Heliyon 10 (2024) e29994

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Empowering sustainable manufacturing: Unleashing digital innovation in spool fabrication industries

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ARTICLE INFO

Keywords:
Digitalized sustainable manufacturing
Sustainable manufacturing
Spool fabrication industries

ABSTRACT

In industrial landscapes, spool fabrication industries play a crucial role in the successful completion of numerous industrial projects by providing prefabricated modules. However, the implementation of digitalized sustainable practices in spool fabrication industries is progressing slowly and is still in its embryonic stage due to several challenges. To implement digitalized sustainable manufacturing (SM), digital technologies such as Internet of Things, Cloud computing, Big data analytics, Cyber-physical systems, Augmented reality, Virtual reality, and Machine learning are required in the context of sustainability. The scope of the present study entails prioritization of the enablers that promote the implementation of digitalized sustainable practices in spool fabrication industries using the Improved Fuzzy Stepwise Weight Assessment Ratio Analysis (IMF-SWARA) method integrated with Triangular Fuzzy Bonferroni Mean (TFBM). The enablers are identified through a systematic literature review and are validated by a team of seven experts through a questionnaire survey. Then the finally identified enablers are analyzed by the IMF-SWARA and TFBM integrated approach. The results indicate that the most significant enablers are management support, leadership, governmental policies and regulations to implement digitalized SM. The study provides a comprehensive analysis of digital SM enablers in the spool fabrication industry and offers guidelines for the transformation of conventional systems into digitalized SM practices.

1. Introduction

Rapid industrialization in recent years, coupled with the ineffective utilization of capital resources and deforestation, has led to severe environmental issues and health hazards [1,2] Consequently, the concept of sustainability has evolved worldwide. However,

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https://doi.org/10.1016/j.heliyon.2024.e29994
Received 10 December 2023; Received in revised form 15 April 2024; Accepted 18 April 2024

the challenges of implementing sustainability practices in the current era of digitalization are formidable. These challenges arise due to various impediments within organizations, which can vary based on their size, nature, and the type of processes and products they handle. These barriers encompass organizational rigidity, insufficient financial funds, lack of training and awareness, inadequate education, fear of risk, low stakeholder participation in sustainable practices, and lack of governmental support and regulations, etc. [3–6]. Sustainable manufacturing involves the production of goods that meet the needs and requirements of the present generation without compromising the ability to meet those of future generations [1,7]. To achieve sustainable manufacturing, every activity in the supply chain must adhere to sustainability principles, from raw materials processing to the finished product [1,7]. Furthermore, the pressure from stakeholders for sustainable production practices in industries is an inevitable factor. Sustainable manufacturing has evolved to embrace the 6R concept, in contrast to the traditional 3R concept. The 6R concept involves Reuse, Recycle, Recover, Redesign, Reduce, and Remanufacture. Unlike the linear economy of 'use and throw,' the 6R approach encourages the reuse, recycling, and repair of products at the end of their lifecycle [8,9]. The practices related to the utilization of digital technologies in accomplishing sustainability are termed digitalized sustainable initiatives. These practices are selected depending on the nature of the industry, product type, and stakeholder participation [10]. For example, the automation of welding in spool fabrication industries by digital technologies like Internet of things, Big data and Cloud computing will enhance productivity and produce a defect-free products with good quality [11,12]. The adaptation of digital technologies in spool inventory will reduce the huge quantity of pipe drop pieces and subsequently reduce the waste, energy, and, time ultimately leading to sustainable manufacturing [13]. In a highly competitive global market, industries are striving for success, and the implementation of digital technologies is a key element in gaining a competitive edge [14]. Digital manufacturing has evolved from Computer Numerical Control (CNC) and Material Requirements Planning (MRP), and the integration of virtual and artificial networks has unlocked its full potential [15]. Digital technologies encompass various elements, including virtual and augmented reality, Artificial Intelligence, blockchain technology, cyber-physical systems, and machine learning techniques. While implementing these technologies can boost overall productivity, ensuring sustainability remains uncertain. Previous studies have demonstrated the significant potential of digital technologies in achieving sustainable manufacturing goals [16,17]. However, it's important to note that digitalization alone may primarily address environmental sustainability. Achieving sustainability across all dimensions environmental, economic, and social, requires a thorough analysis of current conditions and meticulous planning in the industrial sector. While numerous articles discuss the implementation of digitalized sustainability in various industrial sectors, this study focuses specifically on the spool fabrication industry [12,18–20].

The spool fabrication industry plays a pivotal role in the construction sector, especially within the Oil and Gas industry. It serves as the pre-fabrication unit where spool modules are manufactured and subsequently used in erection and installation. The spools undergo a series of processes, including cutting, fit-up, welding, and painting, all following stringent quality standards. Enormous conventional methods of production are deployed in spool fabrication industries. The implementation of digital technologies and utilizing their potential in promoting sustainability should be taken intensive care, especially in the case of spool fabrication industries. This is due to the product uniqueness and the fragmented structure of the organization. In each process of the spool fabrication, technical quality assurance is mandatory. Hence, while deploying digital technologies, special care should be taken to sustain quality and tolerance. Moreover, the industry's workforce entails skilled categories like Tungsten Inert Gas Welding & Shielded Metal Arc welding (TIG & ARC) welder, Fitter, spool tracker. Material controller, Piping Supervisor, Welding Supervisor, and Cutter, etc. [13,21]. The transformation must take place in this scenario and faces severe challenges in convincing them about the long-term benefits of digitalized sustainable manufacturing. They will be facing challenges like job security and the complexity associated with it. This can be overcome by top management support and other stakeholders' participation by formulating pertinent strategies and policies. Some cases of digitalization of the spool fabrication sector are explained below: A lot of time is consumed in spool tracking and allocating the missing spools in the yard, which is done by the conventional barcode system with manual checking. This can be automated by the utilization of the digital tracking system with big data analytics in material inventory. Another case is the complexity associated with the utilization of drop pieces in the spool as-built drawing by conventional methods of physical dimension checking. This process will lead to more manpower consumption, time, money and inaccuracy. By employing cloud computing and big data, the entire process can be automated, eventually leading to less resource consumption and less waste generation [13,21]. The company will face severe financial losses if the repair rate of the product exceeds a certain limit in welding. The welding is done via manual welding or semi-automatic welding, which is solely dependent upon the welder's skill [11]. This concern can be resolved by the deployment of fully automatic welding machines in the process, which will eventually lead to defect-free products with a lower repair rate, less power consumption, enhanced productivity, and less waste generation [11]. Hence it is clearly understood that spool fabrication industries are lagging in the implementation of digitalized sustainable practices. The following paragraph elucidates the research updates in spool fabrication industries. The current research in spool fabrication industries focuses on the job rescheduling process in the system by the novel linear programming model [13]. Genetic algorithm is also used in job scheduling in the spool fabrication process [22]. The measurement of fabricated spools is made accurate and faster compared to manual checking by isometric transformation and robust estimation [23]. A Bayesian inference-based simulation was developed to estimate welding nonconformities in spool fabrication [24]. A recent update in monitoring and analyzing fabricated spools is using automated scan-to-BIM registration [25]. Another study was on simulation flow modelling and comparison with the conventional batch and queue system in spool fabrication industries [26]. Hence past research reveals the dearth of studies in digital sustainability implementation in spool fabrication industries. To address these gaps, the following research questions are formulated.

RQ.1. What are the enablers for digitalized sustainable manufacturing in the spool fabrication industry?

RQ.2. Which enabler is the most significant for digitalized sustainable manufacturing in the industry?

To answer the research questions posed above, the following objectives have been formulated.

- To identify the enablers of digitalized sustainable manufacturing in the spool fabrication industry.
- To prioritize the identified enablers using the IMF-SWARA method.

Various methodologies for criteria weight determination and alternative ranking have gained popularity in the field of sustainability research, including MCDM (Multi-Criteria Decision Making) and hybrid MCDM methods [27,28]. Achieving three-dimensional sustainability through the implementation of digital technologies requires the selection of specific technologies that align with sustainability initiatives. Various MCDM techniques have been developed to determine criteria selection and alternative ranking in different sectors, including sustainable manufacturing, sustainable supply chain, sustainable production and consumption, digitalized sustainable manufacturing, and lifecycle analysis [29,30]. This research employs the Improved Fuzzy-Stepwise Weight Assessment Ratio Analysis (IMF-SWARA) method to evaluate the significance of digitalized sustainable manufacturing enablers. IMF-SWARA was initially developed for ranking road sections in 2021 [31] and it is an improved method of the previously developed fuzzy SWARA method.

The remainder of the paper is structured as follows: Section 2 provides a systematic literature review, Section 3 explains the research methodology and related techniques, followed by the presentation of results in Section 4 and discussions in Section 5. Finally, the conclusion and future scope are in the last section, Section 6.

