation. Further, with the help of a literature review, we have identified various stakeholders, which have been used as an alternative in the later part of the research, and their roles in promoting digitalized sustainable manufacturing, which are detailed in Table 1.

Table 1: Stakeholder's role in digitalized sustainable manufacturing

Stakeholders (Alternatives)	Coding	Description	Role	References
Customer	A1	A clear insight into the benefits of digitalized sustainable manufacturing and its inevitability for existence for human beings' survival.	Mandatory requirement of sustainable products in the market. Promulgate the benefits of digitalized sustainable manufacturing and delineate the necessity to maintain nature's ecological balance.	(Ore, 2019) (Freeman, 2010) (Haleem et al., 2022)
		Awareness of Sustainability has long-term benefits for the community. Suppliers should be pioneered in the data acquisition in the digitalized sustainable manufacturing arena.	Self-advertise the necessity of digitalized sustainable manufacturing and subsequently, its impact on the industries and public health care. Must perceive the customer perceptions on sustainability and the acquisition data.	(Ore, 2019) (Freeman, 2010) (Ma et al., 2018) (Haleem et al., 2022)
Communities, Labor unions, NGOs, Media, and Environmental groups	A3	Foster the implementation of digitalized sustainability concepts.	Initiate persuasive sustainable strategies in society.	(Ore, 2019) (Freeman, 2010) (Yip & To, 2021) (Haleem et al., 2022)
Managers	A4	Able to understand the changes incurred due to the adaption of the digitalized	Formulation of a systematic plan for the implementation of digitalized sustainable manufacturing and	(Ore, 2019) (Freeman, 2010) (Haleem et al., 2022)

		sustainable manufacturing	forecasting the consequences due to the adaptation. Must impart adequate skillset to the human resources, especially workforces.	
Government and related authorities	A5	Government should be able to recognize the necessity of implementation of digitalized sustainable manufacturing in the industries and provide guidelines for its adaptation.	Allocate funding/ specialized resources. Implement sustainability regulations and policies. Enact special condition taxes and local regulations. Development of a framework for conducting the business.	(Ore, 2019) (Freeman, 2010) (Gonzales et al., 2022) (Haleem et al., 2022) (Alayón et al., 2022) (Yip & To, 2021) (Ma et al., 2018)
Manufacturers OR owners	A6	They should promote sustainability practices and readiness for implementation.	Initiate sustainable development strategies. Provide adequate training and knowledge to the employees.	(Yip & To, 2021) (Ma et al., 2018) (Bhatt et al., 2020)
Employees	A7	Should have the willingness to adopt the innovation technologies for achieving sustainability.	Promote the initiatives by advertising the long-term benefits of the digitalized sustainable manufacturing.	(Ma et al., 2018) (Dabić et al., 2023)
Shareholders	A8	Promotion of digitalized sustainable manufacturing initiatives	Self-advertising of the benefits of digitalized sustainable manufacturing in and out of the industry.	(Pinheiro et al., 2022).

Furthermore, systematic and rigorous planning is indispensable in implementing digitalized sustainable manufacturing strategies in large-scale industries. However, stakeholder strategies vary based on industry processes, products, and overall systems. Stakeholders comprise internal and external entities, primary and secondary encompassing employees, managers, customers, suppliers, government bodies and regulations, local bodies, and committees (Martínez-Peláez et al., 2023; Shahzad et al., 2023; Taticchi et al., 2023). Their collaborative approach is crucial for achieving digital sustainability manufacturing. With the help of literature review, strategies for digitalized sustainable manufacturing implementation and their correlation with stakeholders' roles are presented in Table 2.

Table 2: Strategies and Stakeholder Roles

S. No.	STRATEGIES	Stakeholders (Alternatives)
1	Remanufacturing (Ngu et al., 2020) (Hina et al., 2022).	A7, A5, A2
2	Reuse (Ingemarsdotter et al., 2019) (Takacs et al., 2022).	A1, A3, A6,
3	Recycling (Ingemarsdotter et al., 2019) (Hermundsdottir & Aspelund, 2022)	A1, A3, A6,
4	Increased utilization and product repair (Ingemarsdotter et al., 2019).	A1, A3, A6,
5	Longer product life (Ingemarsdotter et al., 2019)	A1, A3, A6,
6	Sustainable manufacturing education and workforce development (Hermundsdottir & Aspelund, 2022) (Manninen & Huiskonen, 2022).	A8, A6, A5, A3,
7	Product Lifecycle Management (PLM) (Hermundsdottir & Aspelund, 2022).	A3, A2, A7
8	Cycle cost models (Hermundsdottir & Aspelund, 2022)	A3, A2, A7
9	Sustainable manufacturing metric (Hermundsdottir & Aspelund, 2022)	A7, A6.
10	Next-generation decision support toolset (Hermundsdottir & Aspelund, 2022)	A7, A6.

11	Risk, uncertainty, and unintended consequences (Hermundsdottir & Aspelund, 2022)	A7, A6.
12	6R-focused end-of-life management (Hermundsdottir & Aspelund, 2022) (Hina et al., 2022).	A7, A6.
13	Flexible and scalable manufacturing alternatives (Hermundsdottir & Aspelund, 2022)	A7, A6.
14	Legacy transformations (Fernandez-Vidal et al., 2022)	A7, A6.
15	Internal R&D/business-driven innovation (Fernandez-Vidal et al., 2022) (Kinnunen et al., 2022) (Manninen & Huiskonen, 2022).	A7, A6.
16	Agile innovation (Fernandez-Vidal et al., 2022)	A7, A6.
17	Corporate venture builders (Fernandez-Vidal et al., 2022)	A9, A7, A6, A1
18	Corporate venture capital (Fernandez-Vidal et al., 2022)	A9, A7, A6, A1
19	Incubators and accelerators (Fernandez-Vidal et al., 2022)	A7, A1
20	Alliances & joint ventures (Fernandez-Vidal et al., 2022)	A9, A7, A6, A1
21	Mergers & acquisitions (Fernandez-Vidal et al., 2022)	A7, A6, A1
22	Total quality environmental management (Ocampo, 2019) (Hina et al., 2022)	A3, A1, A2, A5
23	Resource-conservative manufacturing (Rashid et al., 2013)	A2, A3, A5, A6, A4
24	Waste minimisation (Ocampo, 2019) (Hermundsdottir & Aspelund, 2022)	A3, A6, A7
25	Eco-efficiency (Ocampo, 2019) (Kinnunen et al., 2022).	A2, A3, A5, A6, A4
26	Material efficiency (Ocampo, 2019) (Manninen & Huiskonen, 2022).	A3, A6, A7
27	Just-in-time manufacturing (Ocampo, 2019)	A3, A6, A7
28	Green manufacturing (Ocampo, 2019) (Kinnunen et al., 2022).	A3, A6, A7

Further, we have conducted different brainstorming sessions between authors to select and finalize the different strategies as a criterion for this study, which is presented in Table 3.

