MATEMATIKA, MJIAM, Volume 42, Number 2, 141–153

Green Manufacturing Evaluation Using Intuitionistic Trapezoidal Fuzzy DEMATEL Method

[1]Noor Azzah Awang, [2]Norsyahida Zulkifli*, [3]Lazim Abdullah, [3]Wan Rosanisah Wan Mohd and [4]Raden Sulaiman

[1]School of Mathematical Sciences, College of Computing, Informatics and Mathematics, Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia.
[2]Department of Mathematical Sciences, Faculty of Science, Universiti Teknologi Malaysia, 81310, Johor Bharu, Johor, Malaysia.
[3]Faculty of Computer Science and Mathematics, Universiti Malaysia Terengganu, 21030, Kuala Nerus, Terengganu, Malaysia.
[4]Department of Mathematics, State University of Surabaya, 60231, Surabaya, Indonesia.
*Corresponding author: norsyahida.zulkifli@utm.my

Article history
Received: 21 November 2024
Received in revised form: 25 November 2025
Accepted: 14 May 2026
Published on line: 20 July 2026

Abstract Green Manufacturing (GM) promotes environmentally responsible production practices that minimize waste, energy consumption, and ecological impact while sustaining product quality and profitability. However, existing decision-making methods such as fundamental Decision-Making Trial and Evaluation Laboratory (DEMATEL) and fuzzy DEMATEL often exhibit limitations in handling uncertainty, vagueness, and hesitation in expert evaluations, resulting in less accurate causal analysis. Therefore, a more robust approach is needed to effectively model such ambiguity in assessing interrelated GM factors. This study proposes an Intuitionistic Trapezoidal Fuzzy DEMATEL (ITF-DEMATEL) model to evaluate the key factors influencing GM adoption. The ITF-DEMATEL integrates intuitionistic and trapezoidal fuzzy theories to more accurately represent uncertainty and expert hesitation in complex decision contexts. Eight influential factors were analyzed: leadership dedication and support, company policies, influence from peer governments, social influence, customer characteristics, green supply chain management, government support, and integration of novel methods. The results reveal that leadership dedication and support is the most important criterion, while government support is the most influential factor. Comparative analysis with fundamental DEMATEL and fuzzy DEMATEL reveals that the proposed ITF-DEMATEL improves ranking stability, causal differentiation, and interpretive reliability, offering valuable insights for sustainable manufacturing decision-making.

Keywords Green manufacturing; Fuzzy set; Intuitionistic fuzzy set; Intuitionistic trapezoidal fuzzy set; DEMATEL.

Mathematics Subject Classification 90B50, 03E72, 90C70.

---

1 Introduction

The manufacturing sector contributes significantly to a country's economic development. It contributes to the nation's export revenue and opens the door to a plethora of job opportunities, allowing the country to thrive despite global economic uncertainties. Manufacturing is connected to many sectors such as retail, construction, and transportation. Today, consumers are increasingly mindful of green manufacturing (GM) practices and their repercussions on the environment and society, prompting businesses to adopt GM approaches. GM involves reinvigorating manufacturing processes and establishing eco-conscious operations within the sector. Essentially, it entails the transformation of manufacturing into a more environmentally friendly endeavor, wherein workers utilize natural resources, minimize pollution and waste, and engage in recycling and reusing materials while mitigating emissions. To achieve this, GM conducts research, develops, and implements technologies and practices aimed at reducing their environmental footprint. Beyond its environmental benefits, GM is proving advantageous for many firms nationwide as they realize that emphasizing recycling and waste reduction can positively impact their bottom line.

