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Original Article

Assessment of Sustainable Manufacturing Enablers: Pythagorean Fuzzy AHP Approach

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Abstract *- This research aims to identify the enablers of Sustainable Manufacturing (SM) adoption in manufacturing organizations and assess them according to the interrelations between each enabler. Expert opinions and a comprehensive literature search have been employed to identify the formation of contextual relationships among 28 sustainable manufacturing enablers (SMEs). The developed hierarchical model identifies the interrelationships among each SME and illustrates the contextual relationship that is constructed with the help of Fuzzy Pythagorean Analytics Hierarchical Processes. The designed mechanism would help upper management concentrate on the most essential SMEs to implement SM successfully. The outcome indicates that the primary enabler for the initialization and development of the most optimal organizational structure and culture, which can result in the successful adoption of SM, is the commitment of the top management. The findings suggest that the commitment of top management is the main facilitator for establishing and growing the most ideal organizational structure and culture, which can lead to the effective adoption of SM. Here, the deployment of SM is driven by two essential enablers: technological investment and favorable government policies. These enablers directly impact the long-term strategic objectives of SM. This investigation has substantial effects on both academics and practitioners. Academics may encourage management to classify numerous significant issues in addressing SMEs, while practitioners should concentrate on driving SMEs during the implementation of SM within their organizations.*

Keywords *- Sustainable Manufacturing (SM), Sustainable Manufacturing Enablers (SME), Pythagorean fuzzy AHP (PFAHP), Industrial Organizations, Analytics Hierarchical Processes.*

1. Introduction

The world is experiencing a serious shortage of materials due to finite resources because of intense global rivalry, technological innovation, and the enormous demand for commodities brought on by growing populations. When a manufacturing organization operates, a significant amount of hazardous materials are released into the environment and society as byproducts (Herrmann et al., 2014).

Further ongoing demand from non-governmental organisations and other social organisations has compelled businesses to enhance employee safety and mitigate adverse environmental impacts (Yorem Koren et al. 2018). These environmental and social concerns (H.T.S. Caldera et al. 2019) have lowered the manufacturing sector's growth. To resolve these issues, manufacturing organisations are compelled to implement Sustainable Manufacturing (SM) practices, as these organizations substantially contribute to national economic growth by offering the required products and services essential to expand the global economy (Malek et al., 2019).

Indian industrial organizations and businesses face sustainability challenges in both domestic and international markets as a result of the linear economic system paradigm. Statistics show that India is ranked 7th globally in solid waste generation. In addition, urban areas generate 62 million tons of municipal waste per year and are expected to reach 165 million by 2030, increasing GHG to 41 million tons CO2e by 2030. Consumer plastic in India was 20 million tons in 2019–20, whereas 3.4 million tons were recycled, which comes to 30% only of total consumption (www.narendramodi.in). India generated 1.6 million tons of e-waste in the year 2021-22 and recycled only 33% out of the total. Regarding extraction rate, it is currently 1,580 tonnes/acre for India, which is 251% higher than the world average. The recycling rate of India is 20%, many times less against Europe and emits 9.2% of the total world's emissions. The MSME sector of India is facing high virgin material price and environmental norms issues along with a lack of skill and knowledge for adopting sustainable manufacturing practices. On the global front, environmental awareness is the key reason behind the widespread SM practices in the manufacturing sector in countries like the EU, South Africa, Austria, India, and China, whereas countries like South Africa, Austria and India adopted SM practices for the purpose of unit cost reduction and to reduce virgin material demand. The green manufacturing approach is widespread in the USA, EU, Brazil, Russia, India and China due to strict environmental regulations, whereas Germany, Brazil, and India have initiated the development of green SC due to automotive OEMs. Developing countries like Bangladesh, Sri Lanka and India escorts' adoption of cleaner SM technologies.

Though adopting SM practices has achieved promising advancements, the manufacturing sector faces challenges such as unclear vision and road map, lack of industry enthusiasm, infrastructural challenges, cultural challenges, and growth of the materialistic economy and consumers. Therefore, the adoption of SM in manufacturing organizations will require a shift in focus from just recycling to the design and implementation of SM techniques in manufacturing, the identification of facilitators/ enablers to support SM practices in production, and the adoption of related innovative technologies to reduce waste, protect the environment, and address other economic issues. All in all, the linear economic model of the Indian manufacturing sector has created issues, necessitating radical solutions such as SM practices adoption to address energy, waste, environment, social equity, and long-term economic growth.

The manufacturing industry has the potential to facilitate the maintenance and growth of the national economy. India's industrial sector substantially contributes to exports and foreign exchange inflows into the nation. It also generates a significant amount of employment for all demographic groups. The development of stable economies in developing countries is greatly aided by the expansion of the manufacturing sector (Jeya and Vinodh, 2012). In order to achieve economic stability, it is imperative that the manufacturing sector should maintain its pace in such a manner that it minimises adverse environmental impacts (Bogue, 2014). To achieve this, developing nations such as India must implement SM practices (Bhanot et al. 2017) to remain environmentally cognizant and globally competitive.

The adoption of SM in manufacturing includes environmental, social, and economic factors that make the decision-making process more complex (Zhang and Haapala, 2015). The ability of developed nations to incorporate environmental and social considerations into their strategies is readily apparent, pertaining to their well-established economic systems and sophisticated infrastructure (Cherrafi et al., 2016). However, these factors are neglected by organisations in developing countries during the formulation of strategies (Xia et al., 2015). Developing countries may find it challenging to incorporate SM with environmental and social considerations into their business strategies due to technological and financial constraints and inadequate infrastructure (Bhanot et al., 2017).

SM integrates economic profit, environmental sustainability, and social well-being (Garetti and Taisch, 2012). Choosing between environmental, social, and economic reasons for adopting SM is a complex decision-making process (Zhang and Haapala, 2015). Organisations in developing countries neglect to consider environmental and social factors while developing future paths (Xia et al., 2015). Developing nations may face challenges incorporating environmental and social considerations into their business strategy due to technological and budgetary constraints and inadequate infrastructure (Bhanot et al., 2017). Developed nations pertains the ability to include environmental and social factors in their policies due to the availability of sophisticated infrastructure and robust economic growth (Cherrafi et al., 2016).