Table 3: Finalized criteria

Co ding	CRITERIA
C ₁	Internal R&D/ Incubators and Digitalized Innovation strategies
C ₂	Mergers & acquisitions
C ₃	Sustainable manufacturing metrics for performance evaluation
C ₄	Risk, uncertainty, and unintended consequence model development
C ₅	Flexible and scalable manufacturing initiatives
C ₆	Stakeholders' skill and education improvement programs
C ₇	6R-focused life cycle manufacturing model
C ₈	Increased Utilization and Product repair system developments
C ₉	Green and Just-in-time manufacturing strategy
C ₁₀	Government regulations and policies

3.1. Preliminaries - FUCOM & EDAS Method

The prioritization of stakeholders with distinct strategies is a multi-criteria decision-making process. Hence to resolve it hybrid multi-criteria tools must be deployed. This research employs FUCOM and F-EDAS as solutions. MCDM methods are an inevitable part of optimal selection among various alternatives. According to Zavadskas et al. (2016), the HMCDM approach can be identified as follows: MCDM Method + Other methods for identifying criteria significance, MCDM Method + fuzzy sets or grey numbers, and MCDM Method + MCDM Methods. Among these, FUCOM (Fully Consistency Method) is a recent method developed for determining the weights of the criteria (Pamucar et al., 2018). It is based on pairwise comparisons of the criteria and requires only $(n-1)$ comparisons in the model criteria (Pamucar et al., 2018).

FUCOM method is preferred over other methods due to the following reasons: 1) Very few criteria pairwise comparisons are required ($n(n-1)/2$ for AHP and $2n-3$ for BWM method), 2) Evaluation of deviation from full consistency of comparison, and 3) Satisfaction of mathematical transitivity

conditions (Pamucar et al., 2018). FUCOM combined with the MOORA method yields more reliable outputs in exploring targeting criteria of skarn iron deposits from central Iran (Feizi et al., 2021). The tourist potential of rural areas in Breko District of Bosnia has been evaluated, and Bejla with the highest potential is selected using the FUCOM-MARCOS method (Feizi et al., 2021). FUCOM-MARCOS HMCDM prioritizes green innovation aspects in Nigeria's textile industry, revealing that product innovation and greening suppliers are the most influential factors (Badi et al., 2022).

Fuzzy numbers are used to express uncertainty and vagueness in decision-making, introduced by Zadeh (Finlayson & Scriven, 1983). Trapezoidal Fuzzy numbers accurately express linguistic terms in decision-making problems. Uncertainty in decision-making is represented by Triangular Fuzzy numbers / Trapezoidal Fuzzy numbers / Neutrosophic Fuzzy numbers, etc. Triangular fuzzy numbers (TFN) belong to the special category of Trapezoidal fuzzy numbers (TpFN). For alternative ranking, a new method based on the distance from the average solution, EDAS (Evaluation based on distance from average solution), is used in ABC classification for inventory (Ghorabae et al., 2015). EDAS was introduced by Keshavarz Ghorabae et al. in inventory classification (Ghorabae et al., 2015). Alternatives are ranked based on the distance of each alternative from the average solution concerning each criterion. Fuzzy extended EDAS is utilized for finding the best supplier selection in the Industry, yielding more reliable and accurate results (Emma, 2007). Moreover, Fuzzy-EDAS requires fewer computations than other methods. Fuzzy-Fucom integrated with Fuzzy-EDAS provides 78 product prioritizations against different criteria: price, cost, demand, and quantity (Vukasović et al., 2021). The selection of hospital sites from given alternatives yields reliable and accurate results using the Fuzzy-EDAS HMCDM method (Yilmaz & Atan, 2021).

4. Case Application

The oil and gas construction sector is one of the prominent contributors to the country's overall GDP (Ann Susan Mathew, 2022). The spool fabrication industry is an integral part of the oil and gas construction project, as it involves fabricating spools in a separate yard and transporting them to the site for final erection (Wang et al., 2009a). The digitalized sustainable manufacturing paradigm in the spool fabrication industry is at an embryonic stage and still relies on conventional manufacturing methods (Sankar et al., 2023). Recent work in the spool fabrication industry has

focused on the development of simulation models to enhance the lean manufacturing paradigm (Wang et al., 2009b). The model enhances the system's performance compared to the conventional batch and queue system. In a study by Tomasz et al. (2020), the application of isometric transformation in the spool model allows accurate verification of element geometry to ensure it fits the design (Tomasz et al., 2020). Another research effort has concentrated on developing a heuristic model for scheduling fabrication activities based on the non-linear programming model in spool fabrication industries (Safarzadeh et al., 2018). There is a dearth of studies on digitalized sustainable manufacturing strategies and the role of related stakeholders in the spool fabrication industry (Safarzadeh et al., 2018; Tomasz et al., 2020). Therefore, the digitalized sustainable manufacturing scenario in spool fabrication needs in-depth investigation. In the effective management of numerous industrial projects, it is imperative that spool fabrication companies provide the prefabricated modules (Sankar M. S. et al., 2024). While the implementation of digitalized sustainable activities in such business areas is becoming arguably sluggish due to a variety of barriers, it may yet be necessary (Sankar M. S. et al., 2024). Therefore, as per the relevancy and accessibility of industry, we have considered Indian spool fabrication industry for the case application of the study. Based on the above research methodology, the prioritization of strategies is computed by the FUCOM method, and the significance of each stakeholder is evaluated by the F-EDAS method. The following section reveals the detailed steps of each method adopted.

