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Closing the gap: The role of distributed manufacturing systems for overcoming the barriers to manufacturing sustainability

GUPTA, Himanshu, LAWAL, Jennifer Nguseer, ORJI, Ifeyinwa Juliet and KUSI-SARPONG, Simonov <http://orcid.org/0000-0003-1618-2518>

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Himanshu Gupta
Department of Management Studies, Indian Institute of Technology (Indian School of Mines)
Dhanbad, India
Email: himanshuguptadoms@gmail.com

Jennifer Lawal
Portsmouth Business School, University of Portsmouth
United Kingdom
Email: jennifernlawal@gmail.com

Ifeyinwa Juliet Orji
Research Centre for Smarter Supply Chain, Dongwu Business School, Soochow University,
215021, Suzhou, Jiangsu Province, China
Email: ifyorji09@yahoo.com

Simonov Kusi-Sarpong*
Southampton Business School, University of Southampton, Southampton S017 1BJ,
United Kingdom
Email: simonov2002@yahoo.com

*Corresponding author: **Simonov Kusi-Sarpong** <simonov2002@yahoo.com>

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Closing the gap: The role of distributed manufacturing systems for overcoming the barriers to manufacturing sustainability

Abstract- The demand for distributed manufacturing systems (DMS) in the manufacturing sector has notably gained vast popularity as a suitable choice to accomplish sustainability benefits. Manufacturing companies are bound to face critical barriers in their pursuit of sustainability goals. However, the extent to which the DMS attributes relate to sustainable performance and impact on critical barriers to sustainability is considerably unknown. To help close this gap, this study proposes a methodology to determine the relative importance of sustainability barriers, the influence of DMS on these barriers, and the relationship between DMS attributes and sustainable performance. Drawing upon a rich data pool from the Chinese manufacturing industry, the Best-Worst Method (BWM) is used to investigate the relative importance of the sustainability barriers and determine how the DMS attributes influence these barriers and relate to sustainability. The study findings show that 'organizational barriers' are the most severe barriers and indicate that 'reduced carbon emissions' has the highest impact on 'organizational' and 'socio-cultural barriers' whereas 'public approval' has the highest impact on 'organizational barriers. The results infer that 'reduction of carbon emission' is the DMS strategy strongly linked to improved sustainable performance. Hence, the results can offer in-depth insight to decision-makers, practitioners, and regulatory bodies on the criticality of the barriers and the influence of DMS attributes on the sustainability barriers and improve sustainable performance for increased global competitiveness. Moreover, our study offers a solid foundation for further studies on the link between DMS and sustainable performance.

1. Introduction

Industries' environmental sensitivity is on the ascent because of increased demands from customers and regulatory bodies (Man et al, 2020; Rajesh, 2020). Moreover, numerous manufacturing organizations have faced tremendous financial losses due to environmental fines, energy consumption costs, etc. (Kusi-Sarpong et al., 2016) caused by their ignorance of the advantages of implementing sustainability (Yadav et al, 2020). Hence, several firms have started integrating innovative initiatives to address sustainability issues within their manufacturing operations and supply chains (Kusi-Sarpong et al., 2019, Gupta et al., 2020a). Supply chain innovations have matured as an effective way to promote sustainability (Adamson et al, 2017; Behnam et al, 2018; Belz, 2013; Horn and Brem, 2013; Mousavi and Bossink, 2017; Seebode et al, 2012; Yoon et al, 2016; Zailani et al, 2015). Currently, Distributed Manufacturing Systems (DMS) is getting mounting recognition as an innovative strategy for decentralized networks of adaptable and flexible mini factories with the capacity of maximizing economic gains and reducing negative environmental and social consequences. As manufacturing companies face the challenge of increasing global competition and energy-saving requirements, it becomes essential to seek out distributed systems to minimize energy waste and costs (Zou et al, 2017; Ishizaka et a., 2020). DMS comprises technology, systems, and strategies that can alter the economics, and organization of production, particularly concerning site and scale (Durach et al, 2017; Srai et al, 2020; Gupta et

al., 2020b; Khan et al., 2021a). DMS is a profoundly adaptable and versatile system for manufacturing components located in different physical environments then gathered in a particular place for assembling purposes (Srai et al, 2016; Srai et al, 2020). Indeed, the shift from traditional manufacturing systems to cloud-based and geographically distributed manufacturing systems represents a possible manufacturing strategy to produce demand-prompted customized products near to the consumption point (Rauch et al, 2018). Moreover, customized production has emerged because of increasing customer demand for more customized products (Kim et al, 2020). In today's highly competitive and dynamically global business scenario, DMS can potentially result in modern organizational models for less and scalable manufacturing units in distributed manufacturing networks essential to satisfy actual customer specifications and actualize sustainable supply chains (Matt et al, 2015).

Consequently, a unique feature of DMS is its geographic dispersion of operations and the proximity of the supply chain to the consumer which could result in environmental gains that can aid in actualizing sustainability goals (Luthra et al, 2019; Monch and Shen, 2021; Moreno et al, 2019; Srai et al, 2020). Considered a novel manufacturing innovative strategy, DMSs are utilized to modify the scale and location of manufacturing facilities for improved sustainability of production activities (Dertinger et al, 2020; Gimenez- Escalante et al, 2020). In essence, DMS is a broad term that comprises industrial measures, customer requirements, new technologies, and political issues, along with socioeconomic and environmental perspectives for adequate evaluation of future production firms (Kumar et al, 2020). The main benefits and aspects of DMS are greater flexibility to indicate customer demands, lower logistics costs, regulated material and energy use, reduced carbon emissions, in-situ recycling, shorter delivery time, and greener supply chain (Durach et al, 2017; Kohtala, 2015; Kumar et al, 2016; Matt et al, 2015). DMS is considered an essential innovative strategy, that when implemented in manufacturing companies, can improve sustainable performance and increase global competitiveness. However, implementing sustainability initiatives in the manufacturing sector for achieving sustainable performance is usually hindered by numerous barriers. Yet studies that simultaneously establish the critical sustainability barriers in the manufacturing sector, assess the impact of DMS on the sustainability barriers, and determine the link between DMS and improved sustainable performance are currently non-existent in extant literature. This research gap ought to be bridged because a broad understanding of the critical sustainability barriers and the impact of DMS on these barriers is fundamental for devising suitable DMS strategies essential to eliminate the sustainability barriers and accomplish sustainable targets. It is especially significant since the manufacturing sector is in dire need of innovative approaches that have the potential to minimize detrimental environmental and social harm (Kusi-Sarpong et al, 2019; Ahmed et al, 2020; Ardito et al, 2019; Ardito et al, 2020). In essence, those manufacturing companies that fail to implement innovative strategies for sustainability benefits are prone to be made obsolete and become disrupted in a process described as "the perennial gale of creative destruction" (Luqmani et al, 2017).

In this study, we focus on the Chinese manufacturing sector that has experienced a sharp increasing trend in environmental awareness and protection in recent years due to rapidly rising industrial modernization and economic growth, which led to environmental issues (Li et al, 2019). The manufacturing sector in China, just like that of India, which is characterized by recent and

potential future growth forecasted at US$1 trillion by 2025 (Gupta et al, 2020a), and that of Thai that drives economic growth in Thailand still face huge difficulties to implement sustainability (Piyathanavong et al, 2019; Shen and Lin, 2020). However, the Chinese manufacturing sector is significant, given China's role as the world's new factory, and the Chinese government's utilization of innovative industrial development measures to strike a balance between economic advancements and the environmental problems caused by its burgeoning manufacturing sector (Geng et al, 2017). The Chinese government has launched a target since the 11th five-year-plan, to mitigate environmental pollution, reduce waste, and even assigned specific targets to the manufacturing sector (Jiang et al, 2021). These might be attributable to the fact that globally, China emits the highest percentage of carbon emissions, and the Chinese manufacturing sector being the largest contributor and specifically accounted for 12.8% of the world in 2016 (Fan et al, 2021; Lin and Chen, 2018; Lin and Chen, 2020; Liu et al, 2019a; Liu et al, 2019b). Despite the crucial role of the manufacturing industry in the Chinese market traditional manufacturing processes that lack supply chain capabilities are still utilized in the industry resulting in low value-added operations. Additionally, the Chinese manufacturing industry aspires to cope with dynamic and customized customer needs and must integrate industrial operations in a globalized network for increased competitiveness. In the meantime, the green growth level of the Chinese manufacturing industry has declined. Gloomily also, the green growth situation is not optimistic (Qu et al, 2020). Presently, the Chinese manufacturing firms are facing a huge burden of upgrading the modes of production of industries with high consumption and high pollution to align with green initiatives (Zhang et al, 2021). Therefore, the Chinese manufacturing sector has started to become more environmentally conscious and is considering implementing DMS as a novel innovative strategy for pursuing and achieving sustainable development. Notably, barriers/challenges are bound to exist which deter the progression of sustainability in the Chinese manufacturing industry during implementing innovative strategies like DMS. Hence, the motive behind this study is to investigate the criticality of barriers to implementing sustainable strategies in the Chinese manufacturing industry and the impact of DMS attributes on these barriers. This study also exists, to effectively establish how DMS attributes relate to improved sustainable performance. Overall, the current study exists to consider the following research questions:

- How significant (severe) are the barriers that hinder the implementation of innovations for improved sustainable performance in the manufacturing sector?
- How do DMS attributes impact critical sustainability barriers and relate to improved sustainable performance in the Chinese manufacturing industry?