The aforementioned discussion explicitly states that the industrial manufacturing sector is the most significant contributor to the economy of developing countries such as India. It also highlights the perils that manufacturing organisations face if they fail to transition from a conventional approach to a sustainable and environmentally conscious approach (ghobadian et al., 2018).

The transition to the adoption of SM is a difficult task that necessitates the completion of numerous extensive activities, including the separation of products into recyclable and disposable categories, the implementation of advanced technologies, the establishment of effective communication at each node of the supply chain, financial support, and the availability of technical experts (Hu and Hsu 2010). In this context, it is essential to comprehend and recognise the SM enablers (SMEs) that can aid in the successful pursuit of SM adoption activities (Malek et al., 2020) and drive the process smoothly.

Since SMEs aid in the development of strategies for balancing economic, environmental, and societal aspects as well as the achievement of SM objectives, twenty-eight (28) SMEs are identified and categorized in this study based on the literature review and responses from the survey of IMOs. In other words, from the insight of the need for SM and SM enablers, this study focuses on the identification and categorization of SMEs. In this study, SMEs are classified into five primary categories and further analyzed using Fuzzy Pythagorean Analytics Hierarchical Processes (AHP) as the decision-making model.

At this stage, it is vital to go through the process of selecting only those parameters for SM that accurately represent the required functions for rising countries. If the facilitators are there, the adoption process will go more quickly with the following steps.

1. Identification of the critical enablers that successfully facilitate the implementation of sustainable manufacturing processes.
2. Creation of a hierarchical model of the enablers that encourage the use of sustainable manufacturing.
3. Assess the influence and interdependence of the selected enablers.
4. Analyse the theoretical and management consequences arising from the present examination by analysing published literature and considering the feedback from the decision-making panel.

The important classification of the numerous SMEs and sub-SMEs involved in the present study constitutes a challenging DM problem. The Analytic Hierarchy Process is the most frequently used method in the literature for evaluating and prioritising the criterion through data analysis (Sumit Gupta et al. 2015). However, it is conceivable that the information may contain a certain level of imprecision and ambiguity, as the input data for AHP analysis is contingent upon human judgment. The integration of fuzzy sets, as suggested by Zadeh in 1965, with AHP has proven effective in reducing ambiguity and managing imprecision. In 1986, Atanasov proposed the concept of an intuitionistic fuzzy set as a way to expand upon the idea of a fuzzy set. The goal was to tackle issues related to membership functions, non-membership functions, and degrees of reluctance. The intuitionistic fuzzy sets' two membership functions could effectively account for the ambiguity inherent in human judgments.

This study examined twenty-eight Sustainable Manufacturing Enablers (SMEs) to achieve the preceding objectives. It classified them into seven main categories based on an analysis of published research and feedback from the decision-making panel. The important classification of the numerous SMEs and sub-SMEs involved in the present study constitutes a challenging DM problem. The Analytic Hierarchy Process (AHP) is the most frequently used method in the literature for evaluating and prioritising the criterion through data analysis (Sumit Gupta et al. 2015).

Nevertheless, since the input data for AHP analysis depends on human judgment, it is conceivable that the information may contain some degree of imprecision and ambiguity. The integration of fuzzy sets, as suggested by Zadeh in 1965, with AHP has proven effective in reducing ambiguity and managing imprecision. In 1986, Atanasov introduced an intuitionistic fuzzy set as an extension to the fuzzy set concept, aiming to address concerns pertaining to membership functions, non-membership functions, and degree of reluctance. The intuitionistic fuzzy sets' two membership functions could effectively account for the ambiguity inherent in human judgements. Nevertheless, constraints are associated with the two membership functions of intuitionistic fuzzy sets, especially when performing arithmetic addition (shete et al., 2020).yager The aggregate is restricted to one of the membership functions of the intuitionistic fuzzy set. This suggests that intuitionistic fuzzy sets are incapable of handling situations in which the sum of two membership functions exceeds one. Therefore, to overcome this constraint, Pythagorean fuzzy sets were suggested (Yager, 2013). In this case, the squares of each membership are used in place of the aggregate of the two memberships in the intuitionistic fuzzy set, provided that the sum of these two squares is equal to or less than one. If a pair of values (x, y) falls within the interval [0, 1], intuitionistic membership grades include all points below the line $x + y = 1$.

In contrast, Pythagorean membership grades include all points satisfying the equation $x^2 + y^2 = 1$. Thus, the set of Pythagorean membership grades is more extensive than the set of intuitionistic membership grades. This provides decision-makers with increased autonomy in articulating their viewpoints concerning the ambiguity and lack of specificity of the issue at hand (shete et al., 2020). The current study employs the Pythagorean fuzzy AHP framework to evaluate Sustainable Manufacturing Enablers (SMEs). Furthermore, an examination of the manufacturing sector has been undertaken in order to implement the suggested framework. The chosen case industry management for this research is to acquire a comprehensive grasp of SMEs and assess their relative importance.

2. Literature Review

Manufacturing industries within the industrial sector of developing countries must adopt SM techniques to improve their environmental performance (Tseng et al. 2015; Shete et al. 2020). SM is defined as "producing manufactured materials that are financially feasible, safe for consumers, employees, and communities, and conserve energy and natural resources" (US Department of Commerce and of, 2011). The most significant factors that influence the successful adoption of SM practices in industries are enablers. It is effortless for industry professionals to employ the enablers during the adoption process once the enablers are identified. This study covers the variety of findings from the authors towards SM enablers. The following are the varying perspectives and opinions on SM enablers. Organisations are required to contribute to their environmental and social responsibilities by numerous NGOs and unions. Ervin et al. (2013) identified corporate environmental and social obligations as crucial determinants for adopting environmentally sustainable operations.