4.1. Determination of Criteria Weights using the FUCOM Method

The following steps are executed in the FUCOM method.

Step 1: The predefined set of criteria is ranked according to the significance in the order of criteria with highest weight coefficient to lowest weight coefficient.

$$C_{j(1)} > C_{j(2)} > C_{j(3)} \dots\dots\dots C_{j(k)} \quad (1)$$

Where k represents the rank of the criterion. If the criterion with equal significance exists, then instead of “<”, the “=” is used. The identified criteria are labeled as C_1 to C_{10} randomly for the respective criteria. Two groups of decision-making are formed, encompassing academicians and

industrial experts. The significance of the criteria is analyzed by the decision group consisting of 4 members each evaluated, which is shown in Table 4.

Table 4: Significance of criteria

ID	Criteria	Group 1 Experts Ranking of Criteria	Significance (ϕ_k)	Group 2 Experts Ranking of Criteria	Significance (ϕ_k)
C ₂	Mergers & Acquisitions	7	2.5	1	1
C ₁	Internal R&D/ Incubators and Digitalized Innovation Strategies.	1	1	2	1.3
C ₃	Sustainable manufacturing metrics for performance evaluation.	2	1.2	3	1.6
C1 0	Government regulations and policies.	5	2	4	1.8
C ₆	Stakeholders' skill and education improvement programs.	4	1.7	5	2
C ₉	Green and Just in time manufacturing strategy.	6	2.1	6	2.1
C ₇	6R-focused life cycle manufacturing model.	3	1.5	7	2.3
C ₈	Increased Utilization and Product repair system developments.	10	3.8	8	2.6
C ₅	Flexible and scalable manufacturing initiatives.	8	2.9	9	3.2
C ₄	Risk, uncertainty, and unintended consequence model development.	9	3.2	10	3.6

The ranked criterion according to expression (1) is shown below.

Decision group 1 - $C_1 > C_3 > C_7 > C_6 > C_{10} > C_9 > C_2 > C_5 > C_4 > C_8$ (2)

Decision group 2 - $C_2 > C_1 > C_3 > C_{10} > C_6 > C_9 > C_7 > C_8 > C_5 > C_4$ (3)

Step 2: In the second step, a comparative analysis between the ranked criteria is done, and comparative priority ($\phi_{k/(k+1)}$, $k = 1, 2, \dots, n$, where k represents the rank of criteria) of evaluation criteria is resolved. The comparative priority is determined based on subjective references in real problems while taking advantage of one priority over another priority (Fucom, n.d.). If the criterion is of the same significance, then the comparative priority is equal to one. The comparative priority is evaluated in two ways – 1) Using the precise values of the criteria and 2) Comparison of the first ranked criteria w.r.t the other criteria. Then the vector of the comparative priority is defined as

$$\phi = (\phi_1, \phi_2, \phi_3, \dots, \phi_n) \quad (4)$$

Hence the significance of the criteria ($\omega_{Cj(k)}$) for all the criteria in (1). The first ranked criterion is compared with itself. hence $\omega_{Cj(1)} = 1$ (Fucom, n.d.). The comparative priority is defined as follows in (5).

$$\phi_{k/(k+1)} = \omega_k / \omega_{k+1} \quad (5)$$

In Table 5, all criteria are ranked w.r.t the significance, and the comparative priority is calculated by the equation (5).

Table 5: Comparative significance of criteria.

Group 1 Experts		Group 2 Experts	
Criteria	Comparative Priority (ϕ_{Ck} / ϕ_{Ck+1})	CRITERIA	Comparative Priority (ϕ_{Ck} / ϕ_{Ck+1})
C1	1.20	C2	1.30
C3	1.25	C1	1.23
C7	1.13	C3	1.13
C6	1.18	C10	1.11
C10	1.05	C6	1.05
C9	1.19	C9	1.10
C2	1.16	C7	1.13
C5	1.10	C8	1.23
C4	1.19	C5	1.13
C8		C4	

Step 3: Determination of the constraints of the nonlinear optimization model and the weight coefficient should satisfy the below two conditions (Fucom, n.d.) (Badi et al., 2022).

Condition (1). The ratio of the weight coefficient is equal to the comparative priority among the observed criteria.

$$\omega_k/\omega_{k+1} = \phi_{k/(k+1)} \quad (6)$$

Condition (2). The final values of the weight coefficient should satisfy the condition of mathematical transitivity and eventually attain full consistency.

$$\phi_{k/(k+1)} \times \phi_{(k+1)/(k+2)} = \phi_{k/(k+2)} \quad (7)$$

Step 4: Formulation of a nonlinear model for the determination of final weights. Based on the above-mentioned criteria, the weight coefficient can be evaluated.

$$\begin{aligned} & \text{Min} \chi \\ & \left| \frac{\omega_{j(k)}}{\omega_{j(k+1)}} - \phi_{k/(k+1)} \right| \leq \chi, \forall j \\ & \left| \frac{\omega_{j(k)}}{\omega_{j(k+2)}} - \phi_{k/(k+1)} \otimes \phi_{k+1/(k+2)} \right| \leq \chi, \forall j \\ & \sum_{j=1}^n \omega_j = 1, \quad \omega_j \geq 0, \forall j \end{aligned} \quad (8)$$

Step 5: Solving the formulated model and obtaining the weight coefficient. In the paper, the model is solved by using LINGO Software. The results are charted in Table 6 showing the individual weights of each criterion.