In answering the above-stated research questions, this study makes notable contributions to academia and practice. The novelty of the current study lies in introducing a decision support system based on the Best-Worst Method (BWM) to quantify the criticality of sustainability barriers and the impact of the DMS attributes on these barriers and further shed light on how the DMS attributes relate to improved sustainable performance. The BWM, just like any other multi-criteria decision-making model, is regarded as a suitable method for evaluating the relative importance of multi-facet factors. Several scholars have become interested in BWM due to the effectiveness of this method in decreasing the times of pairwise comparisons and the excellent performance of this method in upholding consistency between decisions (Gupta and Barua, 2016; Kusi-Sarpong et al,

2019; Orji et al, 2019; Xiaomei et al, 2019; Ahmadi et al, 2020). More specifically, this study pioneers the application of BWM in DMS research (Dertinger et al, 2020; Gorecki et al, 2020; Rauch et al, 2018; Sun et al, 2020) and even the utilization of 'additive value function' in the BWM to effectively determine the overall scores of DMS attributes for accurate quantification of the link between DMS and sustainable performance. Besides, this study presents a novelty by being conducted in a strategic emerging market-China, which is typically regarded as the 'factory of the world'. While DMS research has seen applications in industrialized economies (Lu and Asghar, 2020; Kim et al, 2020; Kumar et al, 2020; Rauch et al, 2018; Shokrani et al, 2020; Sun et al, 2020), there remains significant research gap to consider the emerging markets as well. China provides a suitable arena for enlarging the research stream on DMS since it is expedient for Chinese manufacturing firms to aspire to achieve sustainable objectives for increased global competitiveness. This is because China, like other emerging countries such as India and Brazil, is ranked very low in the global competitive index (Singh et al, 2021). Hence, this study sheds light on the significant sustainability barriers in the Chinese manufacturing industry and supports industry experts and policymakers to establish DMS strategic plans to eliminate the sustainability barriers. Moreover, by establishing a strong association between improved sustainable performance and DMS strategies, this study also provides useful guidelines to regulatory agencies interested in encouraging manufacturing companies to implement DMS for sustainability gains.

The remaining sections of this paper are structured as follows: In Section 2, the relevant literature on sustainability in the manufacturing sector and BWM in related studies are presented. The procedure for identifying the barriers to advancing sustainability and attributes of DMS is presented in Section 3. The proposed methodology for analyzing the barriers to advancing sustainability and attributes of DMS is presented in Section 4. Section 5 presents and discusses the research findings in the current study while providing practical and managerial implications. Section 6 presents the results of sensitivity analysis. Section 7 provides the conclusion and potential areas for further studies.

2.   Literature review

2.1.   *Sustainability in the manufacturing sector*

Broadly, our study adds to the burgeoning stream of studies that focus on improving sustainable performance in the Operations Management domain. Even though several studies propose innovative sustainable strategies in the extant literature (Caiado et al, 2017; Damert et al, 2017; Esmaeilian et al, 2016; Fernado and Hor, 2017; Gandhi et al, 2018; Golini et al, 2014; Gupta et al, 2018; Holmström et al, 2017; Ingarao, 2017; Kusi-Sarpong et al, 2019; Latif et al, 2017; Lim, 2017; Nawaz and Koç, 2018; Sroufe, 2017; Petruzzelli and Lerro, 2020; Yazan et al., 2011) there is yet an eminent requirement for sustainable strategies in the manufacturing industry (Rauch et al, 2016; Reinikainen et al, 2016; Roos et al, 2016; Singla et al, 2017; Stacchezzini et al, 2016). In recent times, DMS are being promoted as innovative strategies for improved sustainable performance in manufacturing organizations. Previous studies have shown the impact of DMS in the industrial sector. Below, we discuss a few papers in this field. Yew et al (2016), described in their work, an augmented reality based DMS that aims to hugely advance the information perception of the various type of workers in a production facility and ensures communication with

manufacturing software is natural and effective. Helo et al (2014) illustrated the issues and problems in the management of distributed manufacturing in a multi-company supply chain and processes these further as aspects of new Information Technology (IT) systems. They infer that cloud-based manufacturing presented a technical solution for the needs and developed a prototype system to aid distributed manufacturing. Adamson et al (2017) presented the concept of feature-based manufacturing for adaptive equipment control and resource-task matching in distributed and collaborative Cyber-Physical Systems (CPS) manufacturing environments. Fay et al (2015) proposed a model-based engineering (MBE) method for distributed manufacturing automation system, which allows considering non-functional requirements along the workflow. Valilai and Houshmand (2013) presented a collaborative and integrated platform in their work to support DMS using a service-oriented approach based on the cloud computing paradigm. Yaqiong et al (2011), in their study, detailed the literature review of fuzzy theory applied in quality management of DMS.

Guo et al (2015), in their work, integrated Radio-Frequency Identification (RFID), cloud technology, and intelligent techniques for monitoring and scheduling to increase efficiency in a distributed manufacturing environment. Zhang et al (2013) presented a novel time-aware probabilistic Bayesian approach for recommending a few optimal manufacturing services based on the user preference for an initial manufacturing service in distributed manufacturing environments. Chan and Chan (2010) studied flexibility and adaptability in delivery quantity and due date through which DMS can increase the performance in a network of two-level multi-product Make-to-Order supply chains. Li et al (2017) proposed a novel scheduling algorithm for DMSs based on Petri net models and genetic algorithms to solve the scheduling problem in distributed manufacturing systems with the objective of mining total energy consumption. Some researchers have also provided a sustainability perspective of the implementation of DMS in manufacturing firms. For instance, Rauch et al (2016) proposed DMS for sustainable production in emerging markets with analysis on the effect on sustainability based on the traditional dimensions of sustainability. Salido et al (2017) in their work developed techniques with significant potential to save energy and actualize sustainable goals based on the rescheduling strategy in dynamic job-shop scheduling in distributed manufacturing systems. Rauch and Dallesega (2017) presented the concept of DMS for more sustainable supply chains while considering the economic, ecological, social, and institutional sustainability. Within the above-mentioned studies, the lack of studies on the relative importance of significant barriers that hinder the actualization of sustainability benefits and the impact of DMS on such barriers has been observed. Thus, we propose to apply a suitable method to investigate the relative importance of sustainability barriers and likewise determine the impact of the aspects of DMS on these barriers.

2.2. Application of BWM

From a methodological perspective, our study is identified with the stream of research that determines the relative importance of system criteria through estimating the pairwise comparisons between the system criteria. Indeed, the BWM has seen successful applications in the manufacturing sustainability domain. For instance, Malek and Desai (2019) prioritized the barriers to implementing sustainable manufacturing by calculating their weights through the application of

BWM in an Indian manufacturing organization. Likewise, Singh et al (2021) in their study, investigated and prioritized the factors which encourage the effective adoption of environmental Lean Six Sigma in manufacturing firms. Yadav et al (2020) developed a framework to increase sustainability adoption across manufacturing firms of developing countries using industry 4.0 technologies and applied the robust BWM to determine the importance of the factors in the developed framework. Additionally, Ahmadi et al (2017), developed a framework to assess the social sustainability of manufacturing firms using BWM. Kusi-Sarpong et al (2019), utilized the BWM to evaluate a framework of identified drivers of sustainable supply chain innovation in the manufacturing sector. In a similar vein, Gupta and Barua (2016), in their work, investigated the enablers contributing significantly towards the technological development of manufacturing Small and Medium-sized Enterprises (SMEs) using the BWM. Munny et al (2020) developed a framework based on BWM and applied such to a footwear manufacturing company to integrate social sustainability practices into operations and supply chains. Likewise, Gupta et al (2020a) used the BWM to investigate and rank the barriers to sustainable supply chains and their overcoming strategies with application in the Indian manufacturing industry.

Given the extensive and successful application of the BWM in the available literature, it becomes convincing that a suitable methodology is developed in our study based on BWM to effectively find the relative importance of the sustainability barriers in the Chinese manufacturing sector. Furthermore, the proposed BWM will be applied to reveal the relationship between the DMS attributes and sustainable performance in addition to the impact of the attributes of DMS on the contexts of the sustainability barriers in the Chinese manufacturing industry.

3. The procedure for identifying both sustainability barriers and DMS attributes.

The manufacturing sustainability barriers and the DMS attributes were identified by searching the keywords, titles, and abstracts of journal contributions in the largest database, Scopus, with keywords such as "distributed manufacturing systems", "attributes", "strategic plans", "Chinese manufacturing sector", "barriers" and "sustainability". After identifying 15 barriers and 6 DMS attributes (see Table 1), the experts in this study were requested to give their opinions on whether the identified criteria are relevant to their company or not while also requesting that they provide any missing criteria to ensure inclusivity of required information and content validity. All the identified criteria were confirmed/finalized by determining the mode of the responses of the experts, thus ensuring the validity of the identified criteria. The experts also agreed that there is no missing information related to the identified criteria, thereby confirming information inclusivity.

3.1. Identification and refinement of sustainability barriers

We identified and finalized 15 barriers to advancing sustainability categorized into three aspects including, organizational, socio-cultural, and geographical via available published literature and experts' inputs (See Table 1) in our study. We now overview these three aspects using the barriers identified and categorized under each of them.

3.1.1 Organizational barriers

Organizational barriers are still the priority of engineering managers in advancing sustainability in the manufacturing sector. Previous research works suggested *Inefficient technology* (OB$_1$) entails the underperformance of available technology to advance sustainability in the industry (Annuziata et al, 2018; Damert et al, 2017). *Insufficient commitment of top management* (*OB$_2$*) refers to the inadequate support of high-ranking executives in the industry to implement sustainability (Govindan et al, 2016; Luthra et al, 2016). *Financial constraints* (*OB$_3$*) are associated with a lack of available capital and budget to actualize sustainable objectives in the industry (Damert et al, 2017; Fernado and Hor, 2017). *Lack of skilled workforce* (*OB$_4$*) refers to unskilled labor or workers without the necessary expertise to implement sustainability in the industry (Esmaeilian et al, 2016; Luthra et al, 2016). *Absence of a globalized network* (*OB$_5$*) relates to an unintegrated system of operations and activities associated with achieving sustainability in the industry (Schröter et al, 2017; Stacchezzini et al, 2016).