The research and industrial sectors have shown growing interest in GM, underscoring the need for a clear and comprehensive understanding of the concept. In a recent study, Sarker and Batok [1] conducted a bibliometric analysis to examine prevailing trends and research patterns in GM within the textile industry, revealing a significant increase in publications since 2013. Waheed et al. [2] investigated the role of GM practices in pollution prevention and environmentally conscious consumer behavior. Gandhi et al. [3] explored the factors for implementing integrated lean–green manufacturing among Indian small and medium-sized enterprises (SMEs), addressing uncertainties in the weighting of GM factors using fuzzy set through the TOPSIS and SAW methods. Similarly, Singh et al. [4] combined TOPSIS with the analytic hierarchy process (AHP) to recognize the most influential GM factors across different SMEs. In another study, Kumar and Barman [5] employed an integrated fuzzy TOPSIS-VIKOR to determine the optimal green suppliers for sponge iron and steel sector.

A series of research has been carried out in this direction of GM. However, the implementation of GM continues to face numerous challenges, particularly when multiple interrelated factors must be considered simultaneously. Multi-criteria decision-making (MCDM) methods have been used to deal with various complicated factors of decision-making problems, and one of those is the DEMATEL method. The DEMATEL approach effectively ranks evaluation factors while simultaneously revealing causal interdependencies through a structured cause–effect representation. Previous literature on DEMATEL and its extension has been widely conducted. A hybrid study of Monte Carlo-DEMATEL simulation has been conducted to identify risk and prioritization in the production sector [6]. Abdullah et al. [7] studied a hybrid approach of Choquet-DEMATEL under interval-valued intuitionistic fuzzy set in assessing the management of solid waste problem and extended it with interval neutrosophic-vague sets [8]. On the other hand, a method for computing the multiplicative inverse matrix of fuzzy DEMATEL was proposed and applied to the problem of coastal erosion in Malaysia [9]. DEMATEL has evolved to accommodate a wide range of information representation types. Conventional DEMATEL methods rely on crisp values, while fuzzy extensions have been developed to better handle imprecision and ambiguity in practical decision-making scenarios. In existing literature, the most frequently employed fuzzy sets are triangular fuzzy sets [10], trapezoidal fuzzy sets [11-13], interval-valued fuzzy sets [14], and intuitionistic fuzzy sets (IFS) [15].

Despite the growing body of literature on GM, several research gaps remain unaddressed. Most previous studies have primarily focused on identifying GM factors or applying traditional MCDM methods such as TOPSIS, AHP, or VIKOR [3-5], which are effective for ranking factors but limited in revealing complex interrelationships among them. Moreover, while the DEMATEL method has been extended using fuzzy, interval, or IFS approaches [6-15], there remains a lack of models that can simultaneously represent both membership and non-membership degrees under trapezoidal fuzzy structures, which is particularly useful in modelling uncertainty and vagueness in expert evaluations of GM factors.

Therefore, this study aims to bridge these gaps by developing an Intuitionistic Trapezoidal Fuzzy DEMATEL (ITF-DEMATEL) model which integrates the concepts of IFS, incorporating both membership and non-membership values, with trapezoidal-shaped functions. This combination enables more effective modeling of uncertainty and vagueness in evaluating GM factors. The objective of this study is to develop an ITF-DEMATEL model to analyze GM issues among Malaysian SMEs. The innovation of this research lies in (i) integrating IFS and trapezoidal fuzzy concepts to enhance the precision of causal relationship analysis in GM, (ii) applying this novel hybrid model to the context of Malaysian SMEs, where empirical evidence on GM implementation remains scarce, and (iii) providing a cause–effect framework that supports policymakers and practitioners in prioritizing key GM enablers under uncertainty. This integrated approach not only contributes methodologically to the advancement of fuzzy MCDM models but also provides a new empirical lens to understand GM adoption in emerging economies.

This study continues with Section 2, which presents a brief fundamental concepts of IFS, ITFS, and DEMATEL. Section 3 describes the GM case study. Section 4 details the proposed ITF-DEMATEL framework, followed by Section 5, which presents the implementation process and comparative evaluation. Finally, Section 6 concludes the study and provides recommendations for future research.