2. Systematic literature review

Recent research is increasingly focused on aligning digitalization with the triple-bottom-line approach of sustainability, often referred to as digitalized sustainable manufacturing, and examining the enablers that facilitate its implementation. However, there is a significant lack of studies addressing the implementation of digitalized sustainable manufacturing in the spool fabrication industry, highlighting the need for comprehensive research in this area. To provide a comprehensive understanding and overview of digitalized sustainable manufacturing in the spool fabrication industry, this study employs a rigorous systematic literature review. Compared to conventional literature reviews, a systematic literature review offers clearer insights into existing systems and helps identify research gaps and issues [32]. The initial stage, which involves defining the research scope and protocol, focuses on analyzing digitalized sustainable manufacturing enablers in the spool fabrication industry. The study's timeframe spans from 2012 to 2024. In the second stage, a search is conducted, and search strings are formulated for data collection from indexed databases. Scopus and Web of Science were chosen as the databases due to their extensive and comprehensive collection of articles. The search string used is TITLE-ABS-KEY ((Driver* OR facilitator* OR "Critical factor*" OR enabler*) AND (sustainable* OR green* OR economic* OR clean* OR environmental* OR smart* OR innovative* OR "Sustainable manufacturing*" OR "Sustainability Develop*" OR "Digital sustainable manufacturing*" OR "Digitalized sustainable*" OR Social*) AND ("Fabrication industries*" OR "Spool fabrication industry*" OR "manufacturing industries*" OR "Oil and gas sector" OR "Mechanical construction" OR "Construction industry*" OR "Mechanical piping*" OR "Piping Industries*" OR "Piping fabrication*")) in Scopus and Web of science. The initial collection of articles is 1364 and 572 in Scopus and Web of Science, respectively. In the third stage, the selected articles undergo various inclusion and exclusion criteria ranging from language, exclusion of books, chapters, and conference proceedings, year range, relevance to the research area, source credibility, and appropriate keywords. The last stage is the final selection of articles resulting in 118 and 62 from Scopus and Web of Science, respectively. The final stage consists of extracting and analyzing relevant data from the selected articles, which is carried out during the synthesis stage. This extracted information contributes to the first stage of the research methodology, and the following paragraph briefs the analysis.

The linear and nonlinear relationship between digitalization and sustainable development has been comprehensively discussed in previous research works [33–37]. Digital innovation facilitates sustainable development by enhancing human capital, environmental impact, and financial benefit. In the transformation of energy sustainability, smart technologies play a crucial role in promoting it [36,38]. Digital technologies entail Cyber-physical systems, Internet of Things, Big data analytics, Cloud computing, Virtual reality, Augmented reality, Machine learning, Artificial Intelligence, and Blockchain technology. The selection of digital technologies should align with specific products and processes to fulfil all dimensions of sustainability [16,39,40]. Using the CS-ARDL technique, the positive impact on resource optimization by digitalization is lucidly discussed in recent studies [41]. Resource optimization and reduction in waste generated are the two major advantages obtained by integrating digitalization in a firm operating in the farm sector [12]. Hence, digitalized sustainability defines the utilization of digital technologies in promoting sustainability in organizations directly or indirectly.

The positive relation between digitalization, sustainability, and profitability performance is depicted in recent research works [35–37,42]. All dimensions of sustainability (economic, environmental, & social) are accomplished by the integration of digitalization and environmental orientation strategies [43]. Digitalization transforms conventional systems into fully or semi-automatic systems capable of self-monitoring and adapting corrective measures in real-time. These transformations entail various sophisticated and complicated machinery, critical database management systems, and skilled manpower capable of handling them. Intensive care should be taken by management in spool fabrication industries while executing digitalization in the quest for sustainable manufacturing by considering the specific and individual contribution of each digital technology. The Internet of Things is the most widely used digital technology, entailing sensors and various network systems for promoting sustainable manufacturing [44]. Big data analytics is an effective tool for handling unstructured and fragmented data formed because of digitalization.

While implementing digitalization, the key point to remember is that sustainability is a multi-dimensional aspect entailing economic, environmental, and social dimensions. Environmental sustainability is enhanced by resource optimization and waste reduction, economic sustainability by improving productivity, and social sustainability by providing safe and healthy working conditions. In the path of adapting digitalized sustainable manufacturing, several impediments must be overcome by appropriate enablers. The evaluation of enablers for adopting digitalized sustainable manufacturing varies across different industrial sectors, and selecting the most appropriate ones for the spool fabrication industry is essential.

In a study on sustainable manufacturing in SMEs, Alayón et al. accurately assessed enablers and categorized them as follows: 1) Organizational, 2) Managerial, 3) Attitudinal and skills development, 4) Financial, 5) Knowledge and social network, 6) Technological, and 7) Governmental [3]. Financial support and knowledge and social networks can significantly mitigate crucial barriers and promote sustainable manufacturing in SMEs [3]. Financial aid is crucial to overcome the impediments occurring in the initial stage of implementation. At the initial stage, a huge financial burden occurs due to adapting innovative technologies and acquiring digital infrastructure entailing sophisticated equipment, complicated data handling systems, and imparting training programs for complete awareness. Previous studies have depicted the significance of financial support in accomplishing digitalized sustainable manufacturing [3,45–48]. This financial burden will be an impediment mostly in the case of SMEs and short-term project industries like spool fabrication industries. They can overcome this with the support of governmental incentives and other stakeholders' support. In these scenarios, government policies and regulations, as well as economic factors, serve as critical enablers for implementing sustainable construction in the Zambian construction industry. Well-defined strategies, financial support, and technological advancements are key enablers for implementing sustainable production and consumption in the Indian manufacturing industries [49,50]. The significance of organizational support, government policies, and economic factors in promoting digitalized sustainable manufacturing in various industry sectors are already illustrated [45–47,51]. Moreover, the organization's readiness to transform from conventional systems to a digitalized sustainable manufacturing paradigm is very significant. The reluctance in the transition is due to the fear of risk and unawareness of the long-term benefits of digital sustainable development. To achieve sustainable development in organizations, management must provide complete awareness of digitalized sustainable manufacturing by imparting training to employees [50]. They should also possess a clear understanding of the risks and uncertainties related to digitalized sustainable manufacturing. Their readiness for transformation is crucial, as they are the final decision-makers.

In the spool fabrication industry, the transformation encompasses huge financial funds due to the adaptation of digitalized equipment like fully automatic welding machines, Spool trackers, Data management systems, High precision sensors, and other auxiliaries [13,22,52]. The management should formulate relevant policies and long-term strategies encompassing governmental financial support, impart training to employees, convince the client and customer of the long-term benefits associated with it, and implement the updated infrastructure [3]. The top management and governmental support are inevitable for all these transformations to happen. Hence the financial hurdles, governmental support, and organizational readiness are crucial enablers in promoting digitalized sustainable manufacturing in the spool fabrication industry [3,45,47,53]. After acquiring readiness for transformation, the industries should form well-defined strategies through systematic and meticulous planning for the successful completion of the task. Any process execution begins with the planning and formulation of strategies, which are inevitable for task completion and scheduling. The uncertainty and ambiguity associated with digitalized sustainable operations adaptation will be very clear for each stakeholder through the explication of strategies. These strategies will mitigate the major impediments like fear of risk, and misunderstanding of sustainability concepts, and provide correct perceptions of digital sustainability to every stakeholder [51]. The strategies should encompass employee welfare policies, product servitization and its related guidelines, company mission and vision in digital sustainability concepts, and the timeframe of completion [53]. The role of sustainable strategies in promoting circular economy practices in water resource management has been depicted in previous studies [54–58]. Moreover, the adaptation should occur at the shop floor level to top management, and convincing the shop labourers of the benefits of digitalized sustainable manufacturing is a tedious and complicated task. In the short-term project industry like spool fabrication, the employees may be relieved after the project completion ultimately leading to low sincerity and commitment to executing digital sustainable practices. Skilled manpower in spool fabrication industries, including TIG & ARC welders, Fitters, Cutters, Material controllers, Spool trackers, Piping engineers, etc., lag of job security will adversely affect the digitalized sustainable transformation in the spool fabrication industry. So, the retention of employees and providing proper guidelines and concepts on digital sustainability are critical success factors in spool fabrication industries [58]. Workplace social capital and senior employee retention will foster the transformation in Danish companies [59]. To mitigate the fear of risks and uncertainties associated with sustainability, stakeholders, especially customers, clients, and employees within the organization must have complete awareness.