Table 6: Final weights of criteria

Criteria	Group 1 Experts	Group 2 Experts	Final Weights
	Weights	Weights	
C1	0.186	0.144	0.165
C2	0.074	0.188	0.131
C3	0.155	0.117	0.136
C4	0.058	0.052	0.055
C5	0.064	0.059	0.0615
C6	0.109	0.094	0.1015
C7	0.124	0.081	0.1025

C8	0.049	0.072	0.0605
C9	0.088	0.089	0.0885
C10	0.093	0.104	0.0985

4.2. Ranking of Stakeholders (Alternatives) using the recently developed Fuzzy-EDAS Method

The EDAS method is efficient in ranking the alternatives constituting conflict criteria. The method relies on the distance from the average solution (Ghorabae et al., 2015). It emphasizes the evaluation of Positive Distance from Average (PDA) and Negative Distance from Average (NDA). In the fuzzy environment, an extended version of EDAS (F-EDAS) is used for ranking by the inclusion of linguistic variables. Trapezoidal Fuzzy numbers (TrFN) are used to represent the linguistic variables to yield precise and accurate results and are executed by the two groups of decision-makers. Some of the basic definitions of TrFN are described below.

Definition 1. A fuzzy number $\tilde{A}$ is a trapezoidal fuzzy number if its membership function is

$$\text{defined(Emma, 2007) as } \mu_{\tilde{A}}(x) = \begin{cases} \frac{x-a_1}{a_2-a_1} & a_1 \leq x \leq a_2 \\ 1 & a_2 \leq x \leq a_3 \\ \frac{a_4-x}{a_4-a_3} & a_3 \leq x \leq a_4 \end{cases} \quad (9)$$

Otherwise $\mu_{\tilde{A}}(x) = 0$.

Definition 2. A crisp number k can be represented by the trapezoidal fuzzy number $\tilde{k} = (k, k, k, k)$

Definition 3. The basic operations between two positive trapezoidal fuzzy numbers $\tilde{A} = (a_1, a_2, a_3, a_4)$ and $\tilde{B} = (b_1, b_2, b_3, b_4)$ are mentioned below.

Addition.

$$\tilde{A} \oplus \tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4) \quad (10)$$

Substruction.

$$\tilde{A} \ominus \tilde{B} = (a_1 - b_1, a_2 - b_2, a_3 - b_3, a_4 - b_4) \quad (11)$$

Multiplication.

$$\tilde{A} \otimes \tilde{B} = (a_1 \times b_1, a_2 \times b_2, a_3 \times b_3, a_4 \times b_4) \quad (12)$$

Division.

$$\frac{\tilde{A}}{\tilde{B}} = \left(\frac{a1}{b4}, \frac{a2}{b3}, \frac{a3}{b2}, \frac{a4}{b1} \right) \quad (13)$$

Definition 3. The crisp value of trapezoidal fuzzy number $\tilde{A} = (a1, a2, a3, a4)$ is given by (Emma, 2007)

$$k(\tilde{A}) = \frac{1}{3} \left(a1 + a2 + a3 + a4 - \frac{a3a4 - a1a2}{(a3 + a4) - (a1 + a2)} \right) \quad (14)$$

Definition 4. A function ψ (psi) is defined in TrFN to evaluate the maximum between zero and trapezoidal fuzzy number.

$$\psi(\tilde{A}) = \{ \tilde{A} \quad \text{if } k(\tilde{A}) > 0 \quad \tilde{0} \quad \text{if } k(\tilde{A}) \leq 0 \quad (15)$$

Where $\tilde{0} = (0, 0, 0, 0)$.

The detailed steps in Fuzzy-EDAS are described below.

Step 1: Calculation of average decision matrix. The mediocrity of decision-makers opinion on alternatives concerning each criteria by the following calculations (Yilmaz & Atan, 2021) (Ghorabae et al., 2015).

$$X = [X_{ij}]_{m \times n} \quad (16)$$

$$X_{IJ} = \frac{1}{k} \times \sum_{p=1}^k X_{jp}^p \quad (17)$$

where X_{jp}^p represents the performance value of the alternative A_{IJ} ($1 \leq i \leq n$) w.r.t criteria c_j ($1 \leq j \leq m$) by the decision maker p ($1 \leq p \leq k$). The linguistic evaluation scale for analyzing the alternatives is expressed in Table 7 and the linguistic evaluation varies from Very low (VL) to Very High (VH).

Table 7: Linguistic evaluation scale

Very low (VL)	VL	(0,0,1,1)
Low (L)	L	(.1,.2,.2,.2)
Medium low (ML)	ML	(.2,.3,.4,.4)
Medium (M)	M	(.4,.5,.5,.5)
Medium high (MH)	MH	(.5,.6,.7,.7)
High (H)	H	(.7,.8,.8,.8)

Very high (VH)	VH	(.8,.9,1,1)
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Step 2: Determine the matrix of average solutions. The average solution matrix is evaluated as per the following equations.

$$AV = [av_j]_{1 \times m} \quad (18)$$

where av_j represents the average solution w.r.t each criteria(Yilmaz & Atan, 2021).

$$av_j = \frac{1}{n} \sum_{i=1}^n x_{ij} \quad (19)$$

Step 3: Analyze the criteria and categorize them into beneficial (B) and non-beneficial (N) for the calculation of PDA (Positive Distance from average solution) and NDA (Negative distance from average solution) matrices.

$$PDA = [pda_{ij}]_{m \times n} \quad (20)$$

$$NDA = [nda_{ij}]_{m \times n} \quad (21)$$

where pda_{ij} and nda_{ij} can be determined by the following equations.

$$pda_{ij} = \frac{\psi(x_{ij}-av_j)}{k(av_j)}, j \in B \quad (22)$$

$$pda_{ij} = \frac{\psi(av_j-x_{ij})}{k(av_j)}, j \in N \quad (23)$$

$$nda_{ij} = \frac{\psi(av_j-x_{ij})}{k(av_j)}, j \in B \quad (24)$$

$$nda_{ij} = \frac{\psi(x_{ij}-av_j)}{k(av_j)}, j \in N \quad (25)$$

pda_{ij} and nda_{ij} represents for positive and negative distance of the performance value of the i^{th} alternative from the average solution w.r.t the j^{th} criterion.

Step 4: Determination of weighted sum of positive sp_i and negative sn_i distance of all alternatives by the following expression.

$$sp_i = \sum_{j=1}^n (w_j \otimes pda_{ij}) \quad (26)$$

$$sn_i = \sum_{j=1}^n (w_j \otimes nda_{ij}) \quad (27)$$

The sp_i & sn_i values are computed by Equations (26) & (27) respectively and portrayed in Appendix 3.