Table 1   Proposed evaluation criteria

Category	Criteria	References
Organizational barriers	Inefficient technology (*OB$_1$*) Insufficient commitment of top management (*OB$_2$*) Financial constraints (*OB$_3$*) Lack of skilled workforce (*OB$_4$*) Lack of a globalized network (*OB$_5$*)	Annuziata et al, 2018; Dong and Bi, 2020; Fernado and Hor, 2017; Gardas et al, 2019; Gupta et al, 2020a; Moktadir, et al 2020; Virmani et al., 2020; Orji, 2019; Schröter et al, 2017; Yadav et al, 2020; Raj et al, 2020
Socio-cultural barriers	Absent corporate social responsibility (*CB$_1$*) Reluctant behavior towards sustainability (*CB$_2$*) Low market growth potential (*CB$_3$*) Ineffective communication (*CB$_4$*) Non-compliance to policies (*CB$_5$*) Inadequate government laws and regulations (*CB$_6$*)	Brunel et al, 2019; Caiado et al, 2017; Kusi-Sarpong et al, 2019; Lim et al, 2017; Damert et al, 2017; Luo et al, 2017; Bux et al, 2020; Orji, 2019; Orji et al, 2019; Schröter et al, 2017; Shou et al, 2020; Singla et al, 2017; Singh et al, 2020
Geographical barriers	Unfavorable climatic conditions (*GB$_1$*) Unsustainable landscape (*GB$_2$*) Scarcity of natural resources (*G$_3$*) Political instability (*GB$_4$*)	Bouaichi et al, 2019; Ulucak et al, 2020; Han et al, 2017; Liu et al, 2020; Moktadir et al, 2019; Nawaz and Koc, 2018; Zhang et al, 2018; Kumar et al, 2020; Wang et al, 2021
Distributed manufacturing systems (DMS) attributes	Reduced carbon emissions (*A$_1$*) Information disclosure (*A$_2$*) Public approval (*A$_3$*) Respect for policy (*A$_4$*) Improved brand/reputation (*A$_5$*) Lower logistics costs (*A$_6$*)	Kumar et al, 2020; Bouzon et al, 2018; Damert et al, 2017; Feernado and Hor, 2017; Gandhi et al, 2018; Han et al, 2017; Lim et al, 2017; Mohanty and Shankar, 2017; Jan et al, 2020; Bian and Xuan, 2020

3.1.2 Socio-cultural barriers

Social-cultural barriers in this study cover six criteria namely, absent of social responsibility, reluctant behavior towards sustainability, ineffective communication, low market growth potential, lack of respect for policy, and lack of adequate government regulations to provide insight into the socio-cultural barriers. *Absent corporate social responsibility* (*CB$_1$*) focuses on the absence of pressure from the public, non-governmental organizations, and media to implement sustainable objectives (Damert et al, 2017; Dutta et al, 2016). *Reluctant behavior towards sustainability* (*CB$_2$*) refers to the reluctance towards sustainable products and innovative methods exhibited due to lack

of awareness on the benefits of sustainability and negative green brand image (Egels-Zandén and Rosén, 2015; Govindan et al, 2016). *Low market growth potential* (*CB₃*) relates to the low output volume which the market for industrial products is expected to achieve due to low awareness and low population growth rate (Caiado et al, 2017; Lim et al, 2017). *Ineffective communication* (*CB₄*) is associated with the difficulty in or barrier to effectively convey information within the industry (Roos et al, 2016). The inadequate policy formulation and implementation on sustainability in the industry are referred to as *Non-compliance to policies* (*CB₅*) (Orji et al, 2015; Schröter et al, 2017; Singla et al, 2017). *Inadequate government law and regulations* (*CB₆*) focuses on the non-availability of necessary government environmental laws and policies to encourage the implementation of sustainability (Govindan et al, 2016; Roos et al, 2016).

3.1.3 Geographical barriers

Although geographical barriers constitute challenges to implementing sustainability, they are rarely taken into considerations due to their complexity. In our study, four criteria namely unfavorable climatic conditions, landscape, scarcity of natural resources, and political instability are proposed to provide an in-depth understanding of geographical aspects. *Unfavorable climatic conditions* (*GB₁*) refer to unpleasant and physically discomforting weather conditions that serve as a barrier to actualizing policy plans for sustainability goals (Nawaz and Koc, 2018; Zhang et al, 2018). *Unsustainable landscape* (*GB₂*) represents scenery that is irresponsive to the environment and poses a challenge to implementing sustainability (Reinikainen et al, 2016). The lack of naturally occurring substance or feature of the environment is referred to as *scarcity of natural resources* (*GB₃*) (Han et al, 2017; Orji and Wei, 2016). The absence of integrity and durability of government regime is termed *Political instability* (*GB₄*) (Kumar et al, 2020).

3.2 Identification of attributes of distributed manufacturing systems

We also identified and finalized 6 attributes of DMS to advancing sustainability from available published literature and experts' inputs (See details in Section 3) in this study.

The aspects of DMS include reduced carbon emissions, public approval, information disclosure, respect for policy, improved brand/reputation, and lower logistics cost. *Reduced carbon emissions* (*A₁*) entail the act of reducing and eliminating damage to the environment caused by the discharge of pollutants especially carbon emissions, leading to sustainable outcomes (Feernado and Hor, 2017; Reinikainen et al, 2016). *Information disclosure* (*A₂*) significantly enhances the ease of information sharing on finances and other relevant industrial operations thereby leading to a shared understanding of performance impacts (Lim et al, 2017; Orji et al, 2015; Reinikainen et al, 2016). *Public approval* (*A₃*) is associated with the satisfaction of consumers on industrial products, thus improving reliability and market growth potential (Jan et al, 2020; Gandhi et al, 2018; Stephanides et al, 2019). *Respect for policy* (*A₄*) involves adhering to the formulation and implementation of proactive policies within the organization, leading to competitive advantage (Orji, 2019; Orji and Wei, 2015; Singla et al, 2017). *Improved reputation/social brand* (*A₅*) defines the favorable perception of industrial operations and products which tend to enhance consumer awareness and attitude towards sustainability (Gandhi et al, 2018; Han et al, 2017). Furthermore, *lower logistics costs* (*A₆*) are a benefit associated with adopting DMS which entails the reduction

in the cost of conveying materials and products in the supply chain network thereby resulting in reducing a significant proportion of business costs (Engblom et al, 2012; Turkensteen et al, 2011; Turkensteen and Klose, 2012).

4. Research methodology

In this study, the research methodology is proposed based on the BWM for investigating the relative importance of identified sustainability barriers in the Chinese manufacturing industry and the impact of the aspects of DMS on these barriers. The detailed research methodology proposed in this study is shown in Fig. 1.

4.1. BWM

The BWM is a multi-criteria decision-making method (MCDM), proposed by Rezaei (2015) and predicted to increase in applications because it provides a structured way of carrying out pairwise comparisons which can aid in eliminating numerous workloads and complexity for experts (Gupta, 2018; Xiaomei et al, 2019). Published research works exist on various MCDMs in extant literature such as Technique for Order of Preference by Similarity to Ideal solutions (TOPSIS) (Abootalebi et al, 2019; Mathew et al, 2020), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) (Mousavi and Lin, 2020), Multiplicative Multi-Objective Optimization by Ration Analysis (MULTIMOORA) (Sarabi and Darestani, 2021; Wang et al, 2021), Analytical Hierarchy Process (AHP) (Yaraghi et al, 2014) and Decision Making Trial and Evaluation Laboratory (DEMATEL) (Amirghodsi et al, 2020; Farooque et al, 2020; Khan et al, 2021b; Cui et al, 2020). Compared with other MCDMs, the BWM is considered preferable due to its consistency during rational decision making (Kheybari et al, 2019; Rezaei, 2015). While using full matrix-based methods like AHP, the number of pairwise comparisons increases, making these methods time consuming (Rezaei, 2015). BWM also has the advantage of reducing the anchoring bias of decision-makers because it uses two opposite reference vectors in a single optimization problem. Since the sustainability barriers and the impact of DMS attributes to such barriers and even the link between DMS attributes and sustainable performance are dependent on each other, effective analysis of such issues should consider the interrelationships. But then, these interrelationships are inherent within the system elements and although other MCDMs like DEMATEL and AHP can be applied in such scenarios, the BWM outperforms them in accurately determining the pairwise comparisons of system elements (Razaei, 2015; Orji et al, 2020). The BWM has been successfully applied in various real-world decision-making scenarios (Gupta and Barua, 2016; Kusi- Sarpong et al, 2019; Orji et al, 2019; Orji et al, 2020; Tarei et al., 2021; Xiaomei et al, 2019). The advantage of the BWM when compared with other MCDMs lies in its simplicity, reliance on less pairwise comparison data, and effectively consistent results (Moktadir et al, 2020; Agyemang et al, 2020), which motivated its use in this study. Thus, we have applied the BWM to determine the relative importance of the identified manufacturing sustainability barriers for effective prioritization. Generally, the steps to applying the BWM are as follows:
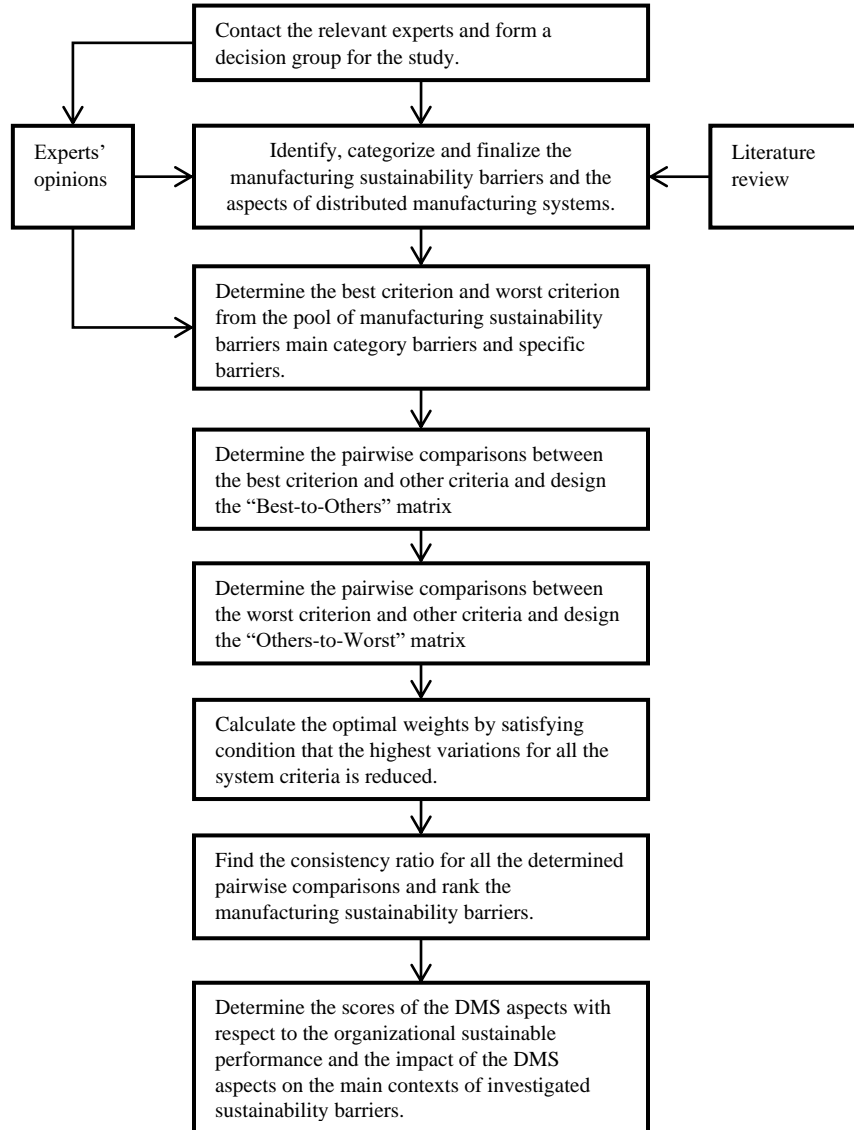
Fig. 1 Proposed evaluating methodology