The significance of employees' perceptiveness in the circular economy transition in industries has been elucidated in past research [60–63]. To ensure employee participation in the transformation, they should be given proper education and training on the concepts of digitalized sustainable manufacturing. This has been emphasized in the research work by Fitriani et al. for promoting sustainable development in the Indonesian construction industry [63]. The omission of employee participation in digital sustainable manufacturing is a severe impediment to task accomplishment. Digital literacy is essential for sustainable digital transformation, and employees' psychological and behavioural attitudes should be assessed to ensure readiness for the implementation of digitalized sustainable manufacturing in the organization [64]. An adaptable mindset toward innovative sustainable technologies is imperative for the successful execution of sustainability practices [64]. Top management should formulate training programs and strategies for promoting digital sustainability in the spool fabrication industries. Awareness to clients on digital sustainability manufacturing is vital in the spool fabrication industries as they are the focal point in the daily technical clarifications of the industry. Moreover, educational policies should be framed to educate all stakeholders in the industry to provide awareness of the risks and long-term benefits associated with the implementation of digitalized sustainable manufacturing. Recent research in the past has revealed the critical role of stakeholders' education in the industrial sector [51,61,64–66]. Hence stakeholder educational policies evolve as a crucial enabler in the spool fabrication industries.

Exchange and collaboration of technical ideas and concepts are essential in any product development. The platform for this communication will occur through open innovation and technical collaboration. This will mitigate the impediments related to complexity and uncertainty associated with the execution and implementation of digitalized sustainable manufacturing in spool fabrication industries. Ambiguity and vagueness related to the use and development of digital technologies like cyber-physical systems, the Internet of Things, data management systems, cloud computing, etc., can be mitigated and optimized through open innovation and technical collaboration. Moreover, technical collaboration between counterparts will be beneficial in the analysis and explication of various technical concerns in the adaptation process. Ambidextrous organizational learning will optimistically foster sustainable implementation [67]. The knowledge capability of the company in digitalized sustainable manufacturing is enhanced by open innovation and technical collaboration [67]. Hence the role of open innovation in promoting digitalized sustainable manufacturing in the spool fabrication industry is evident and also elucidated in past research [68].

A backbone of digitalized sustainability implementation is the governmental laws and regulations for organizations. Strict laws and regulations will enhance adaptation as a mandatory requirement in companies. Violation of these laws may lead to severe penalties and other major consequences. Hence the implementation will ensure the implementation of digitalized sustainable practices in the industries. The role of government regulations in enhancing sustainable development is elucidated in recent research works [67–70]. The government's perspective and its high impact on the successful implementation of circular economy practices in the context of the supply chain are depicted in the work by Govindan et al. [71]. The huge potential of government regulations in fostering digitalized sustainable transition is explained lucidly and is a prominent enabler in this transformation. The preceding paragraph reveals the significance of each enabler, and the identified ones are shown in Table 1 below.

The significant enablers of digitalized sustainable manufacturing are determined using the Improved Fuzzy-Stepwise Weight Assessment Ratio Analysis (IMF-SWARA) technique. IMF-SWARA was developed to rank various road sections in 2021 [31]. The next section discusses IMF-SWARA in detail to identify these significant enablers.

3. Research methodology

The research methodology adopted in the current study is presented in Fig. 1 below. After identifying the research problem and objectives, a systematic literature review is conducted to identify digitalized sustainable manufacturing enablers in the spool fabrication industry. These identified enablers are then validated by an expert panel and finalized. A panel of experts is formed for the validation and analysis of identified enablers. The identified enablers are sent to the experts via a questionnaire survey to mark their significance using the Likert Scale method. The opinions are marked on a well-defined linguistic scale from "very less significant" with a value of 1 to "extremely significant" with a value of 5. Furthermore, another questionnaire survey is formulated for the weight

Table 1
Identified enablers.

Code	Enablers	Description	References
DSME1	Educational policies for stakeholders.	Stakeholder support is a crucial element in adopting sustainability initiatives. A clear insight into the awareness and concepts will foster the digitalized sustainable transformation. The employees should be motivated and encouraged by considering their psychological characteristics.	[3,49,51,63,64,72–81]
DSM E2	Management Support and leadership.	The full support of management support is inevitable for the accomplishment of digital sustainability practices.	[3,45,46,49,72,75,76,81–85]
DSM E3	Formulation of long-term digitalized sustainable strategies.	The long-term strategies will aid in the inclusion of sustainable policies in line with the company's business policies. Moreover, it will enable us to anticipate the requirements and be competent with the market fluctuations.	[3,49,76,80,86–91]
DSM E4	Assuring continuous employee participation in digitalized sustainable initiatives.	Advertise the benefits and employee inclusions in sustainable practices by daily routines and practices.	[3,49,76,77,84,92–94]
DSM E5	Developing and retaining trained and proficient human resources.	The skilled workforce is mandatory for the sustainable transformation.	[3,28,49,59,74,76,77,93,94]
DSME6	Development of adequate sustainable technological capabilities.	For adapting the digital technologies, the organization's infrastructure must be compatible with the new transition and must be reliable to provide accurate results. Continuous improvement and technical upgradation are required for maintaining the proposed sustainability framework	[45,49,72,75,76,82,84]
DSME7	Governmental policies and incentives.	The government should provide financial support and incentives for promoting sustainability practices in the organization.	[3,46,49,51,63,70–72,76,79,84,85,91,95–100]
DSM E8	Development of sustainability perspectives in customers.	The customer must have a clear insight into the benefits of digital sustainability practices and should focus on environmentally friendly products and processes.	[3,49,51,63,71,72,75–77,80,81,94]
DSME9	Open innovation and external technical collaboration.	Open innovations can foster corporate sustainability practices in environmental, economic, and social practices. The external collaborations with other organizations and external stakeholders will enhance the sustainability transformation rapidly.	[34,57,68,72,75,101,102]
DSME10	Formulation of relevant legislation and laws.	Effective and simplified legislation and legal laws for fostering the adaptation of sustainability practices.	[3,45,63,77,79,82,85,97,100]
DSME11	Product lifecycle management	To adopt a circular approach in the product lifecycle to accomplish the environmental sustainability aspects.	[9,49,90,93,103]

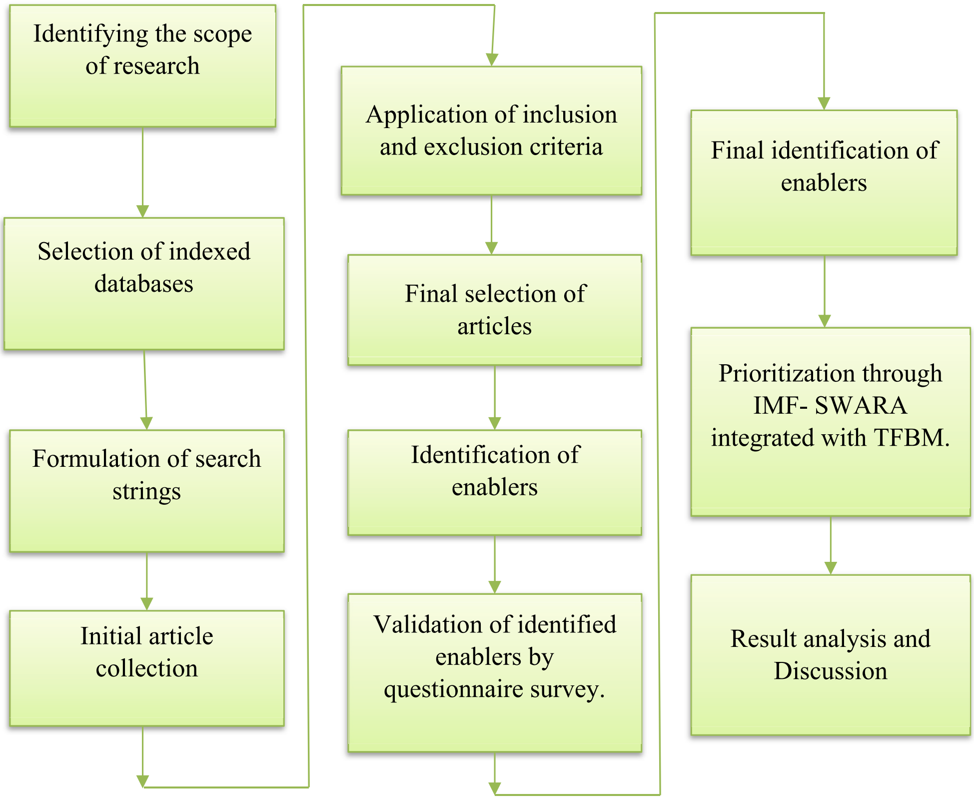

Fig. 1. Research methodology.

determination of each identified enabler using IMF-SWARA integrated with TFBM approach. For each decision maker's opinion, one single model is provided, and a total of seven models are formed for further analysis. Finally, the results are summarized, and conclusions are drawn. The following section describes the IMF-SWARA methodology and is followed by the case study.

