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ORIGINAL RESEARCH

Smart manufacturing as a strategic tool to mitigate sustainable manufacturing challenges: a case approach

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Abstract

Due to the manufacturing sector's severe negative impacts on sustainable development, sustainable manufacturing is gaining more momentum than ever. Despite the advantages of sustainable manufacturing, academic literature resources report that practitioners still face several challenges while implementing sustainable manufacturing. To eliminate such challenges, numerous mitigation strategies have been proposed, including those that identify Industry 4.0 technologies as a key factor. However, current studies are generally more focused on the application of Industry 4.0 technologies/smart manufacturing in sustainable manufacturing; most fail to provide an in-depth understanding of how these technologies might mitigate the existing adoption challenges of sustainable manufacturing. In this study, the key challenges of sustainable manufacturing are identified through literature review and analyzed with MCDM tools such as the Best-Worst Method and WASPAS method. The results suggest that governmental challenge demonstrates the greatest weight in the final ranking, followed by technological and organizational challenges. Among the sub-challenges, "lack of support from the government in the form of regulations / policies" and "absence of subsidies and incentives" display the most weight. Further, a framework has been proposed to map the collected challenges with relevant mitigating smart manufacturing technologies to bridge the gap remaining from existing studies. Finally, this study contributes to the new field of approaching smart manufacturing as a mitigating strategy for sustainable manufacturing implementation through highlighting the implications and recommendations.

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1 Introduction

In recent years, immense attention has been paid to the concepts of sustainable manufacturing, including manufacturing industries, governments, societies, and researchers, among other topics of study. Rapid market changes and competition among manufacturing industries worldwide have driven toward sustainable manufacturing practices to remain stable. Sustainable manufacturing covers all manufacturing operations of a company, the end-users, and all in-between stages (Malek & Desai, 2020) with the focus of achieving sustainable development. The manufacturing sector is one of the world's highest contributors of carbon emissions and climate change (Liu et al., 2022a, 2022b; Ruberti, 2023; Mahato & Mahata, 2022). Hence, stakeholders have started to pressure manufacturers to shift towards sustainable manufacturing (Huang & Chen, 2022; Ullah et al., 2022), by which sustainable manufacturing can strive for a timely achievement of zero carbon and sustainable development goals (SDGs) targets.

Despite these advantages, industries face challenges in implementing sustainable manufacturing in their industrial operations; those challenges are especially difficult in developing and underdeveloped nations. Several studies (Bhandari et al., 2019; Malek & Desai, 2019, 2021; Tanco et al., 2021; Verma et al., 2022) have sought to explore both the impediments and the success factors for the implementation of sustainable manufacturing in different applications through a variety of geographical contexts. Most manufacturing industries worldwide confront these issues associated with various challenges (Frank et al., 2019). Hence, it is necessary to determine challenges and their role in developing a policy for the adoption of the sustainability manufacturing (Kamble et al., 2018). It is also necessary to identify the influential challenges among common challenges of sustainable manufacturing for its effective implementation. With the support of these discussions, this study presents two initial research questions (RQs):

RQ1: What are the major challenges to implementing sustainable manufacturing in the manufacturing industries?

RQ2: How are these challenges ranked in sustainable manufacturing in the manufacturing industries?

Today, manufacturing industries utilize modern strategies and technologies to improve their processes in the face of serious challenges associated with the implementation of sustainability, especially economic challenges. Recently, manufacturing industries faced great difficulties from the COVID pandemic (Banik et al., 2023; Mezgebe et al., 2023), and in such situations, many industries used technologies to respond to these adverse impacts. Meanwhile, the development and application of Industry 4.0 technologies has been seriously overlooked even by the manufacturing industries(Govindan & Arampatzis, 2023). Modern technologies have created numerous opportunities available for sustainable manufacturing (Calignano & Mercurio, 2023; Ching et al., 2021; Paraschos et al., 2023), but few manufacturing industries have adopted these benefits.

One technology that could play a main role in future manufacturing is smart manufacturing, an emerging technology described as a "coordinated, performance-oriented enterprise, minimizing energy and material usage while maximizing environmental sustainability, health and safety, and economic competitiveness." An important reason for the fast development of smart /4.0 technologies in processes and operations sustainable manufacturing is their ability to obtain solutions for complex sustainable manufacturing problems at a time when agility, speed, and clarity are of the highest importance (Machado et al., 2020) and alternatively companies can also try circular economy or circular manufacturing (Butt et al., 2023; Govindan, 2022; Govindan et al., 2023; Mahdiraji et al., 2023; Sharma et al., 2023). Several studies (see, for example, Huang, 2022; Psarommatis et al., 2022; Ng et al., 2022) claimed that the smart manufacturing and 4.0 technologies have had positive effects on the manufacturing operations.

The smart manufacturing notion is built upon the advantages of novel technological revolutions like vertical integration, automation, flexibility, energy management, traceability, virtualization,network strategies, and others (Abubakr et al., 2020; Cioffi et al., 2020; Janahi et al., 2022). Accordingly, smart manufacturing is a structured methodology that can be utilized to increase efficiency, improve the production process, and diminish emissions. Many studies (see, for example, Li et al., 2022; Guo et al., 2022; Cao et al., 2023) supported that the goal of smart manufacturing is to achieve zero emission, increase profits of manufacturing factories, and neutralize the danger of accidents in the processes production. Several studies (Ardanza et al., 2019; Krugh & Mears, 2018; de Assis Dornelles et al., 2022; Pozzi et al., 2023) indicated that Industry 4.0 technologies in manufacturing improves trackability, flexibility, and reliability in a system. Integrating smart manufacturing and Industry 4.0 technologies do permanently alter the manufacturing processes for better sustainable management (Olsen & Tomlin, 2020; Li et al., 2022; Su et al., 2023). Despite these advantages, there is no proper study to understand the technologies to eradicate the existing challenges of sustainable manufacturing. Furstenau et al. (2020) argued that there is a notable gap in the sustainable manufacturing literature connected to investigating the solutions and challenges by 4.0 technologies offered in the sustainable manufacturing field to develop a more sustainable production. Based on these discussions, this study proposes the third research question (RQ3) as:

RQ3: How can the smart manufacturing and Industry 4.0 technologies help to mitigate challenges in the manufacturing industries?

To address the above-mentioned research questions, this study has collected the common challenges of sustainable manufacturing from literature review and validated the same through experts' opinions. Further, the validated challenges have been evaluated based on multi-criteria decision making (MCDM) analysis tools, WASPAS and Best-Worst method (BWM). According to Rezaei (2015) and Chakraborty, (2014), BMW is used to identify key challenges and calculate their weights in order to rank optimal challenges, and WASPAS is an effective tool to rank the alternatives. The input data for both MCDM tools was generated through Iranian case industries. Further based on the ranking of the challenges, respective technologies have been introduced and paired to mitigate those influential challenges of sustainable manufacturing.

This study effort can be seen as a guideline for the implementation of SM processes to mitigate challenges facing sustainable manufacturing by the adoption of smart manufacturing/Industry 4.0. Accordingly, it is recommended the manufacturing industries engage in smart manufacturing practices. This helps industries maximize synergy between sustainable manufacturing and digitalization for greater profit and economic development. The outcomes could be helpful for policymakers, researchers, and manufacturing industries. Furthermore, Industry 4.0 is capable of remote control, using smart technologies that are necessary during global turbulence such as caused by the COVID-19 pandemic. This revolution accelerates the digital transformation and promotes transportation management, production management, and public safety.

The rest of this study is structured as follows. Section 2 describes existing studies in the field of sustainable manufacturing and the application of smart technologies in sustainable manufacturing. Section 3 details the considered MCDM methods used in the article (BWM and WASPAS). Section 4 presents a case study, which includes different subsections, each determined based on the data gathering purpose, data analysis, and techniques. With the findings of the study, Sect. 5 seeks to answer the considered research questions in addition to developing a recommended framework. Managerial implications and policy recommendations of the study are highlighted in Sect. 6. Section 7 provides a summary of results, limitations, and suggestions for future research.

2 Literature review

To improve an understanding of the current status of sustainable manufacturing and smart manufacturing, this section conducts a state-of-the-art review. A detailed discussion of these existing studies, along with the respective literature gap, follows.