Step 1: Identify the system criteria.

In this step, the system criteria which comprises the main category barriers (organizational, socio-cultural, and geographical) and specific manufacturing sustainability barriers are identified from the literature review and experts' inputs.

Step 2: Choose the best and worst system criteria.

Within this step, the experts choose the best and worst criteria from the pool of identified system criteria using their respective perspectives.

Step 3: Determine the pairwise comparisons between the best and other criteria.

Here, the pairwise comparisons between the best and other criteria are determined by the experts aided by the linguistic scale with scores ranging from 1 to 9 shown in Table 2. The pairwise comparisons provide more insight into how important each the best criterion in comparison with other system criteria. The resulting matrix known as "Best-to-Others" matrix is expressed as follows:

$$C_w = (c_{W1}, c_{W2}, ..., c_{Wm})$$

Where c_{Wj} indicates the preferential judgment of the best criterion T over a system criterion j among the system criteria and $c_{wT} = 1$.

Table 2   Linguistic scale for BWM preferential judgments

Linguistic semantics	Scores/Values
Equally important	1
Equal to moderately more important	2
Moderately more important	3
Moderately to strongly more important	4
Strongly more important	5
Strongly to very strongly more important	6
Very strongly more important	7
Very strongly to extremely more important	8
Extremely more important	9

Step 4: Determine the pairwise comparisons between other criteria and the best criterion.

In this step, the "Others-to-Worst" matrix is designed from the determined pairwise comparisons between the other system criteria and the worst criterion with the aid of the scores in the linguistic scale shown in Table 2. The resulting "Others-to-Worst" matrix is shown as follows:

$$C_Q = (c_{Q1}, c_{Q2}, ...c_{Qn})^p$$

Where, c_{Qj} is used to represent the preferential judgment of a system criterion j among other system criteria identified in Step 1 and the worst system criterion K, and $c_{QQ} = 1$.

Step 5: Calculate the optimal weights $(h^*_1, h^*_2, ..., h^*_n)$

In this step, the optimal weights of the system criteria are computed by ensuring that the highest absolute variations for each identified system criterion j is reduced over the following vector set $\{|h_w - c_{Wj}h_j|, |h_j - c_{jQ}h_Q|\}$

A minimax model can be developed as:

$$\min_j \max \{|h_w - c_{Wj}Q_j|, |h_j - c_{jQ}Q_q|\} \tag{1}$$

Subject to:

$$\sum_j h_j = 1$$

And $\qquad\qquad\qquad h_j \geq 0$, for each identified system criterion j

The above stated model can be solved by transforming it to form the linear programming model presented below:

$$MinZ^d \tag{2}$$

Subject to:

$$\left| h_W - ch_j \right| \leq Z^d, \text{ for each identified system criterion } j$$

$$\left| h_j - ch_Q \right| \leq Z^d, \text{ for each identified system criterion } j$$

$$\sum_j h_j = 1$$

$$h_j \geq 0, \text{ for each identified system criterion } j$$

Solving the second model, which is the linear programming model, will lead to optimal vector weights $(h^*_1, h^*_2, \ldots, h^*_n)$ and the optimal vector value Z^D. Generally, a consistency (Z^D) of the pairwise comparisons is estimated and a value that is close to 0 is regarded as more desirable (Rezaei, 2015).

Step 6: Determine the overall scores of DMS attributes.

After estimating the global optimal weights of each sustainability barrier by finding the product of the weights of the main barrier and the specific barrier, we further apply the additive value function to compute the overall score of the DMS attributes using the following equation (Gupta et al, 2020a):

$$P_i = \sum_{j=1}^{n} h_j v_{ij} \tag{3}$$

Where, the index of any DMS attribute is denoted by i, the normalized score of the DMS attribute i with respect to criterion j is denoted by v_{ij}. The score of v_{ij} can be determined using the Equations (4) and (5) which signifies positive criteria (for benefit criteria) and negative criteria (cost criteria) respectively.

$$P_{ij} = \frac{y_{ij}}{\sum_j y_{ij}} \qquad \text{for each value of } i \tag{4}$$

$$P_{ij} = \frac{\dfrac{1}{y_{ij}}}{\displaystyle\sum_{j} \dfrac{1}{y_{ij}}} \qquad \text{for each value of } i \tag{5}$$

Where, y_{ij} represents the overall score of the DMS attribute i with regards to criterion j.

4.2. Data sourcing

We collected data with the aid of designed questionnaires from ten manufacturing companies that specialize in producing automobile parts (shock absorbers) in China with annual revenue ranging from 30 million – 80 million Chinese RMB and the number of employees less than 500. Specifically, the experts that participated in the survey include one General Manager, three Operations Managers, three Production Managers, and three R & D Managers in the middle and higher-level managerial positions with up to ten years of experience in the company and at least a bachelor's degree qualification (see Table 3 for demographic characteristics of experts). These middle and higher-level managers are deemed knowledgeable to complete a survey on their company's operations since they are involved in strategic decisions of their company and so ensure a good firm representation (Orji et al, 2019). Two sets of questionnaires were issued to the ten experts to collect data. The purpose of the first set of questionnaires was to finalize the manufacturing sustainability barriers and attributes of DMS that were identified from the literature review while the second set aimed to find the relative importance of the barriers and the impact of the attributes on the barriers. Conventionally, the questionnaires were designed to contain questions that can determine the demographics of the experts such as their years of experience, job category, and others. In the first set of questionnaires, the experts were required to indicate if the identified system criteria are 'applicable' or 'not applicable' to the manufacturing sector particularly in automobile parts manufacturing as is the case in this study.

Table 3   Demographics characteristics of experts in this study

Characteristic	Number of experts
Age	
25-35	3
36-55	7
Gender	
Male	7
Female	3
Highest educational qualification	
Bachelors	2
Postgraduate	8
Years of experience	
10-15	2
15-20	3
Above 20	5
Managerial roles	
R& D manager	3
Production manager	3
Operations manager	3
General manager	1

Firm size	
10-200	7
210-500	3
Annual revenue (million RMB)	
0-50	7
60-100	3

Some measures such as assuring experts of the confidentiality of their response, sending reminder phone calls and email conversations, and even personal visits were taken to increase the rate of survey response and reduce the response bias among experts. Measures taken resulted in 10 completed questionnaires from the experts out of 20 questionnaires initially sent out, a response rate of 50%. We have employed the BWM as the evaluating methodology in our study which does not require a large sample size for effective decision making even as prior studies have applied BWM for successful evaluations with a sample size of at least five (Gupta and Barua, 2016; Gupta et al, 2020a; Kusi-Sarpong et al, 2019).

5   Results and discussion

5.1 Results

5.1.1   Weight computations of manufacturing sustainability barriers

The best and worst criteria in addition to the resulting pairwise comparison of the main contexts/categories of finalized criteria (sustainability barriers and DMS attributes) determined from the preferential judgment of one of the experts are shown in Table 4. Likewise, all the experts that participated in the survey provided their preferential judgments for main contexts/categories and finalized criteria in other to develop respective pairwise comparisons. Tables 5-7 show the pairwise comparisons as determined by one of the experts for the finalized criteria in each main context/category. Specifically, Table 5 shows the pairwise comparison of the organizational barriers as determined by an expert. Then, the pairwise comparison as determined by an expert for socio-cultural barriers is presented in Table 6. In Table 7, the pairwise comparison as determined by one of the experts for the geographical barriers is shown. The optimal weights of the main contexts and respective barriers were determined from the pairwise comparisons by the experts and relevant formula presented in Section 4 of this study. Then, the determined weights were aggregated by finding the arithmetic mean from the experts' responses.