3.1. IMF-SWARA method

Various Multi-Criteria Decision Making (MCDM) methods are employed in sustainability to rank alternatives and determine criteria weights. Fuzzy-AHP and Fuzzy-TOPSIS are used to rank enablers for sustainable production and consumption as well as green innovation aspects in manufacturing industries [49,101]. The fuzzy integrated AHP is the updated model for resolving the uncertainties and ambiguities associated with the decision maker's opinion. Despite the advantages of AHP in handling large multi-criteria decision problems, the disadvantage includes subjectivity, sensitivity to variations, and complexity [104]. The parsimonious AHP (P-AHP) methodology has been employed in recent studies to overcome the limitations of comparing a large number of surveys for urban transport solutions [104]. The BWM evolved as an alternative to AHP and has the following advantages: simplicity and requires a smaller number of pairwise comparisons. The Best-Worst Method (BWM) with the Kendall Model (BWM-Kendall) is a newly integrated technique employed for the optimum selection of digital voting tools in urban transport decision-making processes [105]. BWM also has the following disadvantages sensitivity and limited information. A new interval-valued intuitionistic fuzzy (IVIF) BWM is developed for additive consistency in multi-criteria decision-making problems [106]. The significance of the hesitancy function of Fermatean fuzzy sets (FFS) integrated with TOPSIS is employed in ranking electric vehicles [107]. Fuzzy-TISM is applied to evaluate key performance indicators for agile manufacturing [108]. In urban areas, the reduction of environmental hazards is achieved through the execution of Sustainable Urban Mobility Plans, and the significance of each plan is computed using the Fuzzy-FUCOM method [109]. A new novel method, Fermatean Fuzzy Archimedean Heronian Mean-Based Model, is utilized in the supply quality of the urban transport system [110]. The Improved Fuzzy-Stepwise Weight Assessment Ratio Analysis (IMF-SWARA) was developed by Vrtagić for ranking road sections in 2021 [31]. IMF-SWARA is utilized to assess sustainability studies in public transportation [111]. Another study employs IMF-SWARA for the selection of distribution centers in industries [112]. It is also used in an integrated IMF-SWARA-CRADIS model to evaluate the sustainability of economic systems. IMF-SWARA addresses the drawbacks associated with the Fuzzy-SWARA method in criteria weight determination. In Fuzzy-SWARA, equal-weight criteria are represented by the linguistic scale in Triangular fuzzy numbers as (1,1,1), which can lead to unequal weight determination. In contrast, IMF-SWARA uses (0,0,0) and achieves accurate criteria weights. The current study employs this methodology for determining the weights of digitalized sustainable manufacturing enablers due to the similarity in the previously addressed problems. In the current study, the choice of the significant one from identified enablers is a multi-criteria problem and correlated with various factors encompassing the stakeholder's role, specific contribution to digitalized sustainable manufacturing, and key role in eliminating the barriers. For assigning the criteria weights from various experts' opinions with uncertainty and ambiguity, the MCDM method integrated with fuzzy is the best option. Hence the prioritization of identified enablers is a multi-decision modeling integrated with fuzzy methods. The present study employs the recently developed technique IMF-SWARA integrated with TFBM for the analysis due to its advantages compared to other MCDM methods, including a concise process with only five computational steps, an appropriate linguistic scale for evaluation, and precise methods for weight calculation due to its predefined scale [111]. The steps in the IMF-SWARA method are shown in Fig. 2 and outlined below [31].

- Expert evaluation of criteria in descending order of significance.
- Evaluation of the comparative significance of all criteria.
- Calculation of coefficient values, fuzzy recalculated weights, and the final criteria weights.
- Defuzzification of the fuzzy weights of evaluation criteria.

Step 1. After finalizing the criteria, arrange them in descending order of significance. For example, place the most significant criteria at the top and the least significant ones at the bottom.

Step 2. Formulation pairwise comparisons between criteria. Decision-makers determine the comparative significance of the jth criterion in relation to the [jth-1) criterion, using linguistic variables expressed as Triangular fuzzy numbers. The linguistic variables and their corresponding TFNs are shown in Table 2 below [113–115]. This is referred to as the comparative significance of average value and symbolized as $\underline{s}_j$ [31,108].

Step 3. Determining the fuzzy coefficient ($\underline{k}_j$).

The computation of fuzzy coefficient is determined as follows by Equation (1).

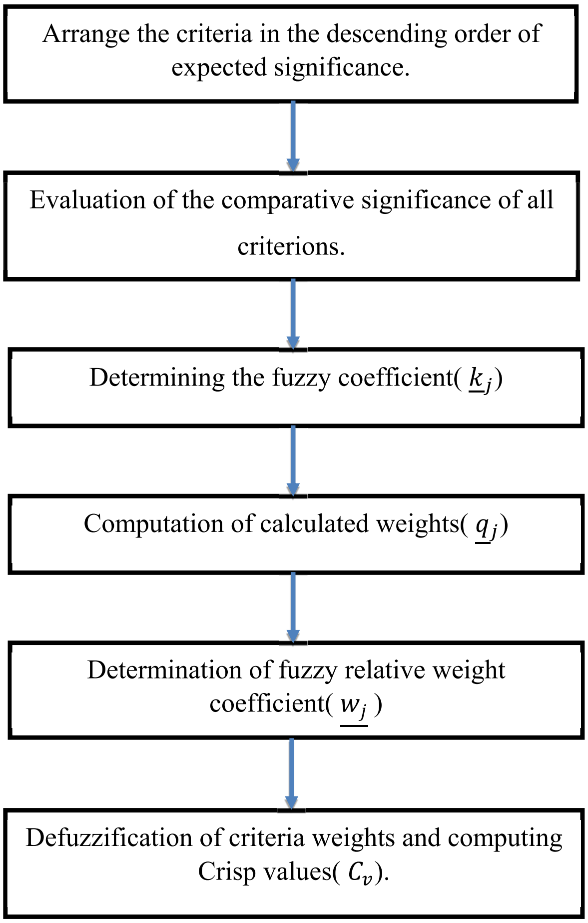

Fig. 2. IMF-SWARA methodology.

Table 2
IMF-SWARA linguistic variables and TFN [114,115,116].

Linguistic Variable	TFN Scale		
Absolutely less	1.000	1.000	1.000
Dominantly less	0.500	0.667	1.000
Much less	0.400	0.500	0.667
Really less	0.333	0.400	0.500
Less	0.286	0.333	0.400
Moderately less	0.250	0.286	0.333
Weakly less	0.222	0.250	0.286
Equally	0.000	0.000	0.000

$$\underline{k_j} = \left\{ j, j = 0 \ and \ \underline{s_j} + 1, j > 0 \right. \tag{1}$$

Step 4. Computation of calculated weights ($\underline{q_j}$) by Equation (2).

$$\underline{q_j} = \left\{ 1, j = 1 \ and \ \frac{\underline{q_{j-1}}}{\underline{k_j}}, j > 0 \right. \tag{2}$$

Step 5. Determination of fuzzy relative weight coefficient($\underline{w_j}$)by Equation (3).

$$\underline{w_j} = \frac{\underline{q_j}}{\sum_{j=1}^{m} \underline{q_j}} \tag{3}$$

where m is the total number of criteria.

Step 6. Defuzzification of criteria weights and computing Crisp values(C_v) by Equation (4).

$$C_v = \frac{\left(w^{(l)} + 4w^{(m)} + w^{(u)}\right)}{6} \tag{4}$$

3.2. Triangular Fuzzy Bonferroni Mean (TFBM)

This operator is utilized to get the aggregate values of the fuzzy information [116]. TFBM depicts the interrelationship between the fuzzy elements despite considering it as independent as given in Equation (5). TFBM, or Fuzzy Bonferroni operator, is also employed in

Table 3
Final identified enablers.