Step 5: Calculation of normalized weighted sum of positive nsp_i and negative nsn_i for all alternatives by the following equations.

$$nsp_i = \frac{sp_i}{\max_i(k(sp_i))} \quad (28)$$

$$nsn_i = 1 - \frac{sn_i}{\max_i(k(sn_i))} \quad (29)$$

Step 6: Determination of appraisal score of all alternatives and ranking of alternatives with the highest score as rank 1.

$$as_i = \frac{1}{2} (nsp_i \oplus nsn_i) \quad (30)$$

The nsp_i , nsn_i & as_i values of all alternatives are computed by Equations (28), (29) & (30) and shown in Table 8 and Table 9 respectively.

Table 8: nsp_i and nsn_i values

	nsn_i					nsp_i			
A1	-0.607	0.130	0.329	0.329	A1	0.413	0.430	0.426	0.426
A2	-0.274	-0.001	0.159	0.159	A2	0.146	0.164	0.139	0.139
A3	0.045	0.345	0.400	0.400	A3	0.250	0.271	0.259	0.259
A4	-0.499	0.478	1.050	1.050	A4	0.943	0.998	1.033	1.033
A5	-0.702	0.584	0.652	0.652	A5	0.244	0.258	0.272	0.272
A6	0.434	-0.983	-0.363	-0.363	A6	0.904	0.959	0.988	0.988
A7	-0.733	1.327	0.583	0.910	A7	0.191	0.195	0.218	0.218
A8	0.364	1.000	1.000	1.000	A8	0.400	0.441	0.444	0.444

Table 9: as_i values.

	as_i			
A1	-0.097	0.280	0.378	0.378
A2	-0.064	0.082	0.149	0.149
A3	0.148	0.308	0.329	0.329

A4	0.222	0.738	1.042	1.042
A5	-0.229	0.421	0.462	0.462
A6	0.669	-0.012	0.312	0.312
A7	-0.271	0.761	0.401	0.564
A8	0.382	0.720	0.722	0.722

4.3. Sensitivity Analysis

The sensitivity analysis is performed to evaluate the model's robustness and compute the consequences by varying the criteria weights. By altering the criteria weights, the deviation in the alternative precedence is examined (Senthil et al., 2018). In the study, a total of 5 experiments are conducted by emphasizing one criterion in each step by keeping all other values the same. Different scenarios (S1-S5) are formulated which may vary the precedence of alternatives. In S1, the criteria's C1, C2, & C3 are given half percentage weightage and other criteria are weighted equal. Manufacture is prioritized first preceded by the Managers, Shareholders and others, and results reveal that varying different criteria weights, the alternatives ranking remains consistent. The criteria's C1, C2, C3 and C6 are awarded 60% of weightage and other criteria are equally distributed, subsequently alternatives ranking remains invariant. However, in the case of S3, S4 & S5; (C1, C2, C3, C6 & C7 constitute 70% and other criteria's equally distributed), All equal criteria and (C4, C5, C8, C9 & C10 constitute 70% and other criteria's equally distributed) respectively, the managers prioritized by manufacturers preceded by shareholders and others. The graph of analysis is exhibited in Figure 2 below.

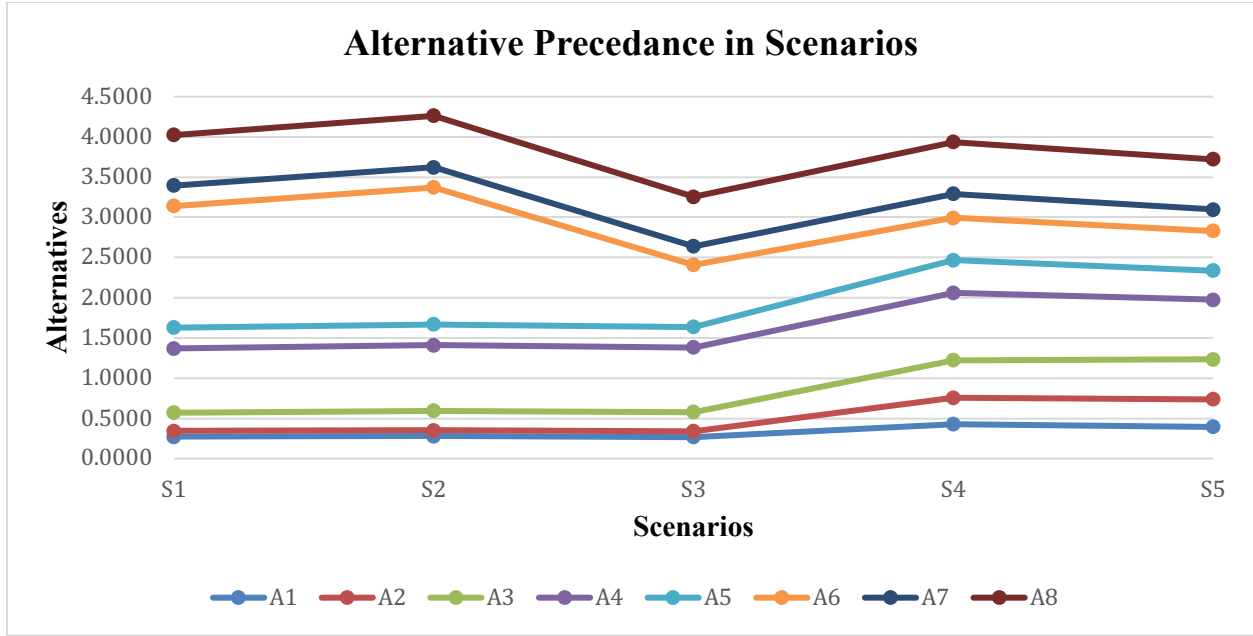


Figure 2: Precedence of alternatives in different scenarios

It depicts the alternatives prioritized between managers, shareholders, and manufacturers. The strategies are the functions depending upon the type and policies of the industry. The manufacturer, shareholders and managers are the key stakeholders in the industry's strategic implementation and contribute accordingly to the industry's strategies. Moreover, the interdependencies and interrelation between the strategies and stakeholders is another prime factor in prioritization. Consequently, the model is subjected to the nature of the industry where digitalized sustainable transformation is adopted.