2.1 Sustainable manufacturing

Owing to the popularity and success of sustainable manufacturing, several studies have been published with different streams of applications. To understand the present status, this study emphasizes recent literature published in sustainable manufacturing. Even now, there are many studies that seek to explore the basics of sustainable manufacturing. For instance, Reiff et al. (2021) proposed a novel framework for process planning with the specific application of sustainable manufacturing with the case of laser machine modeling. Alayón et al. (2022) explored different barriers and enablers of sustainable manufacturing adoption with the specific focus on small and medium scale enterprises (SMEs). Yip and To (2021) made a study on barriers of sustainable manufacturing specifically related to stakeholders with the assistance of social network analysis. Bhatt et al. (2020) studied the structure of sustainable manufacturing through bibliometrics and content analysis; their study concluded that the sustainable manufacturing literature often focused on green and lean principles rather than criticality of sustainability. Bastas (2021) reviewed the latest trends and themes involved in sustainable manufacturing technologies; sustainability assessment technologies and sustainability indicators were explored. Kamble et al. (2022) explored the impacts of digital twins in sustainable manufacturing and sought to understand the current trends, implementation frameworks, and future perspectives of successful implementation.

Some studies involved in the assessment of sustainable manufacturing, for instance, Ali et al. (2021) explored the relationship between sustainable manufacturing capabilities and practices with sustainable performances. Holgado et al. (2020) studied the relationship between the maintenance function and sustainable manufacturing; their work highlighted the impacts and contributions of maintenance functions with sustainable plant operations through the consideration of economic, environment, and social benefits. Swarnakar et al. (2022) explored the indicators for sustainability assessment in manufacturing and sought to prioritize the same with an integrated approach.

In addition, this study explored the existing role of environmental regulations to improve the sustainable performances of the firm through sustainable manufacturing. Li et al. (2020)

explored existing challenges and different concepts (including technologies, framework features, application effects, and resource optimization) involved in internet-based intelligent sustainable manufacturing. Malek and Desai (2022) studied the role of sustainable manufacturing implementation in the overall organization's performances. Initially, a hypothesis was framed along with a framework among enablers of sustainable manufacturing and organizational performances. Due to such a high volume of studies on sustainable manufacturing, there are a considerable number of literature review studies. Malek and Desai (2020) reviewed the existing literature published in sustainable manufacturing theme through a systematic literature review. This review includes several functions including sustainable dimensions, data analysis techniques, and focused areas.

As discussed above, several different areas of sustainable manufacturing have been explored. Some studies (Alayón et al., 2022; Li et al., 2020) explored the challenges of sustainable manufacturing, but these studies are limited with providing in-depth practical solutions to address these challenges. To address this limitation, this study explores different ways to mitigate these sustainable manufacturing challenges.

2.2 Smart manufacturing/industry 4.0 in sustainable manufacturing

Recent developments in Industry 4.0 technologies have interested researchers with a manufacturing theme to integrate such technological developments into a sustainable manufacturing paradigm. Most existing studies investigated the relationship between sustainable manufacturing and smart manufacturing through exploring the performances, practices, challenges, and other basic phenomenon. Abubakr et al. (2020) explored the relationship between sustainable manufacturing and smart manufacturing by considering sustainable manufacturing performance measures with Industry 4.0 technologies. Aggarwal et al. (2022) highlighted the relationship between smart and sustainable manufacturing practices with a hypothesis developed to understand the link between the manufacturing competitiveness and top management commitment to those practices. Gholami et al. (2021) made a bibliometric study on sustainable manufacturing 4.0 in which practices and respective pathways were discussed; these pathways are believed to assist managers in shifting towards sustainable manufacturing 5.0 or Industry 5.0.

Several studies applied Industry 4.0 technologies to promote sustainable manufacturing in their considered case operations. Watson et al. (2021) proposed a methodology by which machine learning and sensors might be unified as an intelligent sensors system that promotes sustainable food and drink manufacturing. Park et al. (2022) proposed an effective way through deep learning to detect defects that occur in manufacturing processes. This study argued that the proposed method improves sustainability in manufacturing with the case of a disposable gas lighter manufacturing process. Yun et al. (2022) addressed the sustainability challenges with the introduction of CPS-enabled demand response strategy. Their real time CPS-enabled system provides long term production schedule information to assist managers in supply demand response. Danishvar et al. (2021) discussed the scheduling problem in which multi-objective batch-based flow shop scheduling optimization was proposed; the proposed model was evaluated with a case of AI-driven sustainable manufacturing. Kumar et al. (2021) explored the potential opportunities of involving big data analytics with the application of sustainable manufacturing to understand its strategic factors for efficient operations.

Due to the recent influx of studies, some literature review studies have emerged. He and Bai (2021) made a review on a new concept of sustainable intelligent manufacturing with the consideration of digital twins; the digital twin was discussed with sustainable manufacturing perspectives. In addition, this study explored the supporting systems of sustainable intelligent manufacturing by analyzing the intelligent manufacturing equipment, systems, and services. Ching et al. (2022) made a review on different applications of Industry 4.0 technologies in sustainable manufacturing. At the end of the review, this study suggested 15 sustainability functions of sustainable manufacturing to which Industry 4.0 technologies could contribute.

So far, several studies (Abidi et al., 2022; Sharma et al., 2021a, 2021b; Cinar et al., 2020) sought to explore smart technologies in sustainable manufacturing as a tool to improve sustainable productivity. However, all these studies either focus on a single technology or they make a general argument on the challenges that accompany technologies. There is not a single in-depth study that presents all key challenges of sustainable manufacturing and appropriate individual mitigating Industry 4.0 technologies. In addition, this study is distinct from existing studies in two important areas. First, this study focuses on sustainable manufacturing challenges with the concern of the global uncertainties created by the recent COVID-19 pandemic. Secondly, the case context selected to consider the challenges and its mitigating technologies is Iran. No single study currently exists to fill these research gaps.

3 Methods

To achieve the study goals, a two-stage methodology has been adopted. The first stage includes "Best-Worst Method", and the second stage applies WASPAS. The MCDM literature proposes different techniques for weight calculation, including AHP, dominance, MAXIMIN, and permutation technique (Sotoudeh-Anvari, 2022; Zavadskas et al., 2014). The adoption of each approach is directly related to the type of problem it pursues. However, these techniques need to be extensively reviewed by decision-makers, and their views may result in scattered judgments. Each technique has some unique characteristics. Also, it is helpful to consider the number of decisions needed to arrive at a special judgment. Hence, to address such conditions, Rezaei (2015) offered BWM to solve the above-mentioned gap. The results suggest that BWM can outperform AHP in four areas: conformity, smallest violation, whole deviation, and consistency (Rezaei, 2015).

Generally, the main characteristics of the BWM are as follows: it needs few "pairwise comparisons" and it presents more consistent outcomes. Given the advantages of BWM over AHP defined in the literature, the BWM was chosen for this article. A comparison is drawn between BWM and AHP to confirm the choice of BWM. However, it is worth noting that the purpose of this article is not to compare the outcomes of these two techniques. The BWM method ensures the consistency of the findings and permits extensive applications in different fields.

A variety of techniques to rank alternatives are available according to their attributed weights: TOPSIS, VIKOR, MOORA-G and SWARA, among others (Simanaviciene et al., 2012; Vasegaard et al., 2022; Zarbakhshnia et al., 2020). For this purpose, WASPAS was chosen as the most suitable approach due to its solution accuracy and ranking criteria; a further criterion is that it is affected by the value of its control parameter. The goal of this paper is to overcome the challenges of sustainable manufacturing implementation during COVID-19 pandemic. Clearly, it is difficult to offer solutions that can eliminate all real-world challenges. Hence, efficient approaches suggest ways to reduce the current challenges. These methods are explained in detail here and their significance and stages are discussed.

3.1 Best-worst method (BWM)

This paper uses BWM, which addresses a significant challenge associated with the case industries and their weight criteria. There are some MCDM techniques for measuring the weight of criteria. One MCDM technique, analytical hierarchy process (AHP), is frequently used to assess the weights of the criteria. Also, new research has introduced a novel technique called BWM as a substitute to AHP for determining the weight of criteria. The AHP has several restrictions that are improved by the BWM method (Rezaei, 2015). In addition, BWM has received increasing scholarly attention for the following reasons: inconsistency in comparisons and lengthy pairwise comparisons. This approach uses two vectors to specify the "weight of criteria" instead of pairwise comparison. It helps improves the reliability of findings and offers convenient analytical processes for decision making. This method has several advantages and various applications discussed by numerous studies (Govindan et al., 2022a, 2022b; Haqbin et al., 2022; Rezaei, 2016). In light of its importance, BMW has been adopted in this paper to determine and rank the main challenges of sustainable manufacturing along with their weights by adhering to the following steps (Rezaei, 2015).

Stage 1 Establish the decision criteria.

This step includes "a set of criteria $\{c_1, c_2, \ldots\ldots\ldots c_n\}$ for 'n' number of attributes that are assessed in this study. However, in some cases, other options (alternatives) are considered.