Code	Enablers	Description
DSME1	Educational policies for stakeholders.	Stakeholder support is a crucial element in adapting sustainability initiatives. A clear insight into the awareness and concepts will foster the digitalized sustainable transformation. The employees should be motivated and encouraged by considering their psychological characteristics.
DSM E2	Management Support and leadership.	The full support of management support is inevitable for the accomplishment of digital sustainability practices.
DSM E3	Formulation of long-term digitalized sustainable strategies.	The long-term strategies will aid in the inclusion of sustainable policies in line with the company's business policies. Moreover, it will enable us to anticipate the requirements and be competent with the market fluctuations.
DSM E4	Assuring continuous employee participation in digitalized sustainable initiatives.	Advertise the benefits and employee inclusions in sustainable practices by daily routines and practices.
DSM E5	Developing and retaining trained and proficient human resources.	The skilled workforce is mandatory for the sustainable transformation.
DSME6	Development of adequate sustainable technological capabilities.	For adapting the digital technologies, the organization's infrastructure must be compatible with the new transition and must be reliable to provide accurate results. Continuous improvement and technical upgradation are required for maintaining the proposed sustainability framework
DSME7	Governmental policies and incentives.	The government should provide financial support and incentives for promoting sustainability practices in the organization.
DSM E8	Development of Sustainability perspectives in customers.	The customer must have a clear insight into the benefits of digital sustainability practices and should focus on environmentally friendly products and processes.
DSME9	Open innovation and external technical collaboration.	Open innovations can foster corporate sustainability practices in environmental, economic, and social practices. The external collaborations with other organizations and external stakeholders will enhance the sustainability transformation rapidly.
DSME10	Formulation of relevant legislation and laws.	Effective and simplified legislation and legal laws for fostering the adaptation of sustainability practices.

research related to aggregating fuzzy values in sustainable public transportation [111]. Let $\underline{a}_i = [a_i^L, a_i^M, a_i^U]$ $(i = 1, 2, 3\ldots\ldots n)$ be a set of triangular fuzzy numbers, Then,

$$TFBM^{p,q}\left(\underline{a}_1, \underline{a}_2 \ldots\ldots \underline{a}_n\right) = \left[\left(\frac{1}{n(n-1)} \sum_{i,j=1\ i\neq j}^{n} \left(a_i^L\right)^p \left(a_j^L\right)^q\right)^{\frac{1}{(p+q)}}, \left(\frac{1}{n(n-1)} \sum_{i,j=1\ i\neq j}^{n} \left(a_i^M\right)^p \left(a_j^M\right)^q\right)^{\frac{1}{(p+q)}}, \left(\frac{1}{n(n-1)} \sum_{i,j=1\ i\neq j}^{n} \left(a_i^U\right)^p \left(a_j^U\right)^q\right)^{\frac{1}{(p+q)}}\right] \tag{5}$$

n is the number of experts, while $p, q \geq 0$ are non-negative numbers. Hence this operator is utilized in the aggregate calculation of the fuzzy information from the different models.

4. Application and results

In the spool fabrication industry, their fabrication activities play a crucial role in the successful completion of projects in the Oil and Gas sector. Enablers were initially identified through a systematic literature review and are listed in Table 2. We formed a panel of seven experts in the field to identify and prioritize enablers. These experts include individuals with diverse backgrounds, such as experienced degree holders, doctorate holders, professionals, and academic experts in the relevant area. The identified enablers were sent for validation through a questionnaire survey. They were advised to prioritize the enablers using the Likert scale, ranging from Very Less Significant with a value of 1 to Extremely Significant with a value of 5. Moreover, experts were permitted to suggest additional enablers based on their opinions. Enablers with a median score exceeding 3.5 were selected and finalized. Ultimately, experts eliminated one enabler, DSME11 (Product Lifecycle Management), resulting in a final selection of ten enablers for prioritization, as shown in Table 3 below.

4.1. Determination of criteria weights by IMF- SWARA

Another questionnaire survey is sent to the experts for analyzing the enablers for prioritization by IMF-SWARA with the TFBM approach. The enablers are advised to mark their Sj (Comparative Significance) to each enabler. The first enabler is marked as null, and the following ones are compared to the previous enabler and assigned comparative significance. The linguistic values and corresponding Triangular Fuzzy numbers are assigned by the experts as per the values shown in Table 2. By computing other fuzzy coefficients and weights, seven models are generated according to each expert. The enablers are ranked in descending order of significance within each group. In each model, the criteria's weights are calculated using equations (1)–(4). Finally, the aggregate of all seven models is computed by applying the Triangular Fuzzy Bonferroni Mean (TFBM) using equation (5). For example, below are the sample calculations in decision-making Group 1.

According to decision-makers in Group 1, the criteria are ranked in ascending order of significance as follows: DSME2 > DSME7 > DSME5 > DSME1 > DSME6 > DSME3 > DSME4 > DSME10 > DSME9 > DSME8, and the calculated coefficients are shown in Table 4 below.

For **DSME7**:

$$\underline{k_j} = 0.286 + 1 = 1.286$$

$$\underline{q_j} = \frac{1.00}{1.4} = 0.714$$

$$\underline{w_j} = \frac{0.714}{4.113} = 0.174$$

Table 4
Calculation table for Decision group 1 (Model – 1).

DM1	S_j(Comparative Significance)			K_j(Fuzzy Coefficient)			q_j(Calculated weights)			w_j(Fuzzy weight coefficient)		
DSME2				1	1	1	1.000	1.000	1.000	0.243	0.263	0.292
DSME7	0.286	0.333	0.400	1.286	1.333	1.4	0.714	0.750	0.778	0.174	0.198	0.227
DSME5	0.222	0.25	0.286	1.222	1.25	1.286	0.555	0.600	0.636	0.135	0.158	0.186
DSME1	0.4	0.5	0.667	1.4	1.5	1.667	0.333	0.400	0.455	0.081	0.105	0.133
DSME6	0.25	0.286	0.333	1.25	1.286	1.333	0.250	0.311	0.364	0.061	0.082	0.106
DSME3	0	0	0	1	1	1	0.250	0.311	0.364	0.061	0.082	0.106
DSME4	0.25	0.286	0.333	1.25	1.286	1.333	0.188	0.242	0.291	0.046	0.064	0.085
DSME10	0.286	0.333	0.4	1.286	1.333	1.4	0.134	0.181	0.226	0.033	0.048	0.066

$$\begin{aligned}&\textbf{TFBM}\,[(0.1718\ 0.1812\ 0.1934),(0.1214\ 0.1357\ 0.1523),(0.1438\ 0.1472\ 0.1518),(0.2407\ 0.2558\ 0.2786),(0.1461\ 0.1609\ 0.1790)]\\&\quad=[(.(1718*0.1214)+(.1718*0.1438)+\ldots\ldots.(.1718*0.1461),((0.1812*0.1357)+(0.1812*0.1472)\\&\quad+\ldots\ldots.(0.1812*0.1609)),((0.1934*0.1523)+(0.1934*0.1523)+\ldots\ldots.(0.1934*0.1790))]=(\mathbf{0.0748\ 0.0796\ 0.0858}).\end{aligned}$$

The weights of digitalized sustainable manufacturing enablers were obtained in five different models. The fuzzy aggregate of the five different models is obtained by the application of the Triangular Fuzzy Bonferroni operator (TFBM). The criteria weights of the different models are shown in Tables 5–11 below.

In all models, more significance is given to the criteria: 1) Management support and leadership and 2) Government policies and regulations. The results of the fuzzy aggregator also revealed the same fact, as shown in Table 12 below.

The results highlight the significant role of digitalized sustainable manufacturing enablers, including 1) Management support and leadership, 2) Governmental policies and regulations, 3) Development of proficient human resources, 4) Educational policies of stakeholders followed by the Development of adequate sustainable policies, Formulation of long-term sustainable capabilities, Assurance of employee participation in digitalized sustainable initiatives, Open innovation and technical collaboration, Formulation of legislative laws, and Development of sustainability perspectives in customers. The following section presents discussions of the obtained results and the conclusion.

5. Discussions and implications

The present study identified the digitalized sustainable manufacturing enablers in the spool fabrication industry and prioritized their significance in fostering the implementation of digitalized sustainable initiatives in organizations. The final ranking of enablers is presented in Fig. 3 and Table 13 below.

To rank the criteria, this research employs IMF-SWARA integrated with the Fuzzy Bonferroni operator. Experts are selected from the spool fabrication industry to ensure relevance. The analysis is conducted through a comprehensive review of previous literature, expert opinions, and official documents systematically and rigorously.

The most significant identified enabler is (DSME2) Management support and leadership in the spool fabrication industry. In the case of the spool fabrication industry, the biggest challenge in implementing digital sustainability is organizational rigidity and management reluctance. This occurs due to the fear of associated risks, unawareness of long-term benefits, the temporary nature of projects, changes in location, and lack of training. Especially in Oil and Gas sector expansion projects, the spool fabrication industry plays a subsidiary role and is temporary. Hence, high initial investments in the fabrication shop may not be entertained by management due to unawareness. In this scenario, it is up to management to take the initiative for the adaptation of digitalized sustainable manufacturing in the industry. By imparting proper training and knowledge and convincing clients and customers, management should formulate well-defined strategies and policies for implementing digitalized sustainable manufacturing in the spool fabrication industry. This will significantly boost the implementation.

Previous research has highlighted the crucial role of management support in initiating digitalized sustainability initiatives in start-

Table 5
Decision model # 1.