5. Results and Discussions

This research reveals the substantial contribution and prioritization of stakeholders in the adaptation of digitalized sustainable manufacturing through rigorous and systematic methodology encapsulating the innovative hybrid MCDM methods. The findings are supported by existing research in the recent studies.

In phase 1 of the project, the criteria are ranked in the descending order as Internal R&D/Incubators and Digitalized Innovation strategies (C1) at the top, followed by Sustainable manufacturing metrics for performance evaluation (C3), Mergers & Acquisitions (C2), 6R-focused life cycle manufacturing model (C7), Stakeholders' skill and education improvement programs (C6), Government policies and regulations (C10), Green and Just in time manufacturing strategy

(C9), Flexible and scalable manufacturing initiatives (C5), Increased Utilization and Product repair system developments (C8), and Risk, uncertainty, and unintended consequence model development (C4). The innovative technologies and transformation to realization from conceptualization are held in R & D department which enhances the industry's competitiveness in the global market. In the spool fabrication industry, for example, integrating big data analytics with sensor technologies is targeted for effective spool tracking with fewer resources and less time (Sharma et al., 2023). Recent studies emphasize the significance of the R&D department as a critical enabler in digitalized sustainable transformation (Rese et al., 2022). The assessment of past studies supports our findings of R&D initiatives being the major strategies for digitalized sustainable manufacturing adaptation in the spool fabrication industry.

The second prioritized strategy is the sustainability assessment of the industry which elucidates the status of digitalized sustainable manufacturing in the organization. The evaluation of the current status of digitalized sustainable manufacturing in the spool fabrication industry is imperative for the formulation of sustainable strategies for fostering its implementation (Ghosh et al., 2022; Aktaş & Demirel, 2021). Based on the sustainability evaluation, the digitalized sustainability policies and principles are formulated by internal and external collaboration through mergers and acquisitions. The benefits of mergers and acquisitions are depicted below: 1) Reducing the huge financial burden, 2) Exchange of technological ideas and concepts. In the spool fabrication industry, merging with supportive counterparts will enhance the digitalized sustainable manufacturing in the organization. One of the prominent strategies in accomplishing digitalized sustainability manufacturing is the adaptation of 6R. The 6R includes Reuse, Reduce, Rethink, Repair, Recycle, and Refuse. These principles reduce wastage, increase resource efficiency, maximize material utilization, decrease resource consumption, and lower production costs and are proven in Ghanaian manufacturing firms (Afum et al., 2022). Past literature supports our output as 6R is one of the prominent technologies in promoting digitalized sustainable manufacturing. Another critical success factor in promoting digitalized sustainable manufacturing is the Government regulations and policies (C10). One of the major hindrances in implementing digitalized sustainable manufacturing is the substantial financial burden. To alleviate this, the government should formulate relevant policies/strategies and allocate funds and resources to support organizations in their initial transformation (Gonzales et al., 2022). The importance of government support is evident in the Chinese and Pakistan manufacturing industry's

implementation of low-carbon manufacturing initiatives for sustainable development (Li et al., 2023); (Khan et al., 2022. Government support is imperative for transforming conventional systems into digitalized sustainable manufacturing, especially for SMEs (Baah et al., 2021); (Testa et al., 2022); (Ernst et al., 2022). It is evident from past literature reviews that government policies and regulations are critical success factors in the adoption of digitalized sustainable manufacturing practices.

Phase II of the research involves stakeholder prioritization in descending order with the top position being the Manufacturer or Owner (A6), followed by Managers (A4), Shareholders (A8), Communities and Labor groups (A3), Government and related authorities (A5), Customers (A1), Employees (A7), and Suppliers (A2). For stakeholder prioritization, F-EDAS is employed, presented in Table 10

Table 10: Stakeholder ranking

RANK	1.454	0.741	0.609	0.268	0.231	0.214	0.181	0.072
ORDER	A6	A4	A8	A3	A5	A1	A7	A2

The manufacturers are the focal point in the implementation of the following strategies: 1) 6R concepts, 2) Increased utilization and product repair, 3) Sustainable manufacturing education and awareness, 4) Formulation of sustainable benchmarks, 5) Risk uncertainty and unintended consequences, 6) Flexible and scalable manufacturing initiatives, 7) All green manufacturing practices, and 8) Mergers and Acquisitions (Mitra, 2022). In the manufacturing industries, due to its variance and unique nature, the transition to digitalized sustainable manufacturing requires complicated and strategic planning. The manufacturer should initiate sustainability practices by providing adequate skills and training to employees, raising awareness about the concept and benefits of sustainable manufacturing, formulating systematic plans and policies for global market competition, fostering self-motivation and readiness for digital sustainable transitions, and empowering other stakeholders in sustainable manufacturing. Therefore, company owners should be at the forefront of fulfilling the dream journey toward digitalized sustainable manufacturing.

Managers are the pivotal link for deploying innovative techniques in digitalized sustainable manufacturing (Beusch et al., 2022). They serve as the active internal primary stakeholders in escalating sustainable initiatives with a clear vision (Koistinen et al., 2022). Especially project managers in the industry significantly contribute to framing sustainability practices, such as

automated tracking through the integration of sensor technologies and artificial intelligence, and automated manufacturing processes.. The manager's role in fostering the transition to a circular economy for sustainable manufacturing in Finnish companies is delineated in the research work by K. Koistinen et al. (2022). Managerial intensive dialogues and strategies significantly contribute to integrating sustainable policies and frameworks into a company's business models and corporate sustainable strategies (Beusch et al., 2022). Furthermore, the shareholder's contribution in overcoming the initial financial investment is clearly illustrated in past research studies (Ali & Jadoon, 2022). Shareholders in the spool fabrication industry encapsulate specific responsibilities in formulating sustainable strategies, especially during the project's initial stages, including bidding and scheduling. In the case of foreign and domestic investors, a positive impact exists between R&D investment and foreign investment (Shin & Park, 2020); (Jia et al., 2022). The results also reveal that communities and labor groups (A3), key primary external stakeholders, collaborate with other counterparts in achieving strategies, especially Flexible and Scalable Manufacturing Initiatives (C5), 6R-focused life cycle manufacturing model (C7), and Increased Utilization and Product Repair System Developments (C8). However, in the article by Francesco, the significance of external stakeholders, such as local communities, in socially sustainable practices is depicted (Maddaloni & Sabini, 2022). Their immense support is desirable for the digitalized sustainable development of the company.