Table 4   Pairwise comparisons of main context sustainability barriers by an Expert

Best to Others	Organizational (OB)	Socio-cultural (CB)	Geographical (GB)
Best criteria: Organizational (OB)	1	7	2
Others to Worst	Worst criteria: Geographical (GB)		
Organizational (OB)	8		
Socio-cultural (CB)	3		
Geographical (GB)	1		

Table 5   Pairwise comparisons of Organizational barriers (OB) by an Expert

Best to Others	OB1	OB2	OB3	OB4	OB5
Best Criteria:OB1	1	7	8	1	2
Others to Worst	Worst criteria: OB3				
OB1	8				
OB2	3				

OB3	1
OB4	6
OB5	8

Table 6   Pairwise comparisons of Socio-cultural barriers (CB) by an Expert

Best to Others	CB1	CB2	CB3	CB4	CB5	CB6
Best Criteria: CB4	8	7	9	1	2	9
Others to Worst	Worst criteria: CB6					
CB1	2					
CB2	1					
CB3	2					
CB4	9					
CB5	7					
CB6	1					

Table 7   Pairwise comparisons of Geographical barriers (GB) by an Expert

Best to Others	GB1	GB2	GB3	GB4
Best Criteria: GB3	5	8	1	2
Others to Worst	Worst criteria: GB2			
GB1	3			
GB2	1			
GB3	8			
GB4	7			

Table 8 gives the results of the BWM evaluating the methodology for the manufacturing sustainability barriers as determined from the responses of the experts in the current study. The relative importance of the various barriers and their main contexts are indicated by the weights presented in Table 8. Notably, the ranking of the specific barriers presented in Table 7 was derived by the product of each specific criteria weight and the respective context weight. A detailed discussion of the results is provided in the 'discussion section' of this paper.

Table 8   Aggregate weights of main barriers and specific barriers for all the experts

Main Context	Context Weights	Specific Criteria	Specific Weight	Criteria	Global Weights	Ranking
Organizational (OB)	0.496	Inefficient technology (OB_1)	0.324		0.161	1
		Insufficient commitment of top management (OB_2)	0.136		0.067	6
		Financial constraints (OB_3)	0.202		0.100	4
		Lack of skilled workforce (OB_4)	0.111		0.055	9
		Absence of globalized network (OB_5)	0.228		0.113	2
Socio-cultural (CB)	0.308	Absent social responsibility (CB_1)	0.123		0.038	12
		Reluctant behavior towards sustainability (CB_2)	0.068		0.021	15
		Low market growth potential (CB_3)	0.094		0.029	13
		Ineffective communication (CB_4)	0.337		0.104	3
		Non-compliance to policy (CB_5)	0.194		0.060	7
		Inadequate government laws and regulations (CB_6)	0.183		0.056	8
Geographical (GB)	0.196	Unfavorable climatic conditions (GB_1)	0.221		0.043	11
		Unsustainable landscape (GB_2)	0.119		0.023	14
		Scarcity of natural resources(G_3)	0.397		0.078	5
		Political instability (GB_4)	0.264		0.052	10

5.1.2 *Computing the overall score of the attributes of distributed manufacturing systems.*

This was computed by first normalizing the experts' ratings of DMS attributes concerning and then applying the additive value function to compute the overall score of the DMS attributes to overall sustainable performance. The results obtained from the additive value function (Step 6

of the research methodology) are presented in Table 9 which indicates the total effect of the DMS attributes on the barriers for achieving sustainable manufacturing performance.

Table 9   Total score of impact (vector weight) of DMS attributes on sustainability

DMS Attributes	Improved manufacturing sustainable performance	
	Vector weight (Vi)	Rank
Reduced carbon emissions (A_1)	2.275	1
Information disclosure (A_2)	2.238	2
Public approval (A_3)	2.155	3
Respect for policy (A_4)	1.621	4
Improved brand/reputation (A_5)	1.603	5
Lower logistics costs (A_6)	0.472	6

A more detailed illustration of the ranks depicting the individual effect of the attributes of DMS on each specifically investigated barrier is presented in Table 10.

Table 10   Ranking the impact of DMS attributes on each sustainability barrier category.

DMS Attributes	Organizational barriers		Socio-cultural barriers		Geographical barriers	
	Weight (Vi)	Rank	Weight (Vi)	Rank	Weight (Vi)	Rank
Reduced carbon emissions (A_1)	8.747	5	0.060	1	0.040	1
Information disclosure (A_2)	8.777	4	0.058	2	0.035	3
Public approval (A_3)	10.36	1	0.055	3	0.033	5
Respect for policy (A_4)	9.673	3	0.055	4	0.040	2
Improved reputation (A_5)	9.820	2	0.042	5	0.035	4
Lower logistics costs (A_6)	4.577	6	0.038	6	0.013	6

5.2   Discussion

5.2.1   *Ranking of the barriers to manufacturing sustainability.*

A diagrammatic representation of the criticality of the contextual sustainability barriers is presented in Fig. 2 while the ranking of the specific sustainability barriers is presented in Fig. 3. According to the study findings depicted in Fig. 2, the barriers that are related to the organizational context are the most important in the Chinese manufacturing industry. This signifies that the barriers that are classified under the organizational context are critical, and measures need to be put in place to ensure that they are eradicated to encourage improved sustainable performance. As one may think that organizational sustainability implementation programs are usually hindered by external barriers such as "lack of government policy and support" (Orji et al., 2020), "lack of pressure and non-conducive legal system" (Gupta et al., 2020a), in this case, however, the barriers are internal. This tells us that, the Chinese manufacturing organizations may have been looking in the wrong direction (external) for solutions. This result points the Chinese manufacturing organizations in the right direction and they can now channel their scarce resources to eradicate the foundational and internal barriers. Thus, the Chinese manufacturing organizations have the power of reversing the barriers and paving the way to pursue sustainability initiatives to achieve the sustainability goal. The socio-cultural barriers are also extremely critical to sustainability goals in manufacturing as determined from the study results. Although the geographical barriers are the least ranked, industry managers should strive to align their company operations to sustainability

goals by making efforts such as implementing DMS to overcome and control all the barriers for improved sustainable performance.
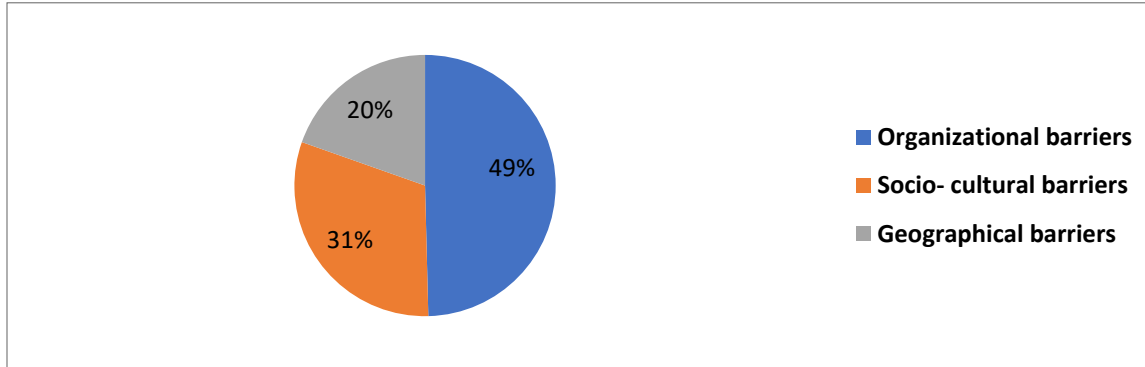

Fig.2 Context weights of the main contexts of investigated sustainability barriers (Percentage)

Among the investigated barriers as indicated in the study results in Fig.3, *inefficient technology* is ranked the highest and followed by *absence of a globalized network. Ineffective communication* and *financial constraints* are the third and fourth-ranked barriers, respectively. The fifth-ranked manufacturing sustainability is *scarcity of natural resources*. Specifically, within the organizational context, the highest-ranked investigated barrier in terms of relative importance is *inefficient technology* (OB_1). In recent years, there is a strong motivation to implement energy-efficient technologies for effective sustainability gains in various industrial sectors (Quader et al, 2015; Dong and Bi, 2020). The second-ranked barrier is *absence of a globalized network* (OB_5). Then, the third most significant barrier within the organizational context is the *financial constraints* (OB_3) while the fourth-ranked barrier is *insufficient commitment of top management* (OB_2). This suggests that adequate investment funds and robust budgetary allocation for sustainable innovations are highly significant to the actualization of sustainability objectives (Moktadir, et.al 2020; Virmani, Bera and Kumar, 2020; Yadav et al, 2020). Moreover, the support and commitment of the top management of firms are critical to the decision to implement innovations for sustainability goals (Gardas et al, 2019). The least barrier within the organizational context is *lack of skilled workforce* (OB_4). Within the socio-cultural context, the highest-ranked barrier which is the most significant is communication gap (CB_4) and this is followed by *non-compliance to policies* (CB_5). This recommends effective communication as very critical to build and strengthen trust among the relevant actors during organizational plans for sustainable development (Orji, 2019; Roos et al, 2016). The third-ranked-most important barrier within the socio-cultural context is *insufficient government regulations* (CB_6). Government environmental policies can stimulate domestic economies to adopt innovations in manufacturing firms (Brunel et al, 2019; Singh et al, 2020). The next ranked barrier within this context is *lack of social responsibility* (CB_1) and *low market growth potential* (CB_3). This indicates that corporate social responsibility has become increasingly significant for manufacturing firms to fulfill the increasing societal requirements for processes that are environmentally and socially responsible (Shou et al, 2020; Bux et al, 2020). The least-ranked barrier in the socio-cultural context is *reluctant behavior towards sustainability* (CB_2). Nevertheless, attitude to sustainability is also critical and considered a predictor of the intention for sustainable development in manufacturing firms (Luo et al, 2017).