Stage 2 Identify and determine the worst (least desirable—W) and the best (most desirable—B) criteria. This step also includes the decision-makers' response but with no comparison or rank.

Stage 3 Determine preferences among criteria. In this step, a scale of 1 to 9 is used to identify the best criterion. It is calculated and shows "the resulting vector from the best to other vectors."

$$A_B = \{a_{B1}, a_{B2}, \ldots\ldots a_{Bj} \ldots a_{Bn}\}$$

where a_{Bj} indicates the priority of the best criterion B over criterion j. Therefore, it is evident that.

$$a_{BB} = 1$$

Stage 4 Specify preferences among criteria. In this step, a scale of 1 to 9 is used to identify the worst the criterion for others. It is calculated and displays "the resulting vector from the others to worst."

$$A_w = (a_{1w}, a_{2w}, \ldots., a_{nw})^T$$

where a_{jw} indicates the priority of the criterion j over the worst factor W. Therefore, it is evident that $a_{WW} = 1$.

Stage 5 Compute the "optimal weights."

This stage calculates the weights of study attributes, indicating that the highest absolute differences for all *js* are reduced of the next set of $\left\{\left|w_B - a_{Bj}w_j\right|, \left|w_j - a_{jw}\, w_W\right|\right\}$. Also, the min and max pattern can be formulated as

$$min\max_j\left\{\left|w_B - a_{Bj}w_j\right|, \left|w_j - a_{jw}\, w_W\right|\right\}$$

Subject to

$$\sum_j w_j = 1 \tag{1}$$

$w_j \geq 0$ for all j.

By transformation through "a linear programming problem," this above model can be solved.

Min ξ.

Subject to

$$|w_B - a_{Bj} w_j| \leq \xi \text{ , for all j}$$

$$|w_j - a_{jw} w_W| \leq \xi \text{ , for all j}$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{ for all j.} \tag{2}$$

This step finds the optimal weights of the assessed criteria using the above two equations.

3.2 WASPAS method

This MCDM technique combines the weighted sum-product pattern (WPM) and weighted sum model (WSM) to make decisions (Zavadskas et al., 2012), and it prioritizes alternatives by combining optimal criteria and calculating them based on the outcomes of these two models. WASPAS includes expert responses to obtain the weight of criteria and to evaluate the consistency of alternative rankings. It is often suggested as the most suitable MCDM technique by many researchers (Chakraborty et al., 2014; Al-Barakati et al., 2022; Pamucar et al., 2022). Several studies have applied this method successfully to different areas ranging from engineering, management, supply chain, and more. Zavadskas et al. (2012) introduced the following stages to WASPAS method.

Stage 1 For benefit criteria,

$$\tilde{x}_{ij} = \frac{x_{ij}}{\max_i \ \mathrm{x}_{ij}}; i = 1,...,\mathrm{m}, \mathrm{j} = 1,...,\mathrm{n} \tag{3}$$

Stage 2 For non-benefits criteria,

$$\tilde{x}_{ij} = \frac{\min_i x_{ij}}{x_{ij}}; i = 1, \ldots, \mathrm{m}, \mathrm{j} = 1, ...,\mathrm{n} \tag{4}$$

where $\widetilde{x}_{ij}$ shows the value of normalized x_{ij}.

Accordingly, the two measures of optimal criteria in WASPAS are as follows.

Stage 3 Compute "the total relative importance" of the WSM option from the following equation:

$$Q_i^{(1)} = \sum_{j=1}^{m} \widetilde{x}_{ij} w_j \tag{5}$$

where w_j indicates the weight (relative significance) and importance (weight) of j^{th} measures.

Stage 4 Calculate the "total relative importance" of j^{th} option for WPM using the following equation:

$$Q_i^{(2)} = \prod_{j=1}^{m} (\widetilde{x}_{ij})^{w_j} \tag{6}$$

Then, a joint total “criterion of weighted aggregation of additive and multiplicative methods” has been provided (Zavadskas et al., 2012):

$$Q_i = 0.5Q_i^{(1)} + 0.5Q_i^{(2)} = 0.5\left(\sum_{j=1}^{m} \tilde{x}_{ij} w_j + \prod_{j=1}^{m} (\tilde{x}_{ij})^{w_j}\right) \tag{7}$$

Stage 5 Determine the total relative impotence of *i* th option in this Equivalent:

$$Q_i = \lambda Q_i^{(1)} + (1-\lambda) Q_i^{(2)} = \lambda \sum_{j=1}^{m} \tilde{x}_{ij} w_j + (1-\lambda) \prod_{j=1}^{m} (\tilde{x}_{ij})^{w_j} \tag{8}$$

$(\lambda = 0,\ 0.1, \ldots\ldots, 1.0)$

The options are rated in terms of Qi values. This method is converted into two parts including WPM ($\lambda = 0$) and WSM ($\lambda = 1$).

4 Case illustration

There is a paucity of literature that identifies challenges of sustainable manufacturing and offers solutions using the “smart manufacturing/Industry 4.0” technologies. In addition, recent research has mainly concentrated on the supply chain and sustainability. Hence, this article surveys the challenges of sustainable manufacturing in manufacturing industries mounted by several global uncertainties, especially with detergents, food, mineral powders, and office machinery industries in Iranian context. We also consider challenges brought on by the COVID-19 pandemic. For this research, a particular search pattern has been selected to identify the challenges of sustainable manufacturing. The overall flow of the study is described in Fig. 1. This pattern includes data gathering strategies, the choice of case studies, and the distribution of questionnaires. The sustainable manufacturing has attracted slight attention recently, but it has not been examined in manufacturing sections. Thus, it calls for deep analysis of the notion. In this paper, the case study method has been used to shed light on the issue.

4.1 Data collection

In the first section, the theoretical basis is presented. The problem is associated with the challenges of sustainable manufacturing. Also, data are collected from secondary and primary sources to determine the current challenges. The information was collected from the following sources:

- From August 2020 to January 2021, the questionnaires were distributed among experts and managers of Iran’s manufacturing industries. Initially the questionnaires were emailed to 70 experts and managers. They filled out a survey questionnaires and ranked 20 challenges in different manufacturing industries. The results are based on the discussion of experts and authors, and review of literature. The questionnaires address key challenges concerning the sustainable manufacturing. According to the questionnaires, 20 key challenges were gathered and applied in this study.
- Secondly, we conducted a systematic literature review in Scopus and Web of Science databases to identify SM challenges. This search keywords included “sustainable”, “manufacturing”, “sustainable manufacturing in Iran”, “challenges”, “Sustainable”, “Industry

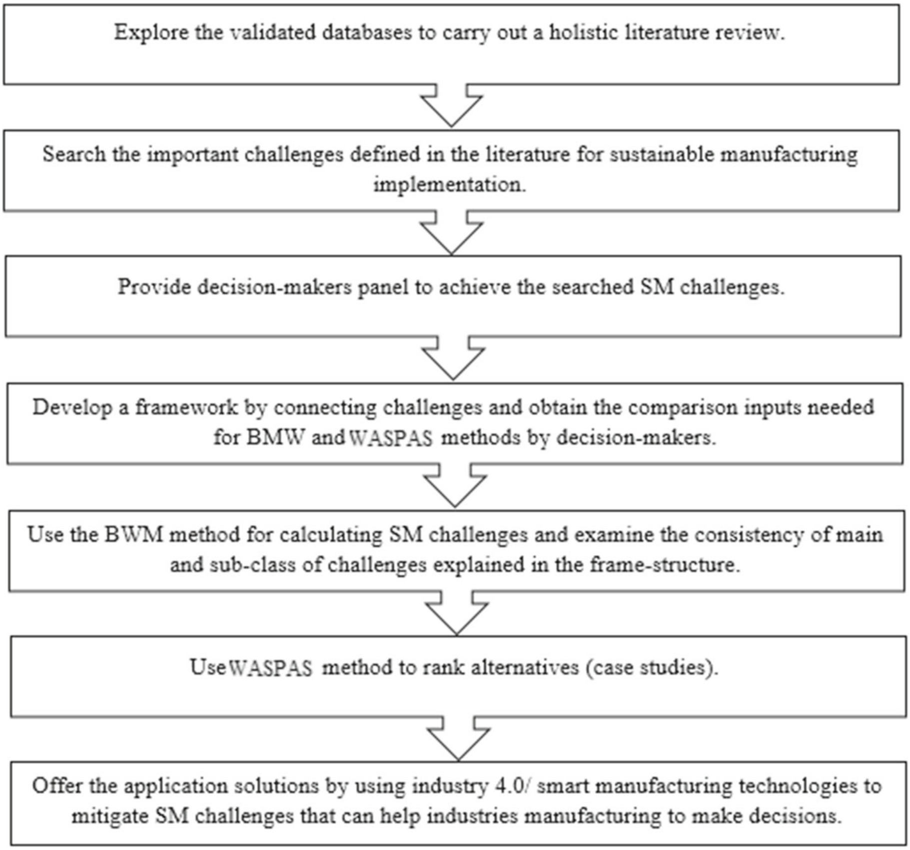

Fig. 1 The overall flow of the current study

4.0", "smart manufacturing", and "manufacturing industries". Moreover, the secondary data was collected by searching the literature, including theses, proposals, media, and key papers. The papers publicly accessible in the domain of manufacturing industries were the main source of data collection. At this step, we compared data about the identification of sustainable manufacturing challenges during one of the recent global uncertainty COVID-19 pandemic.