At the outset of transformation, the Government and related authorities are the supporting pillars for policy regulations and resource funding. Enactment of sustainable policies and regulations is inevitable for digitalized sustainable manufacturing implementation. During the embryonic period of digital sustainable transition, companies face an enormous financial burden due to heavy investment. In this scenario, government support is inescapable for organizations to overcome the crisis (Alayón et al., 2022). The remaining stakeholders: Customer (A1), Supplier (A2), and Employees (A7), are prioritized from the middle level to the bottom. The customer and supplier are external primary stakeholders actively participating in the circular economy circle, which involves the utilization of a product's end-of-life and its usage through repair, redesign, or remanufacturing. For instance, the customer in the spool fabrication industry must ensure the adaptation of digital sustainability technologies, such as automatic spool tracking, fully automatic welding, warehouse management with AI-enabled technologies, IoT-based sensor systems for a healthy and safe working environment, and digitally aided tools for fabrication. These technologies

should be specifically tailored to fulfill the basic pillars of sustainability. Therefore, the overall analysis proves the significant role of stakeholders in realizing digitalized sustainable manufacturing. Furthermore, the interrelation, interdependence, and impact of each strategy with stakeholder roles are depicted. Mutual efforts and meticulous communication between stakeholders are essential for the organizational journey of transitioning to digitalized sustainable transformation.

Furthermore, based on the previous discussion, we have proposed some propositions for the future researchers as follows:

Proposition 1: In the transition toward digitalized sustainable manufacturing, it is recommended that organizations focus on digitalized innovation strategies (C1), as well as internal R&D incubators. By promoting the use of cutting-edge technology in every aspect of the shift toward digitalized sustainable manufacturing, organizations will help their employees focus on these positive trends.

Proposition 2: To understand the current situation regarding digitalized sustainable manufacturing, it is recommended to prioritize the sustainability assessment (C3) process. This allows organizations to use the generated data for the development of digital sustainability strategies and principles through internal and external partnerships, alliances, and acquisitions (C2).

Proposition 3: The realization of reducing the financial burden of transitioning to digitalized sustainable manufacturing is significantly attached to government policies and regulations (C10). Governments can help organizations, specifically small and medium enterprises transition to digital sustainability by formulating policies and allocating resources to support the transformation.

Proposition 4: Stakeholders such as manufacturers, managers, shareholders, communities, labor groups, government authorities, customers, suppliers, and employees are instrumental in achieving digitalized sustainable manufacturing. Prioritizing and engaging these stakeholders should be based on their contributions to certain strategies and approaches, such as the adaptation of 6R (C7), sustainable education, and awareness(C6).

Proposition 5: External stakeholders, such as local communities and labor groups, play significant roles in facilitating ethical and sustainable practices within companies. In particular, the

application of Flexible and Scalable Manufacturing Initiatives (C5) and Increased Utilization and Product Repair System Developments(C8) requires collaboration with diverse stakeholders.

Proposition 6: Since there are many complexities and uncertainties involved in the transition to digitalized sustainable manufacturing, it is suggested that organizations need to focus on building models and frameworks that can address risks, uncertainties, and unintended consequences (C4). By analyzing and mitigating potential risks and uncertainties in the context of sustainability, it is possible to enhance its effectiveness and success.

Proposition 7: In light of the strategy prioritization and the role of the stakeholders in the digitalized sustainable manufacturing framework, it is recommended to strategically prioritize and integrate Green and Just in Time Manufacturing strategies (C9) into the manufacturing processes. Green manufacturing is focused on reducing the environmental impact, while JIT manufacturing is centered on waste minimization and maximum efficiency. Both strategies are generally aligned with the principles of sustainability.

6. Implications

6.1. Theoretical implications

The research has both theoretical and practical implications. In terms of the theoretical implications, the research has shown that prioritizing stakeholders as a model is likely to be effective because it provides for the critical roles of stakeholders, such as governments, research and development institutions, manufacturers, managers, and shareholders, in the adoption of digitalized sustainable manufacturing. Ensuring the prioritization of these stakeholders as a model is a crucial theoretical approach that could be used in a wide array of economic sectors all over the world. Its emphasis on the central role played by stakeholders' synergy in driving sustainability projects is important. In the process of prioritizing digitalized sustainable manufacturing, the research has also noted the need for the determination of the causes and effects of the interactions and interdependencies between various stakeholders. Having a clear understanding of the relationships between stakeholders would be critical in encouraging stakeholders' mutual collaboration, which is crucial for the establishment of environmentally sound manufacturing processes. In light of this theoretical insight, it would be reasonable to conclude that the successful implementation of digitalized sustainable manufacturing would benefit from the promotion of

collaboration and the understanding of the dynamics of the interactions between the numerous stakeholders.