Within the geographical context, the most significant barrier in terms of relative importance is *scarcity of natural resources* (*GB₃*) and this is followed by *political instability* (*GB₄*). Due to unavailable natural resources, it is highly essential to ensure efficient natural resource utilization in other to actualize sustainability objectives (Luo et al, 2017; Ulucak et al, 2020). *Unfavorable climatic conditions* (*GB₁*) are the next ranked barrier within this context while the least-ranked barrier is *unsustainable landscape* (*GB₂*). Thus, unfavorable climatic conditions serve as a critical barrier that has a huge potential to influence the integration of sustainable innovations within an industrial sector (Bouaichi et al, 2019). Although *unsustainable landscape* is ranked the least among the geographical barriers, the optimization of landscape composition can aid in the efficient management of the impacts of climate change for ultimately sustainable development (Liu et al, 2020).
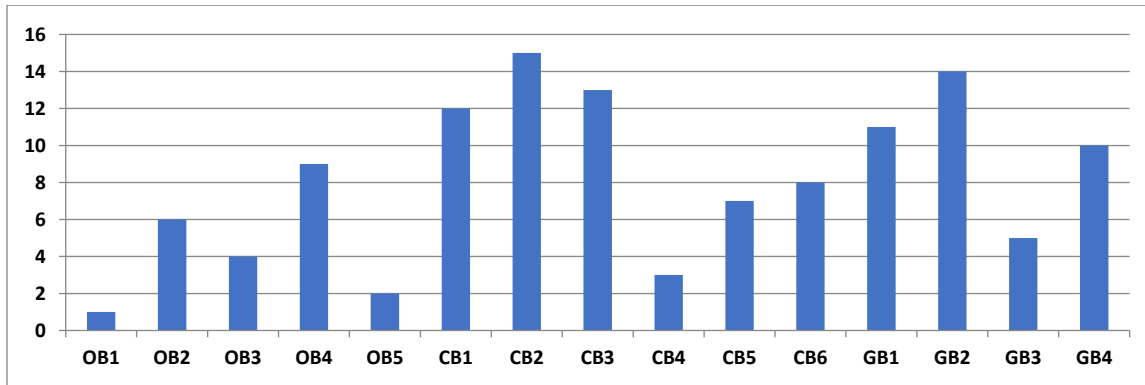

Fig. 3 Ranking of specific sustainability barriers

5.2.2 *Ranking of the attributes of DMS*

The diagrammatic representation of the study results obtained from the additive value function of the BWM is presented in Fig. 4. According to the results, *reduced carbon emissions* (2.275), *information disclosure* (2.238), and *public approval* (2.155) are the attributes that are most strongly linked to sustainable performance and have the highest potential to overcome the investigated manufacturing sustainability barriers. On the other hand, *lower logistics costs* (0.472), *improved brand/reputation* (1.603), and *respect for policy* (1.621) are the DMS attributes that are least linked to manufacturing sustainable performance. The highest-ranked attribute- *reduced carbon emissions* is liable for decreasing the by-product of industrial development and human civilization which present a danger to mankind and the environment (Bafana et al, 2018; Zuo et al, 2017). Additionally, reduced carbon emissions resulting in efficient pollution control can influence the disclosure of information relevant to industrial operations thereby leading to a shared understanding of performance impacts. The second-ranked attribute, *information disclosure* concerns adequate sharing of relevant information on performance and other important issues among the key partners and stakeholders in other to ensure efficiency and collaboration. Consequently, information disclosure can help in ensuring bridging the communication gap between partners and stakeholders by guaranteeing the effective sharing of information (Kumar, et.al, 2020; Li et al, 2017). Indeed, consumer awareness of the benefits of sustainability can be created by implementing transparency. The third-ranked DMS aspect, *public approval* is related

to satisfying consumer demands and requirements concerning products and processes to maximize market potential (Damert et al, 2017; Gandhi et al, 2018). Public approval can aid in eliminating the effect of low market potential. Hence, the Chinese manufacturing industry can benefit from public approval to create awareness and eliminate negative attitudes towards sustainable products.

Typically, *respect for policy* is an aspect of DMS that entails suitable framing of policies for sustainability improvements and effective compliance of such policies for increased competitiveness (Orji, 2019). Hence, respect for policy can enhance the financial advantage of the industry, increase the commitment of top management in industrial strategic goals and ensure the competencies of the workforce are improved (Schröter et al, 2017). Furthermore, the Chinese manufacturing sector can benefit from adequate framing of policies and implementation of preemptive plans on sustainability to increase public approval and aid transparency in business. Likewise, *improved brand/reputation* encompasses a positive and acceptable view of company processes and products by the stakeholders and consumers which has the potential to increase consciousness and ensure a positive mindset about sustainability (Orji and Wei, 2015). Improving social brand can ensure that consumers' negative attitude towards sustainability is minimized thus encouraging corporate social responsibility and advancing sustainability. Although ranked the least among the DMS attributes in terms of relationship with sustainable performance, the Chinese manufacturing sector can benefit from *lower logistics costs* to transport resources to maximize the market potential for increased financial performance (Bouzon et al, 2018).
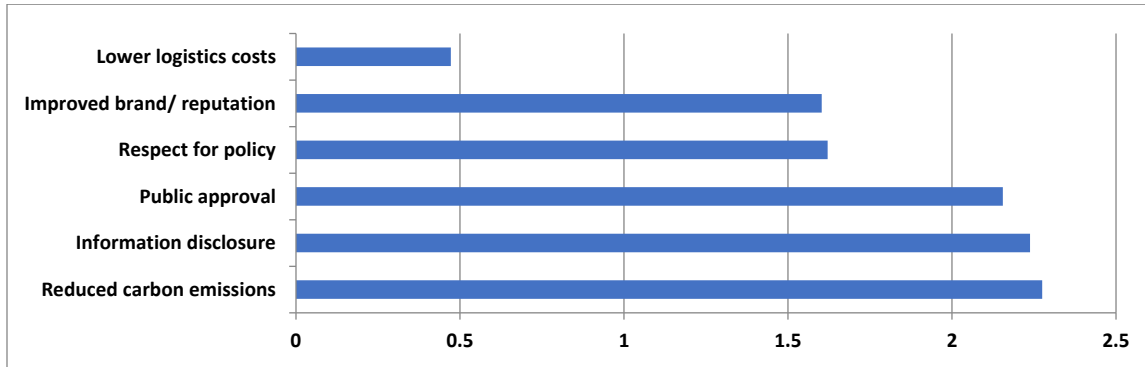

Fig.4 Influence of DMS attributes/strategies on improved sustainable performance in the manufacturing sector (Vector weights)

The findings of this study shed light on how DMS relate to sustainable performance in the manufacturing sector and by so doing corroborates published literature in the emerging economies (Bednar and Modrak, 2014; Hu, 2013; Hunt et al, 2015; Rauch et al, 2015; Yew et al, 2016). Indeed, the attributes of DMS are capable of suppressing the effect of sustainability barriers and are therefore linked to sustainable performance.

The diagrammatic representation of the further details of the individual effect of the attributes of DMS on each specifically investigated barrier is presented in Fig. 5. According to the results, with regards to organizational sustainability barriers, the most impactful DMS attribute is *public approval* (A_3) and followed by *improved brand/reputation* (A_4). The third-ranked DMS attribute in terms of impact on organizational barriers is *respect for policy* (A_4) and followed by

information disclosure (A_2) and reduced carbon emissions (A_1). The least impactful DMS attribute on organizational sustainability barriers is *lower logistics costs* (A_6). To be able to overcome the socio-cultural barriers, the most impactful attribute of distributed manufacturing systems is *reduced carbon emissions* (A_1). The second most impactful attribute of DMS on the socio-cultural barriers is *information disclosure* (A_2). The third and fourth-ranked DMS attributes in terms of impact on socio-cultural barriers are *public approval* (A_3) and *respect for policy* (A_4). Like the results obtained for the impact of the DMS attributes on organizational barriers, the least impactful of the attributes on socio-cultural barriers is *lower logistics costs* (A_6). Furthermore, like the results obtained for the impact of the DMS attributes on socio-cultural barriers, the DMS attribute that has the highest potential to impact on geographical barriers to manufacturing sustainability is *reduced carbon emissions* (A_1). The second-ranked DMS attribute in terms of impact on geographical barriers is *respect for policy* (A_4) while the third-ranked is *information disclosure* (A_2). *Improved social image* (A_5) remains the fourth-ranked in terms of impact on the geographical barriers while *public approval* (A_3) is the fifth-ranked. Like the results on the impact of the DMS attributes on the organizational and socio-cultural barriers, the *lower logistics costs* (A_6) remain the least ranked of all the DMS attributes in terms of impact on the geographical barriers.
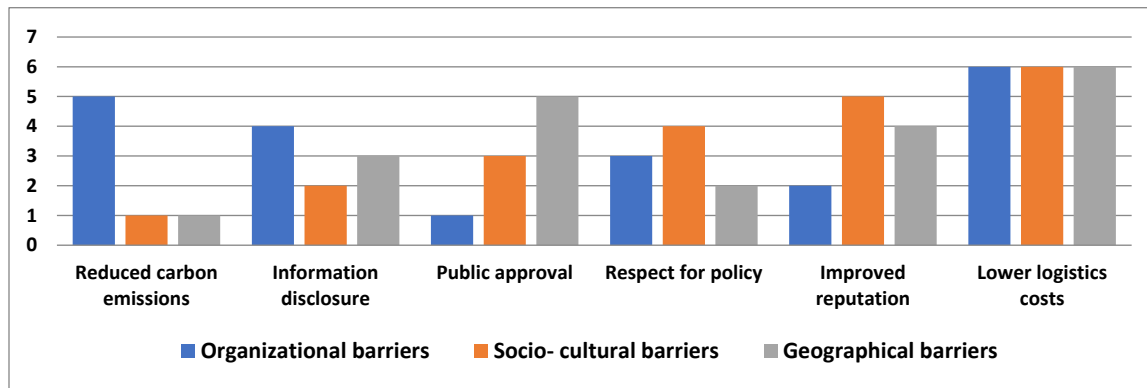

Fig. 5 Impact of the DMS attributes on main contexts of sustainability barriers (Ranking)

Ultimately, the study results show that there is a need for manufacturing firms to implement DMS and to prioritize the appropriate integration of the attributes in other to actualize improved sustainable performance and increased competitiveness.