- Also, experts were presented with a list of 20 challenges gathered from the relevant papers, literature, and ideas of specialists in this field. Table 1 shows key challenges of sustainable manufacturing identified in the study. Some challenges were determined with the assistance of specialists. This study suggests solutions by relating the "smart manufacturing/Industry 4.0 technologies" to existing challenges to mitigate them in Iranian manufacturing industries.

4.2 Case analysis

Sustainable manufacturing in production organizations can be a novel avenue of research. Recently, manufacturing companies have attempted to integrate several strategies to gain

Table 1 Sustainable manufacturing challenges identified from existing studies and experts'

S. No.	Main /sub challenges	Definition	Sources
Organizational challenges			
1	Absence of management support (OC1)	Safety problems, poor job performance, absenteeism, and lack of planning are main issues facing manufacturing industries during COVID-19 pandemic, which can impact the management support due to uncertain events	Fatoki (2019), Malek and Desai (2021), Escoto et al. (2022)
2	Absence of organizational labor force management (OC2)	There is no health monitoring to manage all measures required to keep the productivity of workers during COVID-19	Experts' opinions
3	Difficulty to obtain special technical data, testing standards, tools, diagnostic tools and machinery (**OC3**)	Insufficient government subsidy for manufacturing goods. Manufacturing industries have trouble procuring tools and production equipment. These problems will also affect the supply of technical data and machinery testing	Ngu et al. (2020), Bhanot et al. (2017), Escoto et al. (2022)
4	Absence of programs to build virtual skills (**OC4**)	This challenge includes sudden changes and uncertainties during COVID-19 outbreak	Leng, et al. (2020), Tanco et al. (2021), Escoto et al. (2022)
5	Lack of knowledge sharing / information exchange (**OC5**)	Due to fast execution actions and the integration of information in all organizations, it is an important challenge at the time of the pandemic	Tanco et al. (2021), Alayón et al. (2022)
6	Weak organizational culture to implement sustainable manufacturing practices (**OC6**)	Organizational culture is the cornerstone of each organization. However, there are problems such as lack of planning, poor communication, weak leadership, and poor decision making in organizations caused by the non-acceptance of COVID-19 outbreak by all employees, which weakens the organizational culture	Fatoki (2019), Tanco et al. (2021), Alayón et al. (2022), Escoto et al. (2022)
7	Lack of a review of HR plans/ policies for social sustainability (**OC7**)	Due to employee absenteeism (illness), there are no procedures and plans during the COVID-19 epidemic. Manufacturing industries struggle with this challenge	Kumar et al. (2020), Alayón et al. (2022)

Table 1 (continued)

S. No.	Main /sub challenges	Definition	Sources
8	Lack of employees' safety and health (OC8)	During the prevalence, employees working in units such as logistics and health centers constantly face the risk of infection. Thus, their safety is a key challenge in the organizations	Kumar et al. (2020),
9	Imbalanced demand and supply (OC9)	Sudden changes in the supply and demand process pose unpredictable challenges and provoke disorders in the organization, especially at the time of outbreak	Tanco et al. (2021)
10	Indeterminate return on investments (sanctions/ inflation) (OC10)	Manufacturing industries face challenges like the return on investment due to inflation, sanctions, and low demands for manufacturing and sale of products during the outbreak	Pathak and Singh, (2019), Malek and Desai (2019), Pathak et al., (2020), Malek and Desai (2021), Escoto et al. (2022)
11	Weak industrial infrastructures (OC11)	It describes inflexibility about storage locations and transportations during COVID-19 pandemic	Malek and Desai (2019), Alayón et al. (2022)
12	Distrust among workforces (OC12)	Trust is the pillar of an organization but misunderstanding coworkers' requirements in an uncertain environment can impact the supply and production	Garetti and Taisch (2012), Alayón et al. (2022)
13	"Delay in the supply of materials (OC13)	It suggests that tight controls and lockdown rules enforced to curb the epidemic disrupts supply chain, especially the supply of necessary materials	Herrmann et al. (2014)
Governmental challenges			
14	Lack of support from the government in the form of regulations and policies (GC14)	The governments must introduce regulations and policies that facilitate the implementation of SM. It is due to challenges such as lack of loss contract, cost-sharing, excess production by competitors, and unpredictable demands during the COVID-19 pandemic	Malek and Desai (2019), Malek and Desai (2021), Tanco et al. (2021)
15	Reduction in labor (GC15)	It describes the government's reluctance and policies about inadequate workers during the pandemic	Experts' opinions

Table 1 (continued)

S. No.	Main /sub challenges	Definition	Sources
16	Absence of subsidies and incentives (GC16)	Manufacturing industries face challenges due to the absence of awards, subsidies, research/development protection, tax exemption, etc. at the time of the pandemic	Malek and Desai (2021), Alayón et al. (2022)
Technological challenges			
17	Lack of technology (ICT, IOT) to implement SM in manufacturing industries (TC17)	Manufacturing industries that do not have access to advanced technologies like ICT and IOT, skillful labor, etc. confront this challenge to the implementation of SM processes, especially during the pandemic	Ngu et al. (2020), Malek and Desai (2021)
18	Lack of IT infrastructures (TC18)	Improper tools and plans to buy hardware, software, and operating systems for data storage in the organization due to the lack of financial support and access to new technologies during the COVID-19 pandemic create this challenge	Malek and Desai (2019), Malek and Desai (2021), Tanco et al. (2021), Escoto et al. (2022)
19	High risk of hazards (TC19)	Manufacturing industries must deal with hazards like rising demand, timely provision of necessary resources, disruption of the manufacturing chain, safety of staff, etc. due to the absence of advanced technologies during the COVID-19 outbreak	Boral et al., (2020), Garetti and Taisch, (2012), Alayón et al. (2022)
20	Lack of any prediction about the flow of potential resources (TC20)	This challenge is related to the inflexibility and absence of a regular plan for the distribution of resources due to uncertainties associated with COVID-19 pandemic	Experts' opinions

advantages in environmental, economic, and social dimensions. From different manufacturing industries in this study, we selected relevant industries as case studies for in-depth analysis of this field. Also, this article aims to investigate the methodology used in these industries to examine the attitude of manufacturing industries concerning SM challenges during a global uncertainty like the COVID-19 pandemic in Iranian SMEs. At first, we explored total activities, operations, and all sections in manufacturing processes. Then, we collected information about the challenges of sustainable manufacturing. The manufacturing industries are selected from the pool based on their interests and their accessibility. Five industries were selected under each production sector, and one industry from each sector was selected for the study. To contact the manufacturing industries selected, we arranged Skype meetings for discussion with experts and then emailed questioners to subjects. These experts had in-depth insights into the challenges of sustainable manufacturing and could assist practitioners. Moreover, the specifications of selected industries are shared in Table 2.

Table 2 Profile of selected experts and SMEs industries in Iran

Production area of industry	Year of establishment industry	Industrial experts (respondents)	Years of experience	Location of industry	Kinds of products
Detergent production	2010	Production manager (1)	30–40	South of Iran Qazvin Province in Lia Industrial Estate	Washing liquid
		General manager (1)	10–20		Dish soap liquid
		Safety / environmental manager (1)	10–20		Cleansing fluid
		Operations manager (2)	10–20		Shampoo
Food production	1996	Senior production manager (1)	20–30	South of Iran Qazvin Province in Lia Industrial Estate	Kinds of cookies
		Senior staffs of production (2)	20–30		Kinds of cakes
		Production Engineers (1)	10–20		Toasted powder
		Operations manager (1)	10–20		Cake powder
Mineral powders production	2006	General manager (1)	10–20	South of Iran Qazvin Province in Booin-Zahra city	Calcium carbonate
		Senior production manager (1)	20–30		Crystal barite Talc powder
		Production Engineers (1)	10–20		Lime powder
Office machines production	1965	Production manager (2)	10–20	West of Iran Qazvin Province in Hashtgerd Industrial Estate	TV
		Senior staffs of production (2)	10–20		Computer/ laptop
		Production Engineers (2)	10–20		Refrigerator
		Safety manager (1)	10–20		Washing machine

4.3 Methods application

This article analyzes key challenges to sustainable manufacturing through two methods: BWM and WASPAS. The set of data are provided based on the case studies conducted by distributing questionnaires among manufacturing industry's experts and managers. For this purpose, we prepared two different sets of questionnaires related to these methods. The details of each method and their application are described below.