DM1	S_j(Comparative Significance)			K_j(Fuzzy Coefficient)			q_j(Calculated weights)			w_j(Fuzzy weight coefficient)		
DSME2				1	1	1	1.000	1.000	1.000	0.172	0.181	0.193
DSME7	0.000	0.000	0.000	1	1	1	1.000	1.000	1.000	0.172	0.181	0.193
DSME5	0.250	0.286	0.333	1.25	1.286	1.333	0.750	0.778	0.800	0.129	0.141	0.155
DSME1	0.250	0.286	0.333	1.25	1.286	1.333	0.563	0.605	0.640	0.097	0.110	0.124
DSME6	0.222	0.250	0.286	1.222	1.25	1.286	0.438	0.484	0.524	0.075	0.088	0.101
DSME3	0.000	0.000	0.000	1	1	1	0.438	0.484	0.524	0.075	0.088	0.101
DSME4	0.000	0.000	0.000	1	1	1	0.438	0.484	0.524	0.075	0.088	0.101
DSME10	0.400	0.500	0.667	1.4	1.5	1.667	0.263	0.322	0.374	0.045	0.058	0.072
DSME9	0.286	0.333	0.400	1.286	1.333	1.4	0.188	0.242	0.291	0.032	0.044	0.056
DSME8	1.000	1.000	1.000	2	2	2	0.094	0.121	0.145	0.016	0.022	0.028

Table 6
Decision model # 2.

DM1	Sj(Comparative Significance)			Kj(Fuzzy Coefficient)			qj(Calculated weights)			wj(Fuzzy weight coefficient)		
DSME2				1	1	1	1.000	1.000	1.000	0.170	0.181	0.196
DSME1	0.286	0.333	0.400	1.286	1.333	1.4	0.714	0.750	0.778	0.121	0.136	0.152
DSME5	0.000	0.000	0.000	1	1	1	0.714	0.750	0.778	0.121	0.136	0.152
DSME7	0.000	0.000	0.000	1	1	1	0.714	0.750	0.778	0.121	0.136	0.152
DSME6	0.250	0.286	0.333	1.25	1.286	1.333	0.536	0.583	0.622	0.091	0.106	0.122
DSME3	0.000	0.000	0.000	1	1	1	0.536	0.583	0.622	0.091	0.106	0.122
DSME9	0.222	0.250	0.286	1.222	1.25	1.286	0.417	0.467	0.509	0.071	0.084	0.100
DSME10	0.400	0.500	0.667	1.4	1.5	1.667	0.250	0.311	0.364	0.042	0.056	0.071
DSME4	0.400	0.500	0.667	1.4	1.5	1.667	0.150	0.207	0.260	0.025	0.038	0.051
DSME8	0.500	0.667	1.000	1.5	1.667	2	0.075	0.124	0.173	0.013	0.023	0.034

Table 7
Decision model # 3.

DM1	S_j(Comparative Significance)			K_j(Fuzzy Coefficient)			q_j(Calculated weights)			w_j(Fuzzy weight coefficient)		
DSME2				1	1	1	1.000	1.000	1.000	0.144	0.147	0.152
DSME7	0.000	0.000	0.000	1	1	1	1.000	1.000	1.000	0.144	0.147	0.152
DSME5	0.000	0.000	0.000	1	1	1	1.000	1.000	1.000	0.144	0.147	0.152
DSME1	0.000	0.000	0.000	1	1	1	1.000	1.000	1.000	0.144	0.147	0.152
DSME4	0.286	0.333	0.400	1.286	1.333	1.4	0.714	0.750	0.778	0.103	0.110	0.118
DSME3	0.250	0.286	0.333	1.25	1.286	1.333	0.536	0.583	0.622	0.077	0.086	0.094
DSME6	0.000	0.000	0.000	1	1	1	0.536	0.583	0.622	0.077	0.086	0.094
DSME8	1.000	1.000	1.000	2	2	2	0.268	0.292	0.311	0.039	0.043	0.047
DSME9	0.000	0.000	0.000	1	1	1	0.268	0.292	0.311	0.039	0.043	0.047
DSME10	0.000	0.000	0.000	1	1	1	0.268	0.292	0.311	0.039	0.043	0.047

Table 8
Decision model # 4.

DM1	S_j(Comparative Significance)			K_j(Fuzzy Coefficient)			q_j(Calculated weights)			w_j(Fuzzy weight coefficient)		
DSME7				1	1	1	1.000	1.000	1.000	0.241	0.256	0.279
DSME2	0.222	0.250	0.286	1.222	1.25	1.286	0.778	0.800	0.818	0.187	0.205	0.228
DSME6	0.000	0.000	0.000	1	1	1	0.778	0.800	0.818	0.187	0.205	0.228
DSME1	0.500	0.667	1.000	1.5	1.667	2	0.389	0.480	0.546	0.094	0.123	0.152
DSME5	1.000	1.000	1.000	2	2	2	0.194	0.240	0.273	0.047	0.061	0.076
DSME3	0.286	0.333	0.400	1.286	1.333	1.4	0.139	0.180	0.212	0.033	0.046	0.059
DSME8	0.000	0.000	0.000	1	1	1	0.139	0.180	0.212	0.033	0.046	0.059
DSME10	1.000	1.000	1.000	2	2	2	0.069	0.090	0.106	0.017	0.023	0.030
DSME9	0.250	0.286	0.333	1.25	1.286	1.333	0.052	0.070	0.085	0.013	0.018	0.024
DSME4	0.000	0.000	0.000	1	1	1	0.052	0.070	0.085	0.013	0.018	0.024

up industries [1,75–77,79,80,110]. Implementing sustainability practices in an organization often brings about anxiety related to potential failure and unforeseen risks. In such situations, effective management plays a pivotal role in addressing these concerns and facilitating the path to success in digital sustainability. Neglect by organizational management can lead to the failure of such endeavours, as supported by a study conducted by Men et al., prioritizing top management support in fostering digital sustainability initiatives in sustainability supply chain management within the textile sector [70]. Management, including owners, top managers, and other senior authorities, bears the responsibility of formulating guidelines and creating sustainability awareness among employees. They should be capable of conveying sustainability concepts, emphasizing their long-term benefits, and disseminating relevant information, especially among the working class, including labourers. Due to illiteracy, some employees may fear job loss due to digitalization and initially oppose the implementation of sustainable digital practices. This situation can be mitigated through the strategic intervention of top management officials, providing complete awareness and financial support [117].

Furthermore, management must eliminate organizational rigidity during the transformation process and provide financial support for sustainability initiatives. Despite the management's role in promoting digitalized sustainable manufacturing, they should also consider the opinions of other stakeholders such as suppliers, customers, clients, and local communities. In the case of spool fabrication industries, the involvement of clients and suppliers should be assured by management in the adaptation of digitalized sustainable practices in the industry. Because the client is actively participating in the daily technical clarification process their crucial information enhances the sustainability of the spool fabrication industries. The client, local communities, and suppliers should be convinced of the long-term benefits of digitalized sustainability practices by top management and ensure their full coordination in accomplishing the task. Their participation in sustainability activities is a vital element where management must perform positively with suitable strategies.

The second prioritized enabler for digitalized sustainable manufacturing is Government policies and regulations. Governmental

Table 9
Decision model # 5.

DM1	S_j(Comparative Significance)			K_j(Fuzzy Coefficient)			q_j(Calculated weights)			w_j(Fuzzy weight coefficient)		
DSME2				1	1	1	1.000	1.000	1.000	0.188	0.201	0.219
DSME7	0.222	0.250	0.286	1.222	1.25	1.286	0.778	0.800	0.818	0.146	0.161	0.179
DSME5	0.000	0.000	0.000	1	1	1	0.778	0.800	0.818	0.146	0.161	0.179
DSME8	0.250	0.286	0.333	1.25	1.286	1.333	0.583	0.622	0.655	0.110	0.125	0.143
DSME9	0.222	0.250	0.286	1.222	1.25	1.286	0.454	0.498	0.536	0.085	0.100	0.117
DSME3	0.000	0.000	0.000	1	1	1	0.454	0.498	0.536	0.085	0.100	0.117
DSME4	0.500	0.667	1.000	1.5	1.667	2	0.227	0.299	0.357	0.043	0.060	0.078
DSME6	0.400	0.500	0.667	1.4	1.5	1.667	0.136	0.199	0.255	0.026	0.040	0.056
DSME10	0.286	0.333	0.400	1.286	1.333	1.4	0.097	0.149	0.198	0.018	0.030	0.043
DSME1	0.333	0.400	0.500	1.333	1.4	1.5	0.065	0.107	0.149	0.012	0.021	0.033

Table 10
Decision model # 6.