5.2.3. *Senstivity Analysis*

Sensitivity analysis is performed to check for biasness of experts and to ensure that the framework developed is robust. The method applied by Gupta and Barua (2017) is adopted in this manuscript. Here, the weight of the barrier that obtained the highest weightage in the original results was varied from 0.1 to 0.9 and corresponding weights of sub barriers were calculated. Further using the weights of sub-barriers for different scenarios, the ranking of the DMS attributes (alternatives) was obtained to check for any variation in rankings. Table 11 represents the variation in weights of main category barriers due to variation in weight of OB barrier from 0.1 to 0.9.

Table 11   Variation in weights value of other main category barriers

Barrier	Normalized Weight	Run 1 (0.1)	Run 2 (0.2)	Run 3 (0.3)	Run 4 (0.4)	Run 5 (0.5)	Run 6 (0.6)	Run 7 (0.7)	Run 8 (0.8)	Run 9 (0.9)
OB	0.496	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900
CB	0.308	0.549	0.488	0.427	0.366	0.305	0.244	0.183	0.122	0.061
GB	0.196	0.351	0.312	0.273	0.234	0.195	0.156	0.117	0.078	0.039

Tables 12 -15 represents the ranks of DMS attributes for different runs.

Table 12   Ranking of DMS attributes for main category barriers by changing weights from 0.1 to 0.9

Attributes	Run 1 (0.1) V_i	Rank	Run 2 (0.2) V_i	Rank	Run 3 (0.3) V_i	Rank	Run 4 (0.4) V_i	Rank	Run 5 (0.5) V_i	Rank	Run 6 (0.6) V_i	Rank	Run 7 (0.7) V_i	Rank	Run 8 (0.8) V_i	Rank	Run 9 (0.9) V_i	Rank
A1	3.160	2	2.226	2	2.037	2	2.082	1	2.285	1	2.679	1	3.404	1	4.915	1	9.535	1
A2	3.311	1	2.275	1	2.048	1	2.067	2	2.248	2	2.617	2	3.305	2	4.750	2	9.177	2
A3	2.971	3	2.099	3	1.925	3	1.970	3	2.165	3	2.540	3	3.229	3	4.666	3	9.055	3
A4	2.280	5	1.598	5	1.458	4	1.486	4	1.628	4	1.907	4	2.419	4	3.491	4	6.767	4
A5	2.319	4	1.607	4	1.456	5	1.476	5	1.611	5	1.880	5	2.379	5	3.425	5	6.628	5
A6	0.632	6	0.452	6	0.417	6	0.429	6	0.474	6	0.558	6	0.711	6	1.029	6	2.001	6

Table 13   Ranking of DMS attributes for Organizational Barriers by changing weights from 0.1 to 0.9

Attributes	Run 1 (0.1) V_i	Rank	Run 2 (0.2) V_i	Rank	Run 3 (0.3) V_i	Rank	Run 4 (0.4) V_i	Rank	Run 5 (0.5) V_i	Rank	Run 6 (0.6) V_i	Rank	Run 7 (0.7) V_i	Rank	Run 8 (0.8) V_i	Rank	Run 9 (0.9) V_i	Rank
A1	43.258	5	21.639	5	14.437	5	10.839	5	8.683	5	7.248	5	6.225	5	5.460	5	4.865	5
A2	43.383	4	21.703	4	14.481	4	10.874	4	8.713	4	7.274	4	6.249	4	5.482	4	4.887	4
A3	51.373	1	25.692	1	17.134	1	12.857	1	10.293	1	8.584	1	7.365	1	6.451	1	5.742	1
A4	47.888	3	23.951	3	15.976	3	11.991	3	9.602	3	8.011	3	6.876	3	6.026	3	5.366	3
A5	48.551	2	24.287	2	16.205	2	12.167	2	9.748	2	8.138	2	6.990	2	6.131	2	5.464	2
A6	22.678	6	11.341	6	7.564	6	5.675	6	4.543	6	3.789	6	3.250	6	2.847	6	2.534	6

Table 14   Ranking of DMS attributes for Socio-Cultural Barriers by changing weights from 0.1 to 0.9

Attributes	Run 1 (0.1) V_i	Rank	Run 2 (0.2) V_i	Rank	Run 3 (0.3) V_i	Rank	Run 4 (0.4) V_i	Rank	Run 5 (0.5) V_i	Rank	Run 6 (0.6) V_i	Rank	Run 7 (0.7) V_i	Rank	Run 8 (0.8) V_i	Rank	Run 9 (0.9) V_i	Rank
A1	0.107	1	0.096	1	0.084	1	0.072	1	0.060	1	0.048	1	0.036	1	0.024	1	0.012	1
A2	0.103	2	0.092	2	0.080	2	0.069	2	0.057	2	0.046	2	0.034	2	0.023	2	0.011	2
A3	0.098	3	0.087	3	0.076	3	0.065	3	0.054	3	0.043	3	0.033	3	0.022	3	0.011	3
A4	0.097	4	0.087	4	0.076	4	0.065	4	0.054	4	0.043	4	0.032	4	0.022	4	0.011	4
A5	0.075	5	0.067	5	0.058	5	0.050	5	0.042	5	0.033	5	0.025	5	0.017	5	0.008	5
A6	0.069	6	0.061	6	0.053	6	0.046	6	0.038	6	0.031	6	0.023	6	0.015	6	0.008	6

Table 15   Ranking of DMS attributes for Geographical Barriers by changing weights from 0.1 to 0.9

	Run 1 (0.1)		Run 2 (0.2)		Run 3 (0.3)		Run 4 (0.4)		Run 5 (0.5)		Run 6 (0.6)		Run 7 (0.7)		Run 8 (0.8)		Run 9 (0.9)	
Attributes	V_i	Rank	V_i	Rank	V_i	Rank	V_i	Rank	V_i	Rank	V_i	Rank	V_i	Rank	V_i	Rank	V_i	Rank
A1	0.071	1	0.064	1	0.056	1	0.048	1	0.040	1	0.032	1	0.024	1	0.016	1	0.008	1
A2	0.063	3	0.056	3	0.049	3	0.042	3	0.035	3	0.028	3	0.021	3	0.014	3	0.007	3
A3	0.060	5	0.053	5	0.046	5	0.040	5	0.033	5	0.027	5	0.020	5	0.013	5	0.007	5
A4	0.071	2	0.063	2	0.055	2	0.047	2	0.039	2	0.031	2	0.024	2	0.016	2	0.008	2
A5	0.062	4	0.055	4	0.048	4	0.041	4	0.035	4	0.028	4	0.021	4	0.014	4	0.007	4
A6	0.024	6	0.021	6	0.019	6	0.016	6	0.013	6	0.011	6	0.008	6	0.005	6	0.003	6

The results of the sensitivity analysis show that there is no variation in the final ranking of DMS attributes based on the change in weights of main and sub-category barriers from 0.1 to 0.9. This shows that the framework developed is robust and free from expert bias.

5.2.4. Study implications

Our study contributes theoretically to sustainable development and provides insights that barriers that relate to the organizational, socio-cultural, and geographical aspects can hinder sustainability objectives. Particularly, by providing a geographical perspective, our study indicates that certain barriers can result in spatiotemporal differences in regional cases and such barriers are significant to understanding sustainability (Xu et al, 2020). This study thereby contributes to understanding the factors that relate to the huge variety and spatial unevenness of the pathways to implementing innovations for maximizing sustainable gains (Strambach and Pflitsch, 2020; Virmani et al, 2020). Firms may be resource-constrained to deal with all these barriers at the same time and so may decide to choose among the barriers. Maximizing the output in such an environment is the ultimate goal of most industrial sectors. Therefore, this study and its result can serve as the basis for prioritizing these barriers. It is therefore important to offer some guidance on theoretical grounds and evaluation outcomes to manufacturing companies, which this study provides, especially some initial guidelines to managers for eradicating the barriers. Notably, the outcome of this study tells managers that, organizational barriers are the most significant in terms of the investigated barriers as determined by the BWM computations. This corroborates published studies that suggest that the organizational context of the firms is relevant to sustainability plans and that the barriers that emanate from such a context are highly significant (Gupta et al, 2020a; Luthra et al, 2016). Specifically, as indicated in the study results, *inefficient technology* is ranked the highest among the sustainability barriers and is followed by *absence of a globalized network*. *Ineffective communication* and *financial constraints* are the third and fourth-ranked barriers, respectively. The fifth-ranked manufacturing sustainability is *scarce natural resources*. This study's results corroborate past published literature on the criticality of inefficient technology in hampering sustainability plans within an organization (Annuziata et al, 2018; De et al, 2020; Gupta et al, 2020a; Orji, 2019; Raj et al, 2020). Likewise, the presence of globalized networks has been noted by other researchers as being highly significant in actualizing sustainability goals

(Arampantzi and Minis, 2017; Golini et al, 2014; Oosterveer, 2015). Furthermore, insufficient funds and budgetary allocations remain a significant drawback to actualizing sustainable performance in the manufacturing sector (Zhang et al, 2019; Zhang et al, 2020). Unavailable resources have been noted as being highly significant and should be tackled for efficient resource consumption and improved sustainable performance (Moktadir et al, 2019).