Table 3 Best-to-Others vector of main-criteria

Experts	Organizational	Governmental	Technological
Expert 1	7	1	5
Expert 2	6	7	1
Expert 3	1	9	7
Expert 4	7	1	5
Expert 5	9	7	1
Expert 6	1	8	7
Expert 7	8	1	7
Expert 8	1	9	6
Expert 9	5	1	9
Expert 10	8	9	1
Expert 11	9	7	1
Expert 12	8	1	9
Expert 13	5	9	1
Expert 14	1	9	7
Expert 15	6	7	1
Expert 16	7	1	9
Expert 17	8	9	1
Expert 18	1	7	9
Expert 19	7	8	1
Expert 20	8	9	1

4.3.1 "Best-worst method" (BWM)

Given the importance of BMW, as described earlier, this article utilizes the MCDM method to assess key challenges. The first step was data collection in which 20 challenges were determined. This paper also evaluates challenges facing the selected industries. In addition, to identify some key challenges of this method, we classified the worst and best challenges of sustainable manufacturing. The intermediate steps involved in BWM are listed in Tables 3, 4, and 5. Then, the relevant criteria are displayed based on their global weights in Table 6. The final set of key challenges are indicated from the perspective of manufacturing industries in Table 2. The ranking of each criteria dimension has been highlighted in Fig. 2.

Also, the other outputs of Best-to-Others vector and Others-to-Worst vector sub-criteria are not presented to avoid filling the paper with several outputs tables. As noted above, only the main criteria of SM are included. The final ratings of the main and sub-challenges are displayed in Table 6 and the rankings of sub-criteria of SM is shown in Fig. 3.

4.3.2 Decision making and WASPAS

The final set of challenges was determined by the BWM method. Then, challenges were analyzed using the WASPAS technique. The usage of this method are described as follows:

(a) Construct the decision matrix as shown in Table 7.
(b) Construct the normalized decision making matrix using Eqs. (3) and (4).

Table 4 Others-to-Worst vector of main-criteria”

Experts	Organizational	Governmental	Technological
Expert 1	4	5	1
Expert 2	1	9	3
Expert 3	1	7	9
Expert 4	1	7	6
Expert 5	5	1	9
Expert 6	1	6	9
Expert 7	1	9	6
Expert 8	7	8	1
Expert 9	1	6	7
Expert 10	9	1	7
Expert 11	9	1	6
Expert 12	5	7	1
Expert 13	7	1	9
Expert 14	2	1	9
Expert 15	1	9	3
Expert 16	4	5	1
Expert 17	1	7	5
Expert 18	6	1	9
Expert 19	7	1	6
Expert 20	1	9	5

(c) Compute the “ total relative importance” of the options by Q (1) and Q (2), which are obtained from Eqs. (5) and (6).
(d) Compute the WASPAS value by aggregating Q (1) and Q (2) from Equation (7).
(e) Calculate and rate the options according to “decreasing values” from Equation (8), as displayed in Table 8.

Based on the WASPAS, the ranking for the considered industry alternatives has been highlighted in Table 8 and Fig. 4. From Table 8 and Fig. 4, it can be easily evident that the food industry faces more challenges for the implementation of sustainable manufacturing. However, Tables 2 and 9 depict SM challenges and the results of their analysis. Then, these challenges are briefly explained and linked to new technologies, as shown in Table 9.

5 Discussion and recommendation framework

As stated earlier, the main purpose of this article was to present the existing SM condition in Iran and discuss important challenges to its implementation in the manufacturing industries. This work offers an extensive discussion of findings because it provides profound insights into the challenges of sustainable manufacturing during the disruptive global uncertainty caused by the COVID-19 pandemic in the Iranian context. MCDM techniques have been extensively utilized for sustainable manufacturing. In this study, two new MCDM techniques, hybrid BWM and WASPAS techniques, have been applied to identify the challenges of sustainable manufacturing. The upcoming discussions are based more on COVID pandemic related

Table 5 Major criteria weights

Experts	Organizational	Governmental	Technological
Expert 1	0.1444444	0.755556	0.1
Expert 2	0.0769231	0.179487	0.74359
Expert 3	0.3103448	0.301724	0.387931
Expert 4	0.0714286	0.734694	0.193878
Expert 5	0.1188811	0.076923	0.804196
Expert 6	0.2990654	0.327103	0.373832
Expert 7	0.0666667	0.785185	0.148148
Expert 8	0.821110	0.133333	0.066667
Expert 9	0.0769231	0.79021	0.132867
Expert 10	0.1470588	0.058824	0.794118
Expert 11	0.1363636	0.0625	0.801136
Expert 12	0.1307692	0.792308	0.076923
Expert 13	0.1932773	0.058824	0.747899
Expert 14	0.7314815	0.083333	0.185185
Expert 15	0.0769231	0.179487	0.74359
Expert 16	0.1444444	0.755556	0.1
Expert 17	0.0769231	0.132867	0.79021
Expert 18	0.8011364	0.0625	0.136364
Expert 19	0.1587302	0.071429	0.769841
Expert 20	0.0666667	0.139394	0.793939

sustainable manufacturing challenges, by which the industries in future can be resilient with other global uncertainties.

This paper addresses SM problems and challenges, which have received considerable attention so far, along with challenges of implementing SM processes in Iranian manufacturing industries. Based on the content analysis of reviewed articles, this article identifies key challenges of SM. In our analysis, we explored organizational, governmental, and technological aspects of this issue. Hence, we can now answer the research questions raised in the introduction of this paper.

Q1. What are the major challenges to implementing SM in the manufacturing industries?

To answer the first research question, we have listed challenges in Table 2. The review of literature suggested that uncertainty, and sudden changes during the COVID-19 pandemic in manufacturing industries, generated different challenges to the implementation of sustainable manufacturing. As such, 20 challenges were identified in the literature review. The authors argue that governments and policies have played an important role in the reduction of SM challenges, especially during COVID-19 outbreak. The key challenges were identified during the review, some of which are presented here. The challenges listed in Table 2 can also be divided into three categories (organizational, governmental, and technical aspects). From an environmental standpoint, lack of governmental support in the form of regulations and policies (GC14) and absence of subsidies and incentives (GC16) are key challenges highlighted by authors (Malek & Desai, 2019). The most widely cited challenges from technological perspective included lack of technology (ICT, IOT) to implement SM in manufacturing industries (TC17) and failure to project potential resources flows (TC20). These challenges were

Table 6 Category and sub-categories Best-Worst weights

Category	Weights	Sub-barriers	Local weight	Global weights	Rank
Organizational challenges	0.066666	C1	0.03556969	0.007002783	15
		C2	0.04734362	0.009902271	13
		C3	0.03016550	0.006750766	16
		C4	0.03282482	0.005946614	18
		C5	0.03049715	0.005753669	19
		C6	0.03345946	0.005945297	17
		C7	0.02796436	0.005202886	20
		C8	0.06533237	0.014930364	12
		C9	0.08791696	0.020707733	11
		C10	0.12658703	0.030769983	8
		C11	0.13007659	0.033213884	5
		C12	0.13733175	0.030663372	9
		C13	0.03570463	0.007645231	14
Governmental challenges	0.139393	C14	0.42457279	0.090946856	1
		C15	0.11895748	0.025481636	10
		C16	0.17911990	0.044501843	2
Technological challenges	0.793939	C17	0.22886661	0.042752774	3
		C18	0.15178241	0.032512995	6
		C19	0.14880731	0.031875704	7
		C20	0.17938705	0.036344337	4

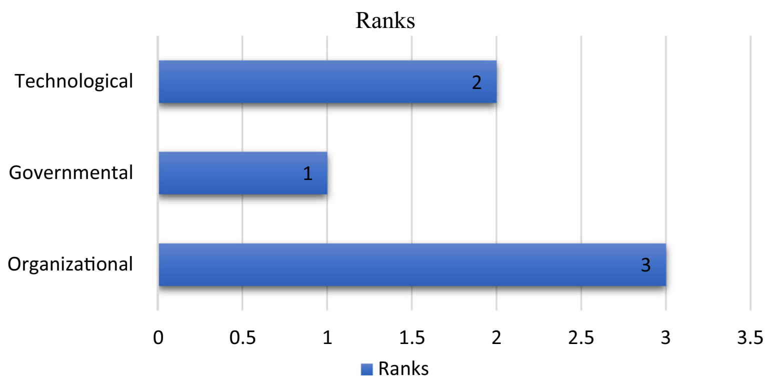

Fig. 2 Ranking the main criteria of SM

mentioned by Ngu et al. (2020). Furthermore, weak industrial infrastructures (OC11) and uncertain return on investment (sanctions/inflation) (OC10) are as other major challenges to SM implementation from an organizational perspective (see Pathak and Singh, 2019; Malek & Desai, 2019).