Neeraj Bhanot (2017) Ervin assert that the E-economy enables technology to link local and global markets, promoting effective communication and guaranteeing the long-term viability of resources in various sectors. Luthra et al. (2015) suggested that the level of involvement of suppliers has a substantial influence on the successful implementation of sustainable practices. An audit plan should be implemented to evaluate and assess the level of adoption and participation of suppliers in sustainable manufacturing (SM) practices. Luthra (2015) suggested that the level of involvement of suppliers has a substantial influence on the effective development of sustainable practices. An audit plan should be implemented to assess the level of adoption and participation of suppliers in sustainable manufacturing (SM) practices. R KSingh and Rastogi (2016) highlighted the importance of evaluating supplier performance based on environmentally conscious criteria to uphold the ecological performance of companies. After evaluating their performances, it is crucial to offer them technical assistance. Brian Griffiths (2012) stated that public demand can act as a catalyst for the green movement and compel organisations to incorporate environmental preservation into their strategic decision-making. In their study, In their study, Shi et al. (2008) discovered that public pressure had a limited effect on the implementation of environmentally friendly practices when compared to other influencing factors.

Joshi and Rahman (2015) highlighted the restricted influence of green purchasing and green procurement, indicating that implementing environmentally friendly practices alone would not enhance sustainability unless accompanied by more efficient enablers. Ali and Deif (2014) determined that environmentally friendly technology can improve process efficiency and decrease waste's negative environmental impacts. Guo et al. (2015) posited that a green corporate image has the ability to serve as a worldwide marketing strategy to acquire a larger client base for environmentally-friendly goods. The successful adoption of SM practices is contingent upon the industries possessing an adequate amount of theoretical and practical knowledge. Environmental education and training are identified as important factors in promoting sustainable practices, as stated by Prasad (2018). Muduli et al. (2013) recognised employee empowerment as a crucial factor that enables and facilitates success.

Muduli et al. (2013) identified employee empowerment as a critical enabler. In contrast, The training programme necessitates the support of upper management, which is capable of formulating strategies, allocating funds, and monitoring the results (Prasad et al., 2018). The adoption of sustainable practices was positively impacted by the commitment and support of senior management, as demonstrated by Dubey et al. (2015). Toke et al. (2017) identified top leadership dedication as a catalyst that influences other factors in enabling the effective execution of sustainability. The significance of senior management support and involvement in development projects is underscored by the contrasting viewpoints of decision-makers and researchers/academics (Toke et al. 2017). According to Malek and Desai (2019), integrating the system encourages collaboration between different departments and improves business communication. Malek and Desai (2019) found that integrating the system promotes interdepartmental collaboration and enhances communication inside organisations. Neeraj et al. (2017) identified system integration as a significant enabler that facilitates the effectiveness of SM. The adoption of SM relies on the collaborative efforts of several stakeholders, including suppliers, workers, consumers, and government entities. Bhanot et al. (2017) said that stakeholder participation is a crucial factor that may promote the adoption of Sustainable Manufacturing (SM) practices. Organisations are pressured to implement environmentally conscious processes and be sustainable due to the demand for green goods. According to a study done by Nishat Faisal (2010), consumer knowledge has a crucial role in promoting the acceptance of sustainable practices. The participation of highly motivated workers is essential as they provide devoted efforts to the process of organisational development. In their study, Mani et al. (2015) investigated the necessity for sustainability leaders to create strategies that encourage adopting socially sustainable practices via direct incentives. In their study, C. Alayon (2017) established the significance of employee involvement and motivation as a vital element in executing sustainable practices.

Environmental certification ensures that every activity conducted inside the organisation supports reducing negative environmental impacts. Diabat et al. (2014) highlighted the beneficial impact of environmental and safety requirements on improving the well-being of consumers, employees, and communities. The organisation is typically motivated to implement novel customer satisfaction strategies by the presence of robust competitive advantage in the marketplace. The incorporation of SM practices by a market competitor organisation can serve as an incentive for other organisations to implement sustainable manufacturing practices. According to Gunasekaran et al. (2012), pressure from competitors' enablers plays a crucial role in influencing the development of other enablers, such as customer expectations and explicit rewards. Bhanot et al. (2015) highlighted the importance of effectively distributing funding and ensuring the availability of resources to ensure the successful adoption of sustainable manufacturing practices.

Foreign direct investment (FDI) promotes the development of comprehensive financial connections and enhanced innovation and management. It also fosters a healthy competitive environment among various industry participants. Bhanot et al. (2017) identified Foreign Direct Investment (FDI) as a critical factor in attaining world-class product performance, characterised by diminished or eliminated detrimental environmental effects. Effective strategic planning is crucial for the environmentally responsible disposal of hazardous wastes and promoting sustainable development. Gunashekaran (2012) concluded that the deployment of funding for the execution of SM practices would result from adopting strategic planning for waste management. Strategic planning is a critical factor that has the potential to enhance the administration of natural resources, as per Singh and Debnath (2012a,b). Kannan et al. (2016) asserted that solid waste management is a pivotal factor in promoting the execution of a sustainable future, notwithstanding its limited integration. The organisation may achieve effective garbage disposal through the use of innovation and modern technologies. Malek and Desai (2020) asserted that the utilisation of innovation and technology has the potential to improve the environmental performances of enterprises.

Malviya and Kant (2017) argue that allocating resources towards innovation and technology enablers significantly impacts the effective execution of sustainable management practices. This influence is high in relation to driving power and low in relation to dependence on other enablers. The literature above indicates that entire investigations mentioned have been conducted in the environment of India. The aforementioned factors highlighted in the research are important in representing the circumstances of developing nations. They may contribute to exploring valuable information for adopting SM strategies in the Indian context. Gaps found in the existing literature.