Furthermore, the results from this study have buttressed the strong relationship of certain DMS attributes to sustainable performance namely *reduced carbon emissions*, *information disclosure,* and *public approval*. By investigating the impact of DMS attributes on the sustainability barriers, this study complements available literature on the flexible innovation techniques that offer many interesting opportunities in supply chain management (Beltagui et al, 2020; Noppers et al, 2014). Moreover, past studies have lauded the potential of technological developments in reducing emissions and improving sustainable performance (Bian and Xuan, 2020; Kang et al, 2020; Wang et al, 2021). Likewise, our study corroborates other published literature on the strong link/relationship between information disclosure for transparency and sustainable performance improvements (Garner et al, 2019; Reid and Rout, 2020). Additionally, past published studies indicate that public approval is extremely critical to implementing innovations for actualizing sustainability objectives within the industrial sectors (Jan et al, 2020; Noppers et al, 2014; Stephanides et al, 2019).

Hence, this study presents a clear outlook to the senior management of the manufacturing sector on how the DMS contributes to sustainable performance and sheds more light on the DMS attributes that firms need to focus on in other to overcome sustainability barriers. China, much the same as other emerging economies, is experiencing rapid growth and the overwhelming environmental pollution generated especially in the manufacturing sector is a hindrance in the way of advancement. Indeed, there is a growing concern about how to minimize the impact of human activities on the environment (Mikulcic and Duic, 2017; Yuan et al, 2020). A viable option to this challenge is therefore to strive to actualize sustainability in the manufacturing industry in other to minimize environmental consequences and increase competitiveness (Mousavi and Bossink, 2017). This study identifies and prioritizes the barriers that hinder the plans to actualize sustainability in the Chinese manufacturing sector and sheds more light on how DMS attributes impact such barriers and relate to sustainable performance. By so doing, this study will provide top management with the required knowledge to devise effective measures based on the significant impact level of the DMS attributes. The industry considered in the current study can improve the efficiency of their manufacturing operations and actualize sustainability objectives by adopting DMS. Based on the perspective of the experts interviewed in this study survey, the senior management aspires to increase their investments in sustainable innovations namely DMS in their bid to become sustainably compliant and are also employing highly skilled manpower to effectively manage such innovations. There lingers an important need for developing supply chain innovations that have the potential to contribute to reducing negative environmental and social consequences in the manufacturing sector (Kusi-Sarpong et al, 2019; Rauch et al, 2016). The current study sheds more light on an emerging trend within the industrial sector regarding implementing innovations for sustainable performance and overall global competitiveness.

Designing a practical guide that assists industry managers and practitioners to determine and integrate their perspectives holistically with regards to adopting DMS would be the next step in this research domain. The guide may include practical information for developing a sustainability compliance culture.

6 Conclusion and future research

6.1 Conclusion

Over the past years, China has achieved remarkable development in the manufacturing sector. Yet, advancing sustainability in the Chinese manufacturing sector is a challenge for concerned organizations and regulatory bodies. This is partly due to certain barriers that hinder plans to actualize sustainability objectives in the Chinese manufacturing sector. Thus, the manufacturing sector considers implementing sustainable innovations as a potential for sustainability improvements (Rauch et al, 2016; Shao et al, 2014). DMS, just like any other innovative initiative, has notable enormous potentials to achieve sustainability benefits and increased global competitiveness in the manufacturing industry (Behnam et al, 2018). Indeed, DMS is considered a novel manufacturing innovative strategy that is utilized to transform the scale and location of manufacturing facilities for expected sustainability benefits and increased competitiveness (Dertinger et al, 2020; Gimenez-Escalante et al, 2020). Despite the enormous potentials of DMS, its implementation is still at the nascent stage in emerging economies like China unlike in developed economies (Kim et al, 2020; Shokrani et al, 2020; Sun et al, 2020). Manufacturing managers in China and other emerging economies still lack the required insight about DMS strategic plans and how such may transform manufacturing operations. There is deficit knowledge on critical sustainability barriers and how DMS might impact these critical barriers and relate to improved sustainable performance especially in the Chinese manufacturing sector. Therefore, in this study, we attempted to identify and investigate sustainability barriers that exist in the Chinese manufacturing industry and also determined how the DMS attributes impact these barriers and relate to improved sustainable performance. This study would enable decision-makers in the Chinese manufacturing sector to understand the various barriers to implementing sustainability and how DMS can suppress or eliminate such barriers and result in sustainability benefits. In short, this would give a clearer insight into how DMS attributes impact sustainability challenges and also establish the link between DMS and improved sustainable performance.

In the current study, we identified fifteen barriers that hinder plans to achieve sustainability benefits in the Chinese manufacturing industry and six notable DMS attributes. The identified barriers were classified as organizational barriers, socio-cultural barriers, and geographical barriers. We then proposed a research methodology based on BWM to determine the relative importance of the identified barriers, investigate the impact of the DMS attributes on such barriers and likewise determine how DMS relates to sustainability gains. Data was sourced from ten managers who were directly concerned with the adoption of sustainable innovations in the Chinese manufacturing sector. This study pioneers the utilization of BWM to assess the criticality of sustainability barriers and determine how DMS might mitigate such barriers and its link to an improved sustainable performance from managers' viewpoint in extant literature. The BWM was utilized to obtain the barrier indices for prioritization in addition to the impact weight value of

DMS on the barriers and the association with improved sustainable performance through using the 'additive value function'. By utilizing this function, efficient computation of the overall scores of the DMS attributes is actualized to ensure accurate quantification of the impact of the DMS attributes. The results of this study indicate that organizational barriers are the most intense in terms of severity during the decision to implement sustainability goals. This is followed by socio-cultural barriers and lastly geographical barriers. Furthermore, our study findings suggest that in terms of relationship to sustainable performance, reduced carbon emissions, information disclosure, and public approval rank the highest among the investigated attributes of DMS. The DMS attributes that relate strongly to sustainable performance are strategic oriented and consequently, competitive advantage can be achieved by continuously improving on them. Additionally, the study results show that reduced carbon emissions have the highest impact on organizational and socio-cultural barriers while public approval has the highest impact on organizational barriers.

The study results provide an in-depth understanding of how DMS impact on critical sustainability barriers in an emerging economy against previously published DMS research that focus on developed economies and discuss broad design and resources issues of DMS (Kim et al, 2020; Kumar et al, 2020; Rauch et al, 2018; Shokrani et al, 2020). Moreover, our study introduces sustainability barriers as a significant aspect of implementing DMS for improved sustainable performance. The implementation of DMS can be hindered by barriers that are related to the organization, social-cultural context, and geographical location of the industry. Manufacturing firms are incessantly pressured by government bodies and other stakeholders (Kusi-Sarpong et al., 2019, Gupta et al., 2020a; Zhang et al, 2021; Zou et al, 2017; Mubarik et al., 2021), hence there is a necessity to integrate relevant contexts when investigating the impact of DMS on sustainability barriers and the relationship with improved sustainable performance. Our study, therefore, provides some useful guidelines that can serve as significant for further exploration and theorization of the link between DMS and sustainability benefits. Indeed, the study results, present policymakers with practical insight on the relative importance of the various barriers to implementing sustainable innovations and to effectively propose strategic solutions to eliminate or suppress such barriers. This is crucial because policymakers consider how to advance sustainability in the manufacturing industry without considering the effect of proposed solutions on the barriers to advancing sustainability. This work will surely assist policymakers to more effectively advance sustainability through efficiently adopting distributed manufacturing systems. Furthermore, the results of this study may assist policymakers in the manufacturing sector in making strategic and tactical decisions. For instance, the managers in the Chinese manufacturing sector can implement DMS strategic plans by utilizing sequential patterns. By so doing, the DMS attributes that are strongly related to improved sustainable performance are initially implemented while others are delayed and introduced systematically since there are bound to be time and resource-constraints (Han et al, 2017).

6.2 Limitations and future research directions

The current study just like other published research works is laden with certain limitations that provide some interesting opportunities for future theorization and subsequent exploration. We

have identified the barriers that hamper sustainability objectives in our study and classified such barriers under organizational, socio-cultural, and geographical contexts. In the future, a set of barriers can be identified and categorized using other mature theoretical frameworks such as the Technology-organization-environment (TOE) framework or Human-Organizational-Technology (HOT), or even a combination of both. This may provide a broader perspective on the sustainability barriers by ensuring the integration of all the relevant contexts of the industry. We have studied the relative importance of the barriers using BWM. Further research efforts can study the same set of barriers using other multi-criteria decision-making models such as Analytic Network Process (ANP) and Interpretive Structural Modeling (ISM) and may also include a comparison of the results from the methods utilized. As also informed in our study, the impact of the DMS aspects on the barriers has been investigated for possible sustainable performance improvements using the BWM evaluating methodology. In the future, research efforts may be geared towards employing systems dynamics to study more on the dynamic relationship between the DMS aspects and sustainable performance improvements for increasing the competitiveness of the organization. Another further research work may also adopt modelling and simulation approaches to sustainable aspects and risks (Sun et al., 2020; Gorecki et al., 2020) of the manufacturing system to anticipate the behavior and links between DMS and sustainable performance. Finally, future studies may consider investigating enterprise interoperability with more connections to enterprise modeling (Vernadat, 2002; Vallespir et al., 2005, Chen and Daclin, 2006) and model-driven approach (Zacharewicz et al., 2020) as approaches for reaching manufacturing sustainability.

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