Table 7 The decision matrix

W	0.035	0.047	0.03	0.032	0.03	0.033	0.027	0.065	0.087	0.126
Industry	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A1	8.10576	8.58581	5.96629	4.78938	5.96629	5.80906	7.23652	7.22467	6.32526	8.79046
A2	1.47235	2.86255	2.75837	2.47382	3.47141	3.64235	2.96719	3.38601	4.36877	4.93091
A3	1.96798	2.05976	5.54444	6.03100	5.38356	5.04537	6.23573	4.35587	3.40865	5.90396
A4	8.45193	5.43878	7.93725	5.66375	5.14369	3.97635	6.19198	4.72871	8.73885	8.45194
W	0.130	0.013	0.035	0.424	0.118	0.179	0.022	0.151	0.148	0.179
Industry	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
A1	6.67285	5.67381	7.23653	6.11853	8.55881	7.65255	5.14352	5.49280	5.07756	6.56017
A2	2.27458	2.75837	5.30420	4.93092	2.27458	4.53378	3.60253	4.58390	4.90224	3.64235
A3	5.43879	4.58257	6.03101	6.85255	4.58258	3.40866	3.83366	5.73266	4.73814	4.60578
A4	6.73537	5.59508	3.83366	7.63719	6.85255	5.79146	8.13242	7.45391	6.11691	5.91608

Table 8 Rank alternatives

Alternatives	WSM	WPM	Score	Rank
Office machines industry 1	1.146156	0.327079	0.736567382	3
Food industry 2	1.819621	0.900757	1.359988736	1
Mineral powders industry 3	1.458095	0.561148	1.009557861	2
Detergent industry 4	1.096737	0.317312	0.706971021	4

Q2. How can the smart manufacturing and Industry 4.0 technologies help to mitigate the challenges in the manufacturing industries?

The implementation of sustainable manufacturing processes is difficult and complex due to different organizational, economic, and governmental rules/standards adopted by each country. The SM processes are still improving. Some researchers have shown that the application of smart manufacturing and 4.0 Industry technologies can reduce challenges to SM. They also assist manufacturing industries to expand their economy.

Moreover, smart manufacturing and Industry 4.0 technologies enhance manufacturing competitiveness by minimizing time/costs and raising market shares in the face of challenges. Table 9 lists modern technologies utilized to overcome SM challenges. These technologies can also be used to overcome a variety of challenges noted by the authors. It then identifies important SM challenges that call for the application of powerful approaches such as smart manufacturing and "Industry 4.0 technologies" to mitigate these kinds of challenges in the industries (Huang, 2022). Given the importance of this issue, this article adopts these technologies to mitigate sustainable manufacturing problems related to the approved cases of COVID-19. Smart manufacturing offers multiple advantages associated with new technological advances such as vertical integration, automation, flexibility, energy management, traceability, virtualization, etc. (Abubakr et al., 2020; Cioffi et al., 2020). In general, integrating these technologies and sustainable manufacturing challenges can provide a broad range of beneficial practices and solutions to different manufacturing industries. These technologies include "cyber-physical system, big data, cloud computing, internet of things" and more (Krugh & Mears, 2018). They can present innovative techniques to alleviate SM challenges. These technologies have remote control ability, utilizing smart technologies that are well-suited for COVID- 19 pandemic. Table 9 presents a list of these technologies.

Q3. How are these challenges ranked in sustainable manufacturing in the manufacturing industries?

To answer this research question, this paper explains these methods, their significance, and stages in three sections. The MCDM literature has proposed different techniques for the calculation of weights such as AHP, Dominance, Maxi Min method, and Permutation technique, to mention a few (Yadav et al., 2017). The adoption of each approach depends on the type of the problem. However, these techniques need to be reviewed by a number of decision-makers, which may result in scattered judgments. Each technique has its unique characteristic. Also, it is necessary to consider the number of decisions required to reach a certain judgment. Thus, Rezaei (2015) offered BWM to solve the above-mentioned gap. According to their findings, BWM outperforms AHP in four dimensions of conformity, weak violation, whole deviation, and consistency (Rezaei, 2015). Generally, the main characteristics of the BWM are the need for few "pairwise comparisons" and consistent outcomes. Given the obvious advantages of

Table 9 Related to the challenges of SM to the new technologies

No	SM Challenges	Solutions to handle SM challenges	Source
1	Absence of management support in industry (OC1)	These technologies help address challenges mounted by COVID-19 pandemic: Expansion of the block-chain Management support to embrace "Industry 4.0 and smart manufacturing technologies"/ paradigms Management and use of digital potentials and methods	Zhang and Chen (2020), Abubakr et al. (2020), Sharma et al. (2021a, 2021b), Bag and Pretorius (2022)
2	Absence of organizational labor force management (OC2)	These technologies help overcome challenges. However, companies need to manage their labor force to mitigate the negative impacts of COVID-19: Using big data analytics Applying the block-chain Focusing on the interoperability of labor forces Standardizations and collaboration to implement principles of manufacturing processes using the Internet of things	Kusiak (2019), Mittal et al. (2018)
3	Difficulty to obtain the special technical data, testing standards, tools, diagnostic and kinds of machinery (OC3)	This is an important issue facing manufacturing industries during COVID-19 epidemic. Also, these technologies help improve this challenge during the COVID-19 pandemic: Applying ICT to identify manufacturing opportunities and offering IOT within manufacturing process Utilizing machines with an Internet connection Adopting 6 R's in the industries	Mittal et al. (2018)

Table 9 (continued)

No	SM Challenges	Solutions to handle SM challenges	Source
4	Absence of virtual abilities “building programs” (OC4)	These technologies have been shown to be effective during COVID-19 pandemic. They can help reduce and predict the spread of the COVID-19 pandemic. The industries are recommended to adopt the following technologies: Applying a digital technology called virtual reality to draw on the benefits of greater productivity, creativity, and comfort Simulating the processes for specific digital manufacturing Utilizing “artificial intelligence” for preparation and planning of the manufacturing processes	Jeschke et al. (2017), Kumar et al. (2019), Gilchrist (2016)
5	Deficiency of knowledge sharing / information exchange (OC5)	Knowledge sharing and information exchange are key factors that will assist overcome COVID-19 challenges. Hence, the manufacturing industries are suggested to use the following technologies: Using the cloud of things to collect data for presenting new services Using the augmented /virtual reality to present customized products and services Utilizing the Internet of things technologies to present innovative ideas for new services Focusing on the interoperability of organization to share data	Kumar et al. (2020), Burritt and Christ (2016), Sharma et al. (2021a, 2021b)

Table 9 (continued)

No	SM Challenges	Solutions to handle SM challenges	Source
6	Weak organizational culture to implement sustainable manufacturing practices (OC6)	During the COVID-19 epidemic, organizational culture helps improve manufacturing practices. Hence, these technologies are suggested: Using the vertical integration of production systems for information sharing to improve operations Applying the virtual reality for the instruction and training of the workforce	Mittal et al. (2018), Franket al. (2019), Abubakr et al. (2020), Sharma et al. (2021a, 2021b), Bag and Pretorius (2022
7	Absence of a review of human resources plans/policies for social sustainability (OC7)	These technologies have been shown to be effective in dealing with COVID-19. They can help reduce and predict the spread of COVID-19 pandemic. Accordingly, the industries are recommended to the following technologies: Using the virtual reality Utilizing the Internet of things as new jobs inside industries poses a threat to the security of work Utilizing the cloud-computing technology to accelerate the provision of resources, diminish operating costs, and improve the potentials of running the infrastructures	Jeschke et al. (2017), Kiel et al. (2017), Bag and Pretorius (2022
8	Absence of employee safety and health (OC8)	This is a key subject facing manufacturing industries during the COVID-19 epidemic. Also, these technologies help improve the challenge mounted by the COVID-19 pandemic: Implementing and using the robotic and automated devices instead of employees in the company Applying collaborative robots Utilizing the digital technology of holography	Javaid et al. (2020)