DM1	S_j(Comparative Significance)			K_j(Fuzzy Coefficient)			q_j(Calculated weights)			w_j(Fuzzy weight coefficient)		
DSME7				1	1	1	1.000	1.000	1.000	0.159	0.168	0.179
DSME2	0.000	0.000	0.000	1	1	1	1.000	1.000	1.000	0.159	0.168	0.179
DSME5	0.000	0.000	0.000	1	1	1	1.000	1.000	1.000	0.159	0.168	0.179
DSME8	0.250	0.286	0.333	1.25	1.286	1.333	0.750	0.778	0.800	0.119	0.130	0.143
DSME9	0.222	0.250	0.286	1.222	1.25	1.286	0.583	0.622	0.655	0.093	0.104	0.117
DSME3	0.000	0.000	0.000	1	1	1	0.583	0.622	0.655	0.093	0.104	0.117
DSME4	0.500	0.667	1.000	1.5	1.667	2	0.292	0.373	0.436	0.046	0.063	0.078
DSME10	0.400	0.500	0.667	1.4	1.5	1.667	0.175	0.249	0.312	0.028	0.042	0.056
DSME6	0.286	0.333	0.400	1.286	1.333	1.4	0.125	0.187	0.242	0.020	0.031	0.043
DSME1	0.333	0.400	0.500	1.333	1.4	1.5	0.083	0.133	0.182	0.013	0.022	0.033

Table 11
Decision model # 7.

DM1	S_j(Comparative Significance)			K_j(Fuzzy Coefficient)			q_j(Calculated weights)			w_j(Fuzzy weight coefficient)		
DSME2				1	1	1	1.000	1.000	1.000	0.158	0.167	0.177
DSME7	0.000	0.000	0.000	1	1	1	1.000	1.000	1.000	0.158	0.167	0.177
DSME5	0.000	0.000	0.000	1	1	1	1.000	1.000	1.000	0.158	0.167	0.177
DSME8	0.250	0.286	0.333	1.25	1.286	1.333	0.750	0.778	0.800	0.119	0.130	0.142
DSME3	0.222	0.250	0.286	1.222	1.25	1.286	0.583	0.622	0.655	0.092	0.104	0.116
DSME9	0.000	0.000	0.000	1	1	1	0.583	0.622	0.655	0.092	0.104	0.116
DSME6	0.500	0.667	1.000	1.5	1.667	2	0.292	0.373	0.436	0.046	0.062	0.077
DSME4	0.333	0.400	0.500	1.333	1.4	1.5	0.194	0.267	0.327	0.031	0.044	0.058
DSME10	0.286	0.333	0.400	1.286	1.333	1.4	0.139	0.200	0.255	0.022	0.033	0.045
DSME1	0.333	0.400	0.500	1.333	1.4	1.5	0.093	0.143	0.191	0.015	0.024	0.034

Table 12
Final criteria weight by TFBM.

Enablers	Description	Crisp value
DSME2	Management Support and leadership.	0.0987
DSME7	Governmental policies and incentives.	0.0866
DSME5	Developing and retaining trained and proficient human resources.	0.0710
DSME1	Educational policies for stakeholders.	0.0647
DSME3	Formulation of long-term digitalized sustainable strategies.	0.0544
DSME6	Development of adequate sustainable technological capabilities.	0.0533
DSME4	Assuring continuous employee participation in digitalized sustainable initiatives.	0.0462
DSME9	Open innovation and external technical collaboration.	0.0261
DSME10	Formulation of relevant legislation and laws.	0.0241
DSME8	Development of Sustainability perspectives in customers.	0.0189

policies and regulations play a pivotal role in the implementation of digital sustainability in industries. For initiating digitalized sustainable manufacturing in the spool fabrication industry, high initial investment is inevitable. Despite organizational rigidity, this is a major impediment in the transition process. To eradicate this hurdle, the only solution is governmental support in terms of incentives and funds. The government should formulate special schemes for this type of industry to support the accomplishment of digitalized sustainable manufacturing. The government should provide pertinent policies and strict regulations for this adaptation. The regulations will make management transformation a mandatory process. Otherwise, no forward steps will be taken by the management itself. Hence governmental support is a major enabler in spool fabrication industries for digital transformation. This observation is supported by previous research aimed at enhancing sustainable production and consumption in manufacturing industries [49]. The initial stage of adaptation often imposes a significant financial burden on industries, particularly small-scale ones [118]. Governments must support organizations by establishing suitable guidelines, incentives, and policies related to digital sustainability. Without the aid of governmental policies and regulations, industries may struggle financially to navigate this phase. The initial stage is accompanied by fears of failure and risks associated with the execution of sustainability practices, creating a dilemma. The lack of governmental support emerges as a critical barrier to implementing sustainable green six sigma lean manufacturing in the Indian manufacturing system [119]. Government pressure can help eliminate organizational rigidity that hinders the adoption of digitalized sustainable manufacturing systems, which is a significant barrier to implementation. Furthermore, governmental initiatives serve as catalysts for implementation, setting special criteria that must be met, thereby redirecting focus from daily routine activities [3].

Another significant enabler in initiating digitalized sustainable practices in the spool fabrication industry is the retention of employees and providing education to stakeholders. The adaptation should take place at the shop level with the employees, including labourers. Due to the project's temporary nature, after the completion of the project, the employees should be retained for the next one.

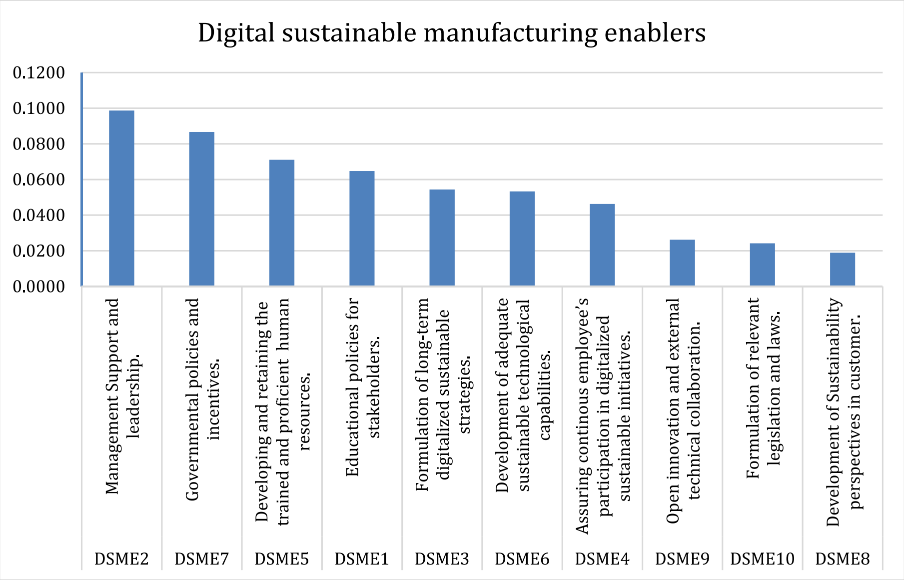

Fig. 3. Final ranking of enablers.

Table 13
Enabler's final ranking.

DM1	Description	Crisp value
DSME2	Management Support and leadership.	0.0987
DSME7	Governmental policies and incentives.	0.0866
DSME5	Developing and retaining trained and proficient human resources.	0.0710
DSME1	Educational policies for stakeholders.	0.0647
DSME3	Formulation of long-term digitalized sustainable strategies.	0.0544
DSME6	Development of adequate sustainable technological capabilities.	0.0533
DSME4	Assuring continuous employee participation in digitalized sustainable initiatives.	0.0462
DSME9	Open innovation and external technical collaboration.	0.0261
DSME10	Formulation of relevant legislation and laws.	0.0241
DSME8	Development of Sustainability perspectives in customers.	0.0189

This is especially true in the case of the spool fabrication industry. This retention is imperative because for training the employees, the company is spending huge funds, and they have a complete awareness of the transformation. But if the employees change, then huge funds should be allocated for this. Moreover, the employees should have a thorough understanding of digitalized sustainability and should be cleared of misunderstandings like job insecurity and its associated complexity. The sincere commitment of the employees is an essential factor in the digital sustainability transition in the spool fabrication industry. Educating employees about sustainability awareness in their daily activities can enhance the implementation of digital sustainability in spool fabrication industries [72]. The time constraints of the project industry pose a major challenge in retaining employees. However, retaining employees is crucial for adapting to digital sustainability in the spool fabrication industry. The primary reasons for retaining employees include 1) lack of commitment, 2) substantial expenses incurred in training employees, and 3) a shortage of trained employees. Employee retention is a vital component of sustainable human resource management [120]. Work satisfaction and job engagement are key elements in sustainable human resource management, as supported by previous research studies conducted by Barbara et al. [121]. Digital literacy among construction workers is essential for the implementation of sustainability in the industry [64]. Overall, these observations align with previous studies, emphasizing that employee retention and education on sustainability awareness are major enablers for overcoming the barriers to adopting digital sustainable manufacturing in the spool fabrication industry.