The gaps observed in the literature have been highlighted below:

- Prior research has assessed the enablers that facilitate a certain outcome. However, only a limited number of studies have classified these enablers according to the specific roles they play inside an organisation.
- The practical and behavioural implications of SM in Indian organisations have been discussed in a limited number of case studies.
- The studies conducted in India to date have not provided a comprehensive roadmap for the adoption of SM.
- There is a dearth of research investigations in the Indian context that have developed a hierarchy-based framework for sustainable manufacturing enablers, which encompasses a diverse array of enablers.
- In the Indian context, there are just a few studies that have examined the identification of the driving and dependent forces of enablers by combining fuzzy features with MICMAC analysis.

3. Research Methodology

Described in detail the stages of SM adoption and enablement in the Indian manufacturing sector was aimed at the initial stage of the research work. To understand the conceptual SM practices, available literature was surveyed. Peer-reviewed journal papers and renowned articles were reviewed from the online database until July 2024. Content analysis methodology represents the ground reality of existing literature available towards CE with an assessment of the variety of SM strategies and practices for SM practices implementation in organizations that led the researcher to the most practicable results. Hence, this study adopts the same for LR. From LR, involving industry and academic experts, research gaps and objectives were finalized. SM enablers drive the SM implementation process and help organizations achieve various SM enablement-related benefits, improving overall organizational and business performance. Based on LR and the involvement of industry and academic experts, 28 SMEs were identified based on a few propositions developed from LR to understand the dynamics between SMEs. Fuzzy Pythagorean Analytics Hierarchical Processes (AHP) as a decision-making model approach was adopted to identify contextual relationships of SMEs, which helps achieve the organization’s strategic goals. The analysis results provide a novel approach in the Indian and global context, as they are not so obvious in terms of research and bring many critical insights into improving SM practices adoption in India.

Experts from the field of SM who are interested in implementing SM practices and working for industries willing to adopt and implement SM. Results of the literature survey were presented to these experts, and a series of meetings were accomplished to identify the exact needs of manufacturing industries to implement SM practices. A number of brainstorming sessions and meetings were carried out with the experts to draft a structured SM model. The draft structure of the developed model framework was presented to the experts, and with rounds of discussions and opinions, the methodological model framework was finalized to be commonly adapted to the manufacturing industries and organizations. Involving industrial and academic experts on the subject of the finalization of 28 SMEs can lead and drive the process of SM enablement in manufacturing to success.

The subsequent stages that are implemented to implement the research framework are as follows:

1. Conduct an exhaustive literature review to determine the enablers that support sustainability in the supply chain for Sustainable Manufacturing Enablers (SMEs), and then create a comprehensive list of these factors.
2. Analyse the literature to identify the enablers of sustainability in the supply chain for SMEs and subsequently compile a list.
3. Discuss the identified SMEs with the Decision Making panel to determine their appropriateness for the case industry and subsequently select twenty-eight SMEs.
4. Develop a Hierarchy by categorising these twenty-eight SMEs under seven major enablers.
5. Apply the Pythagorean fuzzy Analytic Hierarchy Process (AHP) to calculate the local weight of the main enablers and sub-enablers. Furthermore, calculate the total weight of all twenty-eight sustainable manufacturing enablers (SMEs).
6. Once the Decision-Making panel confirms the outcome, embark on ranking the SMEs.

3.1. Pythagorean fuzzy Analytic Hierarchy Process

The input data for real-world Multiple-Criterion Decision-Making (MCDM) situations often exhibit imprecision and ambiguity. The uncertainty is handled by employing intuitionistic fuzzy sets, as proposed by Atanassov in 1986. The degree of reluctance membership function, and non-membership function are all methods for expressing these sets with ambiguity. Intuitionistic fuzzy sets cannot handle uncertainty when the degree of membership and non-membership surpasses 1. Various extensions to intuitionistic fuzzy sets that are capable of addressing this issue include the neurosophic set (Smarandache, 1995), the Pythagorean fuzzy set (Yager, 2013), and the ortho pair fuzzy set. This study utilises Pythagorean fuzzy sets to address the inherent inconsistency and lack of certainty of the data provided by professionals. The total degrees of membership and non-membership in Pythagorean fuzzy sets can be greater than 1, but the sum of their squares cannot exceed 1. This indicates that the intuitionistic membership grades for each point (x, y) that is also a Pythagorean member grade are all points below the line x + y ≤ 1, whereas the Pythagorean membership grades are all points with $x^2 + y^2 \leq 1$. Therefore, the set of membership grades based on Pythagorean principles is larger in size compared to the set of membership grades based on intuitionistic principles. Therefore, Pythagorean fuzzy sets afford decision-makers increased latitude to articulate their viewpoints concerning the problem's ambiguity and lack of precision (Ilbahar et al., 2018). Pythagorean fuzzy sets find extensive utility across various research domains. Fuzzy sets based on Pythagorean theory are determined using mathematical algorithms.

Definition 1. A Pythagorean fuzzy set, designated as P, is an object described by the following form (H.Garg, 2016): A Pythagorean fuzzy set is formally defined as the object referred to as $\tilde{p}$ defined as follows according to Gul et al. (2016):

$$\tilde{p} = \{< x, \mu_{\tilde{p}}(x), v_{\tilde{p}}(x) >; x \in X\} \quad (1)$$

Where the

$$0 \leq \mu_{\tilde{A}}(x)^2 + v_{\tilde{A}}(x)^2 \leq 1 \quad (2)$$

Also, the degree of hesitancy condition is as shown below:

The phases of Pythagorean fuzzy AHP and the underlying mathematical operations of Pythagorean fuzzy sets are as follows:

The function $\mu_{\tilde{p}}(x): X \to [0,1]$ is defined as the degree of membership, whereas $v_{\tilde{p}}(x): X \to [0,1]$ denotes the mapping from X to P. The interval [0, 1] represents the extent to which the element x belongs to the set X.