Table 9 (continued)

No	SM Challenges	Solutions to handle SM challenges	Source
9	Imbalance in demand and supply (OC9)	This is the main challenge facing manufacturing industries at the time of COVID-19. This is because SM is not capable of offering orders due to the unexpected surge in demand and supply deficiencies around the world. Thus, these technologies help improve this challenge during the COVID-19 pandemic: Using big data analytics Integrating new technologies to obtain higher flexibility and resilience Using automated/guided vehicles	Raut et al. (2019)
10	Indeterminate return on investments (sanctions/ inflation) (OC10)	Return on investments is the major factor in efforts to deal with COVID-19. The manufacturing industries are recommended to adopt the following technologies: Specifying the flow of financial sources using the big data analytics technology Assessing the alternatives to return on investments Designing financial plans through smart vehicles Reassessing written plans by data analysis	Kiel et al. (2017), Khanfar et al. (2021)
11	Weak industrial infrastructures (OC11)	These technologies have been effective in dealing with COVID-19. They can help reduce and predict the spread of COVID-19 pandemic. Hence, the industries are recommended to use the following technologies: Using the cyber-physical systems including the interplay of machines, humans, and products Applying industrial Internet including intelligent machines, people, and advanced data analytics for the efficient management of the manufacturing processes	Mittal et al. (2018), Frank et al. (2019)

Table 9 (continued)

No	SM Challenges	Solutions to handle SM challenges	Source
12	Absence of trust among workforces (OC12)	Trust is a crucial element that can be of paramount importance during COVID-19: Using the block-chain The effective coordination of SM workforces leads to the development of the smart information and communication system Using information network including visibility and real-time information exchange	Zheng et al. (2022), Khanfar et al. (2021)
13	Delay in the supply of materials and essentials (OC13)	These technologies have been effective in coping with COVID-19. They can help reduce and predict the spread of COVID-19 pandemic. Accordingly, the industries are recommended to use the following technologies: Artificial intelligence Internet of things Digitalization and smart automation to report accessible resources and materials during manufacturing processes	Frank et al. (2019)
14	Lack of support from the government by regulations and policies (GC14)	During a COVID-19 pandemic, government seeks to create regulations and policies for supporting industries manufacturing. The industries are recommended to use the following technologies: Development of regulations for the labor force by the government based on "Industry 4.0 technologies and strategies" The provision of incentives by the government	Bag et al. (2020), Cioffi et al. (2020), Abubakr et al. (2020)

Table 9 (continued)

No	SM Challenges	Solutions to handle SM challenges	Source
15	Decrease in manpower (GC15)	Because of the COVID-19 pandemic, many industries around the world experienced a sharp decline in manpower. Hence, these technologies are recommended to adopt the following measures: Using cloud-based systems for training and education Using Internet of people	Raut et al. (2019), Abubakr et al. (2020), Khanfar et al. (2021)
16	Absence of subsidies and incentives (GC16)	This is the main challenge confronting manufacturing industries due to the COVID-19 prevalence. This is because SM is not able to cover the high costs incurred by sudden changes in providing materials worldwide. Thus, these technologies assist improving this challenge during the COVID-19 pandemic: Interoperability between industries and governments Income tax reduction Rewards for the implementation of green operations and activities to improve sustainable manufacturing processes	Alayón et al. (2022)
17	Deficiency of technology (ICT, IOT) to implement SM in manufacturing industries (TC17)	This is a key challenge facing manufacturing industries during COVID-19 epidemic. These technologies can help tackle this challenge: Adopting modern ICT Utilizing mobile devices Using machine to machine communication Selecting the platform and standards Utilizing the internet of data	Mittal et al. (2018), Frank et al. (2019), Khanfar et al. (2021), Bag and Pretorius (2022

Table 9 (continued)

No	SM Challenges	Solutions to handle SM challenges	Source
18	Lacking IT infrastructures (TC18)	These technologies are effective in the handling challenges mounted by COVID-19. They can help reduce and predict the spread of the COVID-19 pandemic. The industries are recommended to use the following technologies: Promote IT infrastructures and their availability, security, and scalability Adopting innovation cycles Using modern technologies (Web 3.0, big data, internet of things) Promoting cyber safety and security Using the internet of data	Moktadir et al. (2018), Kusiak (2018), Mittal et al. (2018), Khanfar et al. (2021)
19	High possibility of hazards (TC19)	These technologies can help overcome this challenge. However, companies need to be prepared to manage the possibility of risks during COVID-19 pandemic: Using industrial internet of things Identifying manufacturing hazards by smart software and digitalizing manufacturing processes Using big data analytics Applying cloud computing	Ardolino et al. (2018), Bressanelli et al. (2018)
20	Absence of forecasting on potential resources flow (TC20)	This is a key challenge facing manufacturing industries during COVID-19 epidemic. Also, these technologies help improve this challenge during the COVID-19 pandemic: Vertical integration Machine-to-machine communication enterprise resources	Gilchrist (2016), Jeschke et al. (2017), Bag et al. (2021), Khanfar et al. (2021)

BWM over AHP discussed in the literature, we have chosen BWM in this article. A comparison is drawn between BWM and AHP to confirm the choice of BWM. However, the purpose of this article is not to compare the outcomes of these two techniques. It is because the BWM method ensures consistency in the findings and has extensive application in different fields. Also, there are different techniques to rank options (alternatives) according to the attributed weights such as TOPSIS, VIKOR, SWARA, or others (Simanaviciene et al., 2012). Therefore, WASPAS was selected as the most suitable approach in this paper due to its specific utilization, solution accuracy, and ranking criteria, which are affected through the value of its control parameters. This paper employs effective approaches to rank the SM challenges and alternatives. Moreover, these methods are explained in detail along with their significance and stages.

In the following, the weights of challenges are measured using BWM. Initially, the results of analysis are presented to be evaluated for validity. The outcomes are consistent with the existing literature and feedback from experts. In the last step, the implications of findings are discussed. Table 6 displays and ranks challenges using BWM. The rankings are based on the weight of each item. As depicted in Table 6, 'lack of support from the government by enacting regulations and policies' (C14) is the main challenge and 'the absence of subsidies and incentives' (C16) is the least obstacle to the sustainable manufacturing processes. The third important challenge is 'the lack of proper technology (ICT, IOT) to implement SM in manufacturing industries' (C17). The cause group consists of the following barriers: C14 > C16 > C17 > C20 > C11 > C18 > C19 > C10 > C12 > C15 > C9 > C8 > C2 > C13 > C1 > C3 > C6 > C4 > C5 > C7.

After measuring the weights of challenges, the ranking of options was obtained using the WASPAS method. This is an effective MCDM technique, which as discussed in Section 2–2, is used to rank alternatives. Moreover, this method combines the weighted product model and the sum model. The different phase's methodology applied shows SM challenges in production industries. The resulting ranking of alternatives was obtained: A2 > A3 > A4 > A1. The relevant solutions to SM challenges are presented in Table 9.

In general, integrating these technologies and sustainable manufacturing can provide a wide range of valuable practices and solutions to different manufacturing industries. It includes technologies to gather, store, analyze, transfer, and correctly control and monitor information systems during the manufacturing processes. These technologies provide innovative techniques to mitigate the manufacturing challenges. These technologies are capable of remote control, using smart technologies that are suitable during COVID-19 pandemic. This revolution accelerates the digital transformations.

The framework for overall mitigation of sustainable manufacturing challenges, utilizing the above three dimensions, permits manufacturing industries in different fields to overcome important challenges to the SM such as poor IT infrastructures, delayed supply of materials and essentials, lack of trust between workforces, weak organizational culture to implement sustainable manufacturing practices, and so forth. However, each of the aforementioned dimensions is only obtained by specified applications, and that result warrants further research.