6.2. Practical implications

The research has provided that a mere comprehension of the linkages between causes and effects, as determined through the generalization of the prioritization of stakeholders, would ensure that the obstacles associated with the implementation of digitalized sustainable manufacturing are resolved. This means that it would be possible to address problems that bedevil the transition to sustainability manufacturing practices using a comprehensive understanding of stakeholders' dynamics and effective methods of prioritization. Further, it is essential to allocate government policies and incentives to the organizations to eliminate the huge initial burden in the transition to digitalized sustainable development (Gonzales et al., 2022). The government is one of the key stakeholders and must frame policies for the respective industries. It is clear from past research that the lack of governmental policies in Pakistan's manufacturing industries serves as a main impediment to the path to sustainable development (Khan et al., 2022). Moreover, the enactment of government laws will initiate the implementation of corporate sustainability through green practices in SMEs (Ernst et al., 2022). Also, R&D is capable of incubating and developing technologies customized for meeting industrial requirements and maintaining the system by developing appropriate measures. In past studies, R&D initiatives emerge as a critical enabler for achieving environmental sustainability (Strunge et al., 2022). In the Oil and Gas industries, R&D emerges as a critical enabler for implementing circular economy practices (Sharma et al., 2023). The technological risk associated with the adaptation of digitalized sustainable manufacturing can be curtailed by internal and external technical collaboration. The exchange of technologies while maintaining the confidentiality of the organization will enhance the adaptation of digitalized sustainable manufacturing (Chen & Ario Wibisono, 2023). Green mergers and acquisitions enhance the green transition of Chinese industries and promote sustainability (Yang & Chi, 2023). Also, the generation of sustainability benchmarks for assessing the present status of the organization's sustainability level is another implication of present research. Sustainability assessment in MSMEs is done through the manufacturing sustainability index in the research by Gani (Gani et al., 2022). Past research studies reveal the correlation between stakeholders and strategies regarding mergers and acquisitions (Obagbuwa & Kwenda, 2023). Through these

suppositions, mergers & acquisitions, R&D initiatives, and Government policies must be given high priority by managers in the initial stage of implementation. Additionally, the results also reveal significant strategies for digitalized sustainable manufacturing adaptation and will serve as a yardstick for assorting relevant stakeholders in the industrial/academic sphere. The interdependencies between digitalized sustainable manufacturing strategies and the interrelationship between strategies and stakeholders provide important insights to managers in the decision-making process of sustainability initiatives. A very important facilitator in improving digitalized sustainable manufacturing processes seems to be the increased stakeholders' awareness. In a recent research study conducted on the highway project in Jordan, Aljboor et al. (2023) have found that the absence of education concerning sustainability is a significant barrier to development. It cannot be denied that the stakeholders' anxiety of risk and uncertainty which are developed on the executing projects of sustainability can be reduced by the spread of education concerning sustainability. In addition to enlightening these perplexing situations in the research the three very important focal people that should be given priority when developing digitalized sustainable plans are the manufacturers, managers, and shareholders alike. The research reveals a very clear understanding of the theoretical implications. The first step that should be taken is that a higher priority should be given to stakeholders to facilitate the deployment of digitalized sustainable manufacturing in Industry all over the world. It should be noted that the relative role of stakeholders' priority in the perspective of the improvement of digitalized sustainable production efforts across all industrial sectors does not vary. The next step in these prioritization efforts is to establish a partnership of cause and effect by examining the interdependencies and cause-effect relationship between the stakeholders. It should be remembered that the partnership established by the two of them will account for the two of them to contribute to the implementation of clean manufacturing processes. It should be noted that establishing these cause-effect relationships in addition to generalizing the stakeholder prioritization will be a makeup of the numerous barriers that hinder the implementation of digitalized sustainable manufacturing.

7. Conclusion

The present research offers rich insights into stakeholders' ranking and strategies prioritization in the context of adaptation to digitalized sustainable manufacturing. The study used

an innovative hybrid MCDM approach to rank and prioritize stakeholders and strategies. The study found that manufacturers should rely on various technologies and other stakeholder groups' support to enhance the level of digitalized sustainable manufacturing. Minimal critical requirements imply that manufacturers should integrate with other stakeholders and use R&D, sustainability assessment and adaptations, 6R, mergers and acquisitions, government regulations, and other strategies for enhancing the level of digitalized sustainable manufacturing. Further, the present research identifies manufacturers, managers, and shareholders, among stakeholders, followed by communities and labor. The study advanced several implications and propositions for future research. Further, theoretical implications emphasize the research's role in extending existing knowledge regarding stakeholder prioritization and the development of digitalized sustainable manufacturing. As per this research, it is necessary to understand the relevance of stakeholders and ways to address obstacles by enhancing collaboration and knowledge of their relationships. Moreover, the theoretical implications outline that support from the government and increased R&D activities will enhance the process of transitioning to sustainability. The practical implications of study include the need to consider stakeholders' awareness regarding sustainable manufacturing in the process and establish the priorities that will enhance it. According to the study, three main stakeholders require primary attention in the form of manufacturers, managers, and shareholders. Both theoretical and practical implications suggest that the study contributes to the identification of stakeholder priorities and key enablers of digitalized sustainable manufacturing. This way, the research offered a robust theoretical and practical basis for the development of digitalized sustainable manufacturing. It contributed to stakeholder prioritization and provided a comprehensive review of stakeholders and their interactions, as well as the aspects that will help establish a new facility. The research included various implications concerning the cooperation and government's support, suggesting that increased activities in R&D are necessary to promote sustainability transitions. The study, therefore, offers a valuable contribution to the identification of the type of stakeholders and ways to address their awareness-related issues.

A limitation of the research is that it cannot be tested in practice as it represents an overview and does not relate to any specific context. Several research avenues can be identified based on the results of the study and the associated limitations. To begin with, the scope of research could be extended to include more manufacturing industries, increasing the relevance and generalizability of the results and supporting a more thorough understanding of the phenomenon.

Simultaneously, the choice of a methodology or combination of methodologies could be used to enhance the insight provided by the research into the attitudes and behaviors of multiple stakeholders involved. At the same time, the identification of the issues and obstacles organizations had to overcome on the path to digitalized sustainable manufacturing would allow for the development of effective interventions and strategies. Moreover, the analysis of the role of specific emerging technologies, such as blockchain or artificial intelligence, in the context of sustainable manufacturing could provide new opportunities for the industry. Similarly, a longitudinal approach could be used to test the efficacy of digitalized sustainable manufacturing across time and evaluate the long-term impacts. Therefore, future researchers need to consider addressing issues in the identified subcategories. It should be noted that the complexity of implementing sustainable manufacturing strategies in the age of digitalization requires considering each of the aforementioned aspects. By developing a more well-rounded and detailed picture of sustainable manufacturing processes and creating tools for promoting their implementation, the research mentioned above provides a solid foundation for further exploration of the issue.

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