This relationship may be expressed as:

$$0 \leq \mu_{\tilde{A}}(x)^2 + v_{\tilde{A}}(x)^2 \leq 1 \quad (2)$$

The condition for the degree of hesitancy is also as follows:

$$\pi_{\tilde{p}}(x) = 1 - \mu_{\tilde{p}}(x)^2 - v_{\tilde{p}}(x)^2$$

Definition 2. Let $\tilde{L} = (\mu_1, v_1), \tilde{M} = (\mu_2, v_2)$, consider the two Pythagorean fuzzy values, and Assume that ᴍ > 0 and ᴍ L = (μ1, v1) and λ M = (μ2, v2) represent two Pythagorean fuzzy values $\lambda > 0$, then the mathematical procedure that is possible to execute on these two Pythagorean fuzzy values are as follows (Zhang and Xu, 2014):

$$\tilde{L} + \tilde{M} = \left(\sqrt{\mu_1 + \mu_2 - \mu_1\mu_2}, v_1 v_2\right)$$

$$\tilde{L} \otimes \tilde{M} = \left(\mu_1\mu_2, \sqrt{v_1 + v_2 - v_1 v_2}\right)$$

$$\lambda\tilde{L} = \left(1 - (1 - \mu^2)^\lambda, v^\lambda\right)$$

$$\tilde{L}^\lambda = \left(\mu^\lambda, \sqrt{1 - (1 - v^2)^\lambda}\right)$$

AHP is the commonly used decision-making process for addressing situations that involve numerous rules. This study utilised the Pythagorean fuzzy AHP as a decision-making methodology to resolve the uncertainty in the data provided by the experts.

Step 1: Construct a pairwise comparison matrix utilising the inputs provided by the expert panel, using linguistic concepts as shown in Table 1 (Onar et al., 2020).

$$X = (x_{ik})_{m \times n}$$

Step 2: Compute the dissimilarity matrix $D = (d_{ik})_{m \times n}$ by employing the minimum and maximum values of membership and non-membership functions, as defined in equations (9) and (10).

$$d_{ik_L} = \mu^2{}_{ik_L} - v^2{}_{ik_U}$$
$$d_{ik_U} = \mu^2{}_{ik_U} - v^2{}_{ik_L}$$

Step 3: Calculate the multiplicative matrix of the interval $S = (s_{ik})_{m \times n}$ using Equations (11) and (12) :

$$S_{ik_L} = \sqrt{1000^{d_L}}$$
$$S_{ik_U} = \sqrt{1000^{d_U}}$$

Step 4: Compute the value of determination $\tau = (\tau_{ik})_{m \times n}$ of the x_{ik} using Equation (13) :

Step 5: Calculate the weight matrix, $T = (t_{ik})_{m \times n}$, by multiplying the degrees of determination with $S = (s_{ik})_{m \times m}$ using Equation (14):

$$t_{ik} = \left(\frac{S_{ik_L} + S_{ik_U}}{2}\right)\tau_{ik}$$

Step 6: Compute the normalised priority weights, w i, using Equation (15):

$$w_i = \frac{\sum_{k=1}^{m} t_{ik}}{\sum_{i=1}^{m}\sum_{k=1}^{m} t_{ik}}$$

3.2. Implementation of the Suggested Framework in a Case Study of the Manufacturing Sector

An application of the proposed framework is made to a case study in India that is engaged in the production and refining of steel. The production industry has garnered significant attention from the government in prior years, prompting the execution of diverse initiatives aimed at stimulating its expansion and ensuring employment opportunities Rajan, (2017).

3.2.1. Case Industry

The Pythagorean framework is implemented in the ABC manufacturing firm, selected as the study's emphasis. The manufacturer's name is not disclosed owing to concerns regarding privacy. The ABC manufacturing firm was founded in 2003. The company's yearly revenue is approximately $19.7 million, and it is situated in Gujarat. The case study possesses a very precise production line that can effectively process steel strips for the setting up of body contours. The industry has recently manufactured structural and construction purlins using the roll forming method. Currently, the case industry is actively involved in implementing sustainable ways to mitigate the adverse ecological consequences of their operations. The case study has adopted numerous sustainable practices, such as minimising the carbon emissions linked to shipping, utilising eco-friendly packaging, employing energy-efficient lighting, and actively engaging in Corporate Sustainability Commitment initiatives. The case industry acknowledges the significance of the 3 Ps - People, Planet, and Profits - in constructing enduring shareholder value and guaranteeing a sustainable future for future generations. Furthermore, the industry is also committed to improving the environmental impact and social influence of their businesses in the next years. Under such circumstances, the methodical incorporation of Small and Medium-sized Enterprises (SMEs) will empower them to enhance the sustainability of manufacturing processes in the long run. Therefore, the management of the case industry has agreed to participate in the proposed Pythagorean fuzzy AHP technique to discover and evaluate the significant SMEs.

3.2.2. Application of the Pythagorean fuzzy AHP framework

The framework assesses the SMEs in a two-stage process, as described below.

Stage 1: Determine the sustainable SMEs for the manufacturing organisation in the first phase. The SME initiatives to attain sustainability within the manufacturing industries have been finalised at this juncture. An initial step involved the identification of twenty-eight SMEs through an examination of pertinent literature. Moreover, the DM panel was administered a questionnaire containing the list of SMEs in accordance to ascertain its applicability to the case study. The decision-making panel comprises six industry experts who are authorities on the case industry being examined. All the professionals are credentialed, knowledgeable, and experienced, with over twelve years of manufacturing sector experience. Once enablers have been finalised, the Decision-Making panel classifies them into seven primary SMEs. The primary objective is to determine the ranking of SMEs at the initial level of the hierarchy. The secondary objective comprises the key SMEs, and the third objective comprises the sub-SMEs that support the primary enablers.