The general framework derived from the above studies and their suggestions is provided in Fig. 5. The adoption of the proposed framework can help mitigate the sustainable manufacturing challenges by these technologies, which further improves these challenges. These technologies help remove traditional strategies, prolong the beneficial life of the manufacturing equipment, reduce the unplanned downtime them, improve the production processes, decrease the consumption of resources and energy, and reduce costs. Also, these technologies exert a huge impact on the implementation of manufacturing industries' practices from

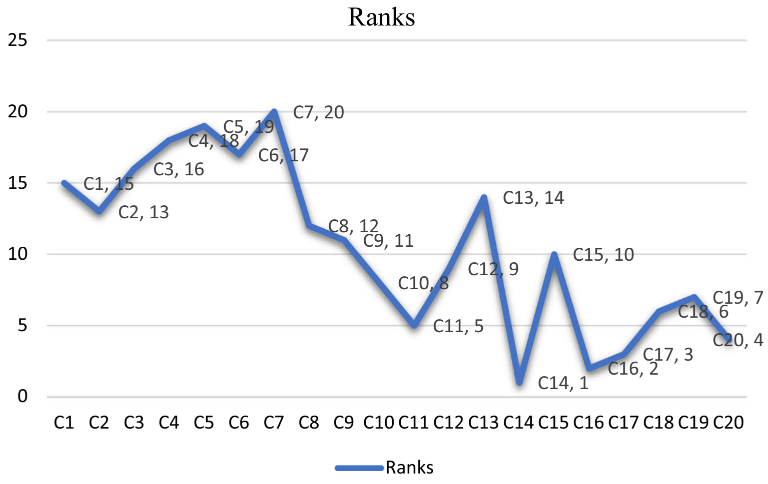

Fig. 3 Ranking the sub-criteria of SM

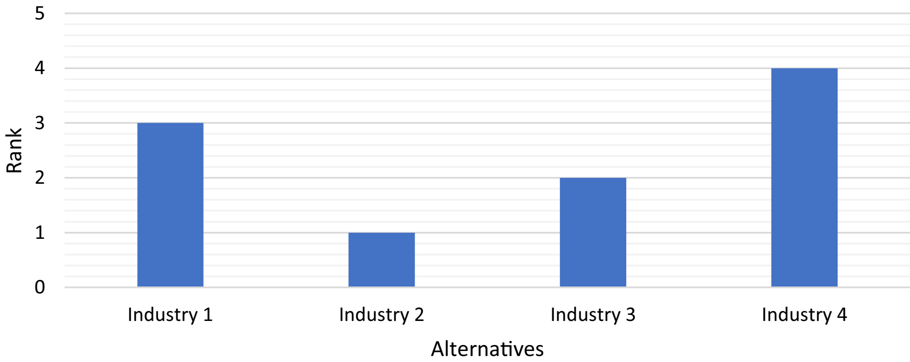

Fig. 4 Ranking SM alternatives

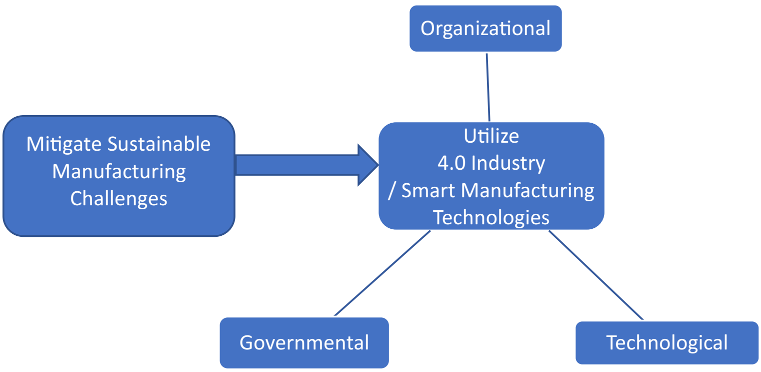

Fig. 5 The framework for mitigation of sustainable manufacturing challenges

diverse organizational, governmental, and technological aspects that have been investigated in this article.

6 Implications and recommendations

6.1 Implications for researchers and practitioners

There is scant research on sustainable manufacturing from these aspects, but this trend is changing. Many studies concentrate on a few aspects of the subjects related to SM. This article explores major practical and theoretical contributions to this field. The implications of this study for practitioners and scholars are presented below.

- Based on the above recommendations and discussions, a general framework was developed (as shown in Fig. 5). This introduced framework can help diminish SM challenges from a manufacturing point of view and achieve the sustainable manufacturing goals. The presented objectives exhibit that the implementation of sustainable manufacturing has a huge effect on practices manufacturing industries by targeting organizational, governmental, and technical aspects and utilizing these technologies to mitigate challenges.
- These new technologies can offer new digitalization strategies from a manufacturing perspective. In general, the integration of Industry 4.0 technologies and smart manufacturing technologies can present a wide range of advantageous activities such as cloud manufacturing, digitalization, and so forth which can help improve practices related to the manufacturing industries. This study provides an exhaustive set of solutions presented by different scholars to mitigate SM challenges.
- The continuous alteration of manufacturing needs has provoked managers and industries to identify main challenges to the efficient implementation of SM. This article offers an extensive list of challenges related to sustainable manufacturing during COVID-19 epidemic through various a review of research on this subject.
- It is difficult for manufacturing industries to implement all solutions practically. Therefore, in the present article, we have made a connection between solutions and challenges, which will help industries concentrate on high-intensity solutions and, finally, on the execution of other solutions.
- Managers in manufacturing industries are constantly in search of innovative ways to improve their sustainable manufacturing processes. For this purpose, the concept of "smart manufacturing and Industry 4.0" has gained significance recently. Furthermore, the literature suggests facilitators that can assist implement sustainable manufacturing processes in the industries. The list of smart manufacturing and Industry 4.0-based solutions can be helpful for researchers in this field. Also, it provides new frameworks and finally improves the acceptance of SM.
- Most of the frameworks presented in the literature have been confirmed using the case study approach. However, the current study employs a case study approach based on the MCDM to increase the applicability of the expanded framework.
- The results of this study provide the managers of manufacturing industries with in-depth insights into challenges and solutions related to their ranking using the hybrid BMW and WASPAS techniques.
- The literature has proposed some frameworks for increasing the acceptance of SM. Still, in terms of framework, various studies have explored challenges of a special frame structure. However, there is a lack of framework linking SM challenges to its solutions. Thus,

the framework explained in the current study can be of great value to the managers of manufacturing industries to promote SM acceptance.

6.2 Recommendations for policy makers

The acceptance of sustainable manufacturing in the manufacturing industries will mark the future of industries. These technologies have helped manufacturing industries offer sustainable products to users with based on environmental considerations, improving manufacturing processes with the digitalization of companies. Therefore, the government should promote strategies and policies favoring the acceptance of "Industry 4.0 and smart manufacturing." The policymakers must grant subsidies to the manufacturing industries for the implementation of the manufacturing processes and activities. Such initiatives will support the interest of manufacturing industries that have embraced green technology prompting them to produce their products by reflecting on smart manufacturing and Industry 4.0. The policymakers are recommended to hold educational courses to raise awareness about this subject and educate industries and customers about how to improve the performance of manufacturing practices. The final rankings of challenges and the solutions provided in this article can be used by other manufacturing industries to expand effective actions and strategies that could help enhance their economy.

7 Conclusion

The main innovation of this article is its exploration of key challenges to SM in the manufacturing industries and its enriching the body of literature on SM challenges in the manufacturing industries in Iran. Informed by the research goals, this study carries out a comprehensive literature review to investigate the important sustainable manufacturing challenges and connect them to Industry 4.0 and smart manufacturing technologies to reduce SM challenges. A unique set of 20 SM challenges and solutions is obtained from a review of literature and ideas of specialists, and the results are analyzed by techniques such as BMW and WASPAS. The results of case analysis indicate that organizational, governmental, and technical challenges explain SM implementation failures especially with the focus of a major global uncertainty of COVID-19. In this study, 20 common challenges were reviewed by BWM, among which "the lack of support from the government by enacting regulations and policies" (C14) and the absence of a "review of human resources" plans/policies for social sustainability" (C7) posed the greatest and least challenges to the sustainable manufacturing, respectively. After measuring the weights of challenges, the options were ranked. Further these challenges were mapped with their respective mitigating Industry 4.0 challenges; for instance, the Internet of things technologies provide innovative opinions (knowledge sharing/information exchange) for presenting new services to improve sustainable manufacturing operations. Finally, based on these findings and its relevant discussions, a recommended framework has been proposed. Despite of having several contributions, this study presents a set of SM challenges and solutions by investigating the literature and the view of specialists. Thus, it is recommended that researchers undertake a large-scale review to enhance the list drafted in this article. It is further necessary to use structural modeling technique, analytical network process, and assessment laboratory to describe structural relations between agents. The expanded framework can be expanded to other sub-categories of sustainable manufacturing to improve its applicability. The framework generated in this investigation is examined for its applicability across Iranian industries. From the authors' viewpoint, if this framework is used for developing economically, it won't be wrong. But it needs to modify applicability before actual implementation. The challenges and solutions introduced in the present article are particularly related to the promotion of environmental and economic aspects. Still, manufacturing industries are recommended to seek advice/information from specialists in developed countries to determine the country-specific challenges and investigate the possible solutions.

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Declarations

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