The development of sustainable strategies, encompassing the long-term benefits, risks, and concerns associated with digital sustainability, is an inevitable parameter in implementing digital sustainable manufacturing initiatives in the spool fabrication industry. These strategies must align with the organization's policies and goals for achieving digitalized sustainable manufacturing [122]. Especially in the case of the spool fabrication industry, the formulation of long-term strategies will enable the organization to make a rigorous and systematic plan optimistically. This will also have a huge reduction in financial impact. The long-term policies will mitigate the risk associated with it and eliminate the major bottlenecks in the transformation. By formulating long-term strategies and policies, the spool fabrication industry will foster the adaptation of digitalized sustainable manufacturing and accomplish its goal. Long-term strategies can help eliminate unnecessary fears and anxieties associated with transformation, as they provide a clear roadmap. For example, in the coal industry, strategies are incorporated to mitigate the consequences of coal pollution and establish green coal policies [123]. The lack of adequate technological capabilities serves as a major impediment to implementing digital sustainable technologies. Therefore, industry must invest in the necessary technological infrastructure to keep pace with the evolution of digital technologies. In the spool fabrication industry, transitioning from semi-automatic welding to fully automatic welding, for instance, requires appropriate infrastructure to support the installation of sophisticated machinery, sensors, and related auxiliary systems. Without the right infrastructure and skilled manpower, achieving digital sustainability is impossible. Developing adequate technical capabilities ensures competency and provides cybersecurity for the secure transition of bulk data associated with new innovative technologies. In manufacturing industries, digital capabilities enhance sustainability-oriented digital innovation [124]. The incorporation of digital technologies such as cyber-physical systems, blockchain technology, cloud computing, big data analytics, machine learning, and artificial intelligence into the system to achieve digitalized sustainable manufacturing requires the appropriate technical infrastructure. Especially in the spool fabrication industry, where the transformation from conventional machining processes like plasma cutting, manual welding, manual fit-up, and manual inventory management to automatic processes necessitates the implementation of sensors, data processing systems, and other auxiliary systems. In such cases, there is a risk of data theft during the transition, difficulties in handling the vast amount of generated data, and compatibility issues with the existing environment. These challenges can be addressed through the provision of adequate technical infrastructure and skilled employees. In the spool fabrication industry, the adequate infrastructure encompasses sophisticated machinery (Fully automatic welding system, spool tracker, Data server, Code reader, big data management system, Cyber-physical system, etc.), skilled employees proficient in the digital environment, and other supporting accessories. As already stated, huge funds are allocated in initialization, and the proper selection of each one is highly significant. Special care should be taken in the utilization of digital technologies and their contribution to sustainability. Thus, the technological infrastructure, proficient employees, and imparting education will foster digital sustainability transformation in the spool fabrication industry.

Open innovation and technical collaboration will foster the exchange of technological skills with counterpart organizations, promoting innovative technologies in the industry. Previous studies have demonstrated that open innovation can promote sustainability, particularly social sustainability, by providing social services to the community [34,66,72,98,123,125]. Integrating the triple-bottom approach of sustainability into existing systems necessitates the inclusion of digitalized sustainable practices in products, processes, and services, leading to open innovation and technical collaboration with third parties. In the spool fabrication industry, open innovation with counterparts enhances the exchange of technological ideas to enhance competence in the field. Technology transformation is one of the principal components of collaboration and innovation. In the spool fabrication industry, for developing innovative concepts and ideas for sustainable manufacturing, technical collaboration with its suppliers, clients, consultants, customers, and manufacturers will enable it. Enormous ideas will be exchanged which will be beneficial to eradicate the major impediments in the path of transformation to digital sustainability. The spool fabrication industry produces unique products with a high product mix; technical collaboration is essential to avoid the risk of failure in implementing digitalized sustainable manufacturing. Open innovation enhances knowledge acquisition and the exchange of ideas, ultimately contributing to the achievement of digital sustainable manufacturing [65,126]. Additionally, legislative laws and policies can compel industries to transition to the sustainability paradigm, serving as enablers for the adoption of digitalized sustainable manufacturing. Without such regulatory pressure, industries may prioritize daily routine activities for short-term economic benefits rather than focusing on sustainability transformation. Therefore, the identified enablers can enhance the adoption of digital sustainable manufacturing in the spool fabrication industry.

5.1. Implications

The practical implications of the findings are revealed in the following paragraph. The findings serve as guidelines for organizations to implement digitalized sustainable manufacturing practices. To accomplish this task, a suite of enablers must be installed with prioritization for each enabler. Hence, the study findings can be utilized for the selection of specific enablers for implementation. Moreover, after identifying the barriers to implementation, the study findings will be used to mitigate the impediments by specific enablers and can form a framework for digitalized sustainable transformation in organizations. For example, the identified crucial barrier is inadequate capital; then, the enabler to mitigate this is to get support from the government in terms of incentives and funds. Thus, management should formulate well-defined strategies and policies to acquire support from the government and local bodies.

Digitalization and sustainable manufacturing are two strategies in the industrial sector for enhancing productivity and firm competitiveness. However, the integration of these two is inevitable and defined as digitalized sustainable manufacturing, which is the new strategy for research about sustainability. The adaptation of these paradigms is influenced by several enablers in the spool fabrication industry, identified in the current study. However, the mitigation of specific barriers by enablers is still pending in the research. The studies can utilize the study findings of enablers and find the interdependencies and interrelationships using hybrid MCDM methods.

6. Conclusion

The spool fabrication industry is significantly lagging in the adaptation of digitalized sustainable manufacturing, which may result in resource exploitation, extensive waste disposal, and an unhealthy and unsafe working environment. Moreover, research in the context of digital sustainability within the spool fabrication industries is scant. Hence, the current research aims to explore and identify the digitalized sustainable manufacturing enablers in the spool fabrication industry. Through a systematic literature review, the enablers are identified and validated by expert opinion. IMF-SWARA integrated with the Fuzzy Bonferroni Operator is employed to analyze the identified enablers.

Substantial initial financial funds are inevitable in the spool fabrication industries due to the procurement of innovative infrastructure, skilled human resources, and other related accessories. This significant capital poses a burden for the spool fabrication industries and necessitates finding alternative solutions. In this financially challenging situation, governmental support in terms of incentives and funds is indispensable for organizations to sustain and overcome financial hurdles. However, adaptation occurs at the shop floor level where employee participation and psychological readiness determine the progress of transformation. Employees' knowledge of digital sustainability will help avoid misconceptions and misunderstandings and enhance the adaptation of digital sustainability practices in spool fabrication industries. To achieve this, employees should undergo training and educational programs to upgrade their skills and knowledge levels. This will mitigate major impediments such as fear of risk, unawareness of long-term benefits, and uncertainties and ambiguities related to the implementation of digitalized sustainable manufacturing practices. The exchange of ideas and knowledge through open innovation and technical collaboration will reduce the complexities of innovative technologies and provide optimum solutions for technical queries. Hence, the identified enablers are crucial elements in the implementation of digitalized sustainable manufacturing in spool fabrication industries.

Despite the noteworthy and constructive contribution, certain limitations exist within the current study. Firstly, the data could be analyzed with more advanced MCDM fuzzy integrated methods, and comparisons could be computed. This would foster the validation of results and be helpful for future research. Moreover, interdependencies and correlations should be evaluated to provide clear insights into the identified enablers, which would help formulate pertinent strategies in organizations. The current research can be expanded by including specific contributions of each enabler to the accomplishment of sustainable manufacturing. The study identified relevant enablers for the spool fabrication industry based on past literature research articles and focused on eradicating barriers to implementing digitalized sustainable manufacturing. Therefore, formulating a structural model and validating it with case studies would be beneficial for management to practically implement these enablers in organizations. Future work based on this research could involve integrating specific digital technologies to promote digitalized sustainable manufacturing in the spool fabrication industry. As the spool fabrication industry has constraints of uniqueness and fragmented structure, the implementation of each digital technology and its potential to accomplish sustainability needs to be explored. Thus, future work encompasses identifying specific challenges in implementing each digital technology for accomplishing sustainability and integrating the results. Furthermore, the analysis should consider the combined viewpoints of suppliers and other stakeholders.

Declaration of interest statement

The corresponding author Sunil Luthera is an Associate Editor in Information Science for Heliyon and was not involved in the editorial review or the decision to publish this article.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Kiran Sankar M.S: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sumit Gupta:** Visualization, Validation, Supervision, Formal analysis. **Sunil Luthra:** Writing – review & editing, Supervision, Project administration. **Anil Kumar:** Writing – review & editing, Supervision. **Sandeep Jagtap:** Writing – review & editing, Supervision, Project administration. **Ashutosh Samadhiya:** Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Sunil Luthra (Corresponding Author) is as an AE of this journal. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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