Apply the Pythagorean fuzzy Analytic Hierarchy Process to calculate the relative weightage of Sustainable Manufacturing Enablers (SMEs) at the second stage. The Pythagorean fuzzy Analytic Hierarchy Process is used to calculate the relative weightage of the main SMEs and their sub-SMEs. This is done by employing the completed questionnaire form collected from the Decision-Making panel. After a thorough discussion about the importance of the matter, the DM panel entered their comments into a table, comparing the main Subject Matter Experts (SMEs) with the sub-SMEs, one pair at a time. The matrix for comparing the primary SMEs and sub-SMEs is shown in Tables 1 to 9. The tables also display the weights obtained by each Sustainable Manufacturing Enabler (SME) and sub-SME. The relative relevance of each SME is determined by using Equations (9) through (15). The overall weight of each Sustainable Manufacturing Enablers (SME) is determined by multiplying the primary SME's weightage by the local weightage of each subsidiary SME.

Table 1. Pairwise Comparison matrix for main SMEs

	MSMEs	OSMEs	OPSMEs	SCSMEs	ESMEs	R&ESMEs	Weight	Rank
MSMEs	EE	BAI	LI	AAI	HI	AAI	0.213908	1
OSMEs	AAI	EE	AI	VHI	VLI	HI	0.197295	2
OPSMEs	HI	AI	EE	BAI	AI	VHI	0.166047	4
T&ISMEs	AI	AI	AI	VHI	LI	AAI	0.191841	3
SCSMEs	BAI	VLI	AAI	EE	LI	BAI	0.042448	7
ESMEs	LI	VHI	AI	HI	EE	LI	0.105358	5
R&ESME	BAI	LI	VLI	AAI	HI	EE	0.08310	6

4. Result and Discussion

The primary enablers are ordered in the following sequence based on their significance weightage: MSMEs >OSMEs > T&ISMEs > OPSMEs > ESMEs > R&ESMEs > SCSMEs. From the findings, it is evident that the strategic/managerial SMEs category has the most significance in enabling SMEs to achieve objectives in the manufacturing organisation. This discovery indicates that manufacturing sectors in developing countries, particularly in the Indian setting, see sustainability as a strategic attempt to implement sustainable techniques for manufacturing organizations.

The highest emphasis is given to the support and commitment from the upper management, which carries a global weight of 0.4068. Therefore, the key factor that has the greatest influence on the manufacturing sector in India is the support and strategic people commitment of a varied set of participants. Senior officials should establish collaboratively developed structures where several stakeholders converge and combine their resources to develop innovative technology, merchandise, and processes to implement sustainable manufacturing practices. It is essential to encourage corporations to shift their focus from self-interest to collective action in accordance with addressing sustainable concerns and promoting a more sustainable ecosystem. Top management must cooperate with stakeholders to provide the required support for integrating environmental practices. This may help to mitigate the adverse effects on the ecological system. The second most crucial strategic management objective is to explore cutting-edge technologies for the purpose of acquiring new innovations. This may be achieved by establishing R&D laboratories collaborating with marketing, manufacturing, educational institutions, and government organisations. The association and participation of many entities are crucial in addressing two major challenges developing nations face: the absence of research and development laboratories and the limited availability of capital to establish such facilities. R&D plays a crucial role in generating innovative ideas and developing new technologies and techniques for implementing cleaner technologies, energy-efficient industrial processes, and eco-friendly practices.

SM-enabled organization culture is ranked third. The culture of a sustainable manufacturing-enabled organisation prioritises environmental responsibility by incorporating eco-friendly practices into all operations. It encourages employees to develop and adopt sustainable technologies and processes, thereby fostering innovation. The culture encourages ongoing development by consistently evaluating and refining practices to conserve resources and reduce waste. It also prioritises stakeholder engagement, working in partnership with suppliers, consumers, and communities to accomplish common sustainability objectives. Implementing SMEs in current manufacturing organisation necessitates significant and transformative changes.

The 4^{th} most important SME is sustainable manufacturing-enabled strategic planning. It incorporates environmental objectives into the fundamental company strategy, guaranteeing a lasting commitment to environmentally friendly operations. It ensures that resources and investments are directed towards sustainable goals, promoting the development of new ideas and ongoing improvement. This strategy proactively considers upcoming legislative changes and market adjustments, establishing the organisation as a frontrunner in sustainability. Companies may improve their competitive edge and achieve profitable development by giving priority to sustainable practices.

Table 2. Pairwise comparison matrix for MSME sub-criteria

	MSMEs1	MSMEs2	MSMEs3	MSMEs4	Weight	Rank
MSMEs1	EE	VHI	HI	AI	0.343375	1
MSMEs2	VLI	EE	VHI	AI	0.264882	3
MSMEs3	LI	VLI	EE	VLI	0.054161	4
MSMEs4	AI	AI	VHI	EE	0.290686	2

Table 3. Pairwise comparison matrix for OSMEs sub-criteria

	OSMEs1	OSMEs2	OSMEs3	OSMEs4	Weight	Rank
OSMEs1	EE	VHI	HI	HI	0.247229	3
OSMEs2	VLI	EE	VHI	VHI	0.267562	2
OSMEs3	LI	VLI	EE	VHI	0.267562	1
OSMEs4	LI	VLI	VLI	EE	0.142898	4

Table 4. Pairwise comparison matrix for OPSMEs sub-criteria

	OPSMEs1	OPSMEs2	OPSMEs3	OPSMEs4	Weight	Rank
OPSMEs1	EE	HI	AAI	AI	0.387936	1
OPSMEs2	LI	EE	AAI	HI	0.170369	3
OPSMEs3	BAI	BAI	EE	BAI	0.273304	2
OPSMEs4	AI	LI	AAI	EE	0.103528	4

Table 5. Pairwise comparison matrix for T&ISMEs sub-criteria

	T&ISMEs1	T&ISMEs2	T&ISMEs3	T&ISMEs4	Weight	Rank
T&ISMEs1	EE	AI	VHI	HI	0.341709	1
T&ISMEs2	AI	EE	AI	VHI	0.324822	2
T&ISMEs3	VLI	AI	EE	HI	0.190221	3
T&ISMEs4	LI	VLI	LI	EE	0.031971	4

Table 6. Pairwise comparison matrix for ESMEs sub-criteria

	ESMEs1	ESMEs2	ESMEs3	ESMEs4	Weight	Rank
ESMEs1	EE	HI	VHI	CHI	0.410591	1
ESMEs2	LI	EE	VHI	AI	0.360641	2
ESMEs3	VLI	VLI	EE	HI	0.164605	3
ESMEs4	CLI	AI	LI	EE	0.02787	4

Table 7. Pairwise comparison matrix for SCSMEs sub-criteria

	SCSMEs1	SCSMEs2	SCSMEs3	SCSMEs4	Weight	Rank
SCSMEs1	EE	LI	BAI	LI	0.153508	3
SCSMEs2	HI	EE	VLI	BAI	0.342889	2
SCSMEs3	AAI	VHI	EE	VHI	0.346142	1
SCSMEs4	HI	AAI	VLI	EE	0.137903	4

Table 8. Pairwise comparison matrix for R&EESMEs sub-criteria

	R&ESMEs1	R&ESMEs2	R&ESMEs3	R&ESMEs4	Weight	Rank
R&ESMEs1	EE	HI	CHI	VHI	0.425308	1
R&ESMEs2	LI	EE	VHI	AAI	0.147668	4
R&ESMEs3	CLI	VLI	EE	VHI	0.160858	3
R&ESMEs4	VLI	BAI	VLI	EE	0.241654	2

Cross-functional integration of departments is the fifth-ranked SME. Sustainable manufacturing is facilitated by the cross-functional integration of departments, which ensures the cohesive implementation of eco-friendly practices by enhancing collaboration and aligning objectives across teams. It optimizes and innovates processes by utilizing various expertise, resulting in sustainable and efficient outcomes across the organization.

The 6th crucial SME is a government policy for promoting SM adoption. Organizations are encouraged to implement eco-friendly practices by government policies that offer incentives, such as tax rebates and grants that promote sustainable manufacturing. Standards and regulations guarantee compliance and motivate industries to pursue sustainable operations. Public awareness campaigns and educational programs facilitate a cultural transition towards implementing and appreciating sustainable production. Industry incentives for manufacturing sustainability are the 7th most important SME because industry incentives for the execution of SM include financial incentives such as rebates and subsidies for implementing green technologies. Certifications and recognition programmes enhance the competitiveness of companies and their reputations. Costs are reduced, and sustainable practices are advanced collectively through collaborative initiatives and resource sharing among enterprises.

Next, the eighth-ranked SME is increasing the profitability of the organization. By implementing sustainable manufacturing practices, an organisation can enhance its profitability by reducing waste and enhancing efficiency, resulting in cost savings. Sustainable practices also attract eco-conscious consumers, thereby propelling sales growth and opening new market opportunities. In addition, the enhanced brand reputation and compliance with regulations facilitate the promotion of long-term financial stability and the mitigation of risks.

The 9th SME is the adoption of acceptable wage standards and incentives. Implementing appropriate compensation norms and incentives guarantees equitable treatment of employees, elevating their morale and productivity, thus improving overall operational efficiency. The dedication to social responsibility enhances the business's reputation and promotes the long-term sustainability of production operations.

Effective capacity utilization is the 10th most crucial SME. It maximizes production efficiency, reducing energy consumption and resource waste, which aligns with sustainable manufacturing goals. Organizations can lower operational costs and environmental impact by optimising equipment and labour use. This approach enhances productivity and supports a sustainable and profitable manufacturing process.The relative order of other sustainable manufacturing enablers (SMEs) depending on their significance score is as follows: T&ISMEs2 > ESMEs3 > ESMEs1 > OPSMEs4> SCSMEs3 > OSMES2 > SCSMEs1> OPSMEs3 > R&ESMEs4 > T&ISMEs3 > ESMEs4 > OPSMEs2 > SCSMEs4 > OSMEs3 > R&ESMEs3 > MSMEs3 > T&ISMEs4 > MSMEs4. The enabler, namely the performance measurement system (MSMEs4), has the lowest rank. It is given the least importance in executing sustainable manufacturing practices since it largely focuses on tracking outputs rather than influencing behavioural change. These systems may delay incorporating sustainability criteria, resulting in an emphasis on conventional financial and operational indicators. Moreover, the intricacy and expense associated with creating thorough sustainability measurements might discourage its prioritisation.

Table 9. Final weight of sub-SMEs

Main SMEs	Main SMEs weight	Sub-SMEs	Sub SMEs local weight	Global weight	Global rank
MSMEs	0.213907821	MSMEs1	0.358937663	0.4068	1
		MSMEs2	0.289515386	0.2947	4
		MSMEs3	0.237606008	0.1322	26
		MSMEs4	0.071408804	0.0876	28
OSMEs	0.197294807	OSMEs1	0.245023596	0.3002	3
		OSMEs2	0.264135893	0.2687	16
		OSMEs3	0.299072427	0.1705	24
		OSMEs4	0.168705176	0.0498	5
OPSMEs	0.166046889	OPSMEs1	0.377089357	0.237	10
		OPSMEs2	0.132068595	0.2147	22
		OPSMEs3	0.132287733	0.2071	18
		OPSMEs4	0.081995586	0.1818	14
T&ISMEs	0.19184113	T&ISMEs1	0.358937663	0.3976	2
		T&ISMEs2	0.289515386	0.2367	11
		T&ISMEs3	0.237606008	0.1929	20
		T&ISMEs4	0.071408804	0.0798	27
SCSMEs	0.042448327	SCSMEs1	0.358937663	0.4068	17
		SCSMEs2	0.289515386	0.2947	9
		SCSMEs3	0.237606008	0.1322	15
		SCSMEs4	0.071408804	0.0787	23
ESMEs	0.105358213	ESMEs1	0.358937663	0.2261	13
		ESMEs2	0.289515386	0.2464	8
		ESMEs3	0.237606008	0.2291	12
		ESMEs4	0.042532139	0.1834	21
R&ESMEs	0.083102813	R&ESMEs1	0.358937663	0.2665	6
		R&ESMEs2	0.289515386	0.2478	7
		R&ESMEs3	0.237606008	0.1983	25
		R&ESMEs4	0.042532139	0.1574	19

This study attempts to introduce a methodical and coherent strategy for implementing SMEs by incorporating the principles of innovation and sustainability into the industrial organisation, which is currently lacking.

- It addresses the absence of research on Sustainable Manufacturing Enablers (SMEs) in the manufacturing sector, particularly in developing countries.
- A thorough examination of the literature and discussions with the DM panel accomplishes the identification of SMEs. A novel Pythagorean fuzzy set is integrated with the Multi Criteria Decision Making approach to rank the SMEs.
- This study addresses the issue of ambiguity and imprecision in human evaluations by using the Pythagorean fuzzy set, which has a larger membership grade set.
- The Pythagorean fuzzy AHP approach is used to rank the twenty-eight SMEs.
- It allows managers and practitioners to concentrate on top-rated variables that promote sustainability in the industrial organisation.
- This research introduces a new method for implementing sustainable manufacturing practices in academic settings by adopting innovative strategies within manufacturing organisations. This study builds upon earlier studies, which mostly focused on identifying sustainability strategies or examining the effects of SMEs on manufacturing sustainability. This study has identified a total of twenty-eight Sustainable Manufacturing Enablers (SMEs) that fall into seven main categories, which are managerial, organisational, operational, technological and infrastructure, socio-cultural, economic, regulatory and environmental. Additionally, the study has ranked both the main SMEs and the sub-SMEs based on their relative importance.

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From a management perspective, it is difficult to include sustainability thinking across the whole industrial organisation and execute it in SMEs. Without a comprehensive understanding of SMEs and their relative significance, it would be difficult to effectively align implementation tactics with the organization's competitive strategy. This research assists managers in prioritising their attention on the 10 most crucial innovative concepts and devising corresponding action plans. A thorough comprehension of each Subject Matter Expert (SME) is essential not only for instilling trust among managers but also for mitigating the risks connected with its execution. Management should prioritise the establishment of a collaborative atmosphere both inside the organisation and with external partners in order to promote the application of sustainable manufacturing practices. Sustainability-related innovations are often intricate and subject to evolution over time within the context of technology and methodologies. Therefore, it is essential for management to proactively train employees on sustainability concepts, cutting-edge methodologies, and environmentally friendly production technology. It will foster a more profound understanding and facilitate the comprehension of the operational challenges associated with cutting-edge technology.

5. Conclusion

The negative impact on the environment has been primarily attributed to the increased production activities of manufacturing organisations in recent years. It has resulted in increased pressure on manufacturing organisations to enhance their efforts to implement sustainable manufacturing practices. The implementation of SMEs has emerged as a potential sustainable strategy for the manufacturing organisation to attain long-term sustainability. To ensure the successful integration of SMEs. Nevertheless, to effectively integrate SMEs into conventional manufacturing processes, managers must identify and comprehend the enabling factors. Consequently, the current research endeavour, which analysed the SMEs, aimed to establish sustainability practices in the manufacturing organization. Twenty-eight SMEs are classified into seven primary enablers: managerial, organisational, operational, technological and infrastructure, socio-cultural, economic, regulatory, and environmental, as determined by the literature search and dialogue with the decision-making panel (experts). The SMEs were evaluated in India's manufacturing context using a Pythagorean fuzzy AHP framework.

The Pythagorean fuzzy AHP method was used to determine the relative importance weight of each SME, which was then used to rank the enablers. The results indicate that the top five SMEs in the manufacturing organisation require "support and commitment from top management; investment in technology to acquire new technology; SM-enabled organisation culture; sustainable manufacturing enabled strategic planning; cross-functional integration of departments" to achieve long-term sustainable solutions. The study's results are crucial for the upper management and managers of the industry to comprehend, oversee, and include SMEs to achieve sustainability in manufacturing organisations. In addition, integrating SMEs yields numerous sustainable benefits, including improved reputation in the market, improved environmental performance, and reduced waste.

The distinctive contribution of the current work may be summarised as follows:

- These findings expand upon previous research by comprehensively identifying twenty-eight SMEs that are crucial in attaining enduring sustainability in traditional manufacturing processes.
- The appropriateness of the selected SMEs is confirmed by engaging in a conversation with the decision-making panel of the case study.
- The SMEs were evaluated and rated using the Pythagorean fuzzy Analytic Hierarchy Process (AHP) framework.
- The unique aspect of this research resides in its focus on the industrial sector inside a developing country. The production operations of manufacturing businesses have a significant impact on environmental degradation and, hence, should adopt sustainable practices.
- These findings give useful perspectives that can help industry practitioners and government entities effectively implement sustainable tools to achieve sustainability in manufacturing firms.

This research study has certain constraints. This research uses the Pythagorean fuzzy Analytic Hierarchy Process (AHP) to determine the significance weight of SM enablers (SMEs). The only source of input data in this technique is the human factor. Therefore, the assessment procedure requires meticulous attention. The research's conclusions are particular to individual countries and are derived from a single case study conducted in the manufacturing sector. Hence, outcomes may differ based on the specific circumstances and geographical location.

Given the aforementioned constraints, this work offers several options for further investigation. In future research, including specialists from other industrial sectors and gathering a larger and more comprehensive dataset would be beneficial. Another potential direction for future research is to do a comparable investigation inside the framework of industrialised nations and provide a comparative assessment. Additionally, researchers may assess the connections between the recognised SM Enablers (SMEs) using alternative Multiple-Criteria Decision-Making (MCDM) methodologies. Finally, further study should explore and prioritise the actual sustainable advantages resulting from the implementation of SM enablers (SMEs) utilising a hybrid Multiple Criteria Decision Making (MCDM) strategy.

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