2 Preliminaries

2.1 Intuitionistic Fuzzy Set

Intuitionistic Fuzzy Set (IFS) was firstly proposed by Atanassov [16] as an extension of fuzzy set (FS). The theory of IFS comprises both membership (MS) and non-membership (NMS) degrees. Besides, IFS also accounts for the hesitancy of experts, making it more effective than FS in handling vague and uncertain conditions. Nehi and Maleki [17] developed ITF numbers with the aim of generating a continuous set from a discrete one [18]. The definitions of IFS and ITF numbers are shown as follows.

Definition 1 [16]
Let X be a finite, non-empty universal set. An IFS A in X is defined as

$$A = \{\langle x, \mu_A(x), \nu_A(x)\rangle \mid x \in X\},$$

where the functions

$$\mu_A(x) : X \to [0,1],$$
$$\nu_A(x) : X \to [0,1]$$

denote the MS and NMS degrees of an element $x \in X$ to the set A, respectively, and satisfy the condition

$$0 \le \mu_A(x) + \nu_A(x) \le 1, \quad x \in X.$$

The hesitation degree of x with respect to A is then given by

$$\pi_A(x) = 1 - \mu_A(x) - \nu_A(x),$$

which quantifies the degree of uncertainty regarding the MS of x in A.

Definition 2 [17]
Let $\mathbb{R}$ denote the set of real numbers. An ITF number A with parameters is given by

$$A = (a_1, a_2, a_3, a_4 : \mu_A, \nu_A),$$

where $a_1, a_2, a_3, a_4 \in \mathbb{R}$ and $a_1 \le a_2 \le a_3 \le a_4$. The parameters μ_A and ν_A denote the membership and non-membership degrees, respectively.

The membership function $\mu_A(x) : \mathbb{R} \to [0,1]$ is defined as

$$\mu_A(x) = \begin{cases} 0, & x < a_1, \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \le x \le a_2, \\ 1, & a_2 \le x \le a_3, \\ 0, & x > a_4. \end{cases} \tag{1}$$

Meanwhile, the non-membership function $\nu_A(x) : \mathbb{R} \to [0,1]$ is defined as

$$\nu_A(x) = \begin{cases} 1, & x < b_1, \\ \dfrac{x - b_1}{b_1 - b_2}, & b_1 \le x \le b_2, \\ 0, & b_2 \le x \le b_3, \\ \dfrac{x - b_3}{b_4 - b_3}, & b_3 \le x \le b_4, \\ 1, & x \ge b_4. \end{cases} \tag{2}$$

2.2 DEMATEL Method

Fontela and Gabus [19] originally proposed the DEMATEL technique under the Science and Human Affairs initiative to analyze intricate, interrelated system problems. The ITF-DEMATEL method is introduced to enhance traditional DEMATEL by incorporating ITFS, allowing for a more accurate and comprehensive representation of uncertainty, vagueness, and imprecision in MCDM processes, thereby improving the reliability and flexibility of causal analysis in complex real-world problems. The five steps of the DEMATEL method are summarized as follows:

Step 1: Evaluate linguistic data.
In the first step, the factors are evaluated using linguistic terms, crisp scores, and ITF numbers as shown in Table 1. These translate qualitative judgments into numerical values for analysis. These evaluations quantify the influence exerted by factor i on factor j.

Table 1: Linguistic Terms, Crisp Scores and ITF Numbers

Linguistic Terms	**Crisp Scores**	**ITF Number**
Very high influence (VH)	4	$((1.0, 1.0, 1.0, 1.0), (1.0, 1.0, 1.0, 1.0))$
High influence (H)	3	$((0.7, 0.8, 0.9, 1.0), (0.7, 0.8, 0.9, 1.0))$
Low influence (L)	2	$((0.3, 0.4, 0.5, 0.6), (0.2, 0.4, 0.5, 0.7))$
Very low influence (VL)	1	$((0.0, 0.1, 0.2, 0.3), (0.0, 0.1, 0.2, 0.3))$
No influence (N)	0	$((0.0, 0.0, 0.0, 0.0), (0.0, 0.0, 0.0, 0.0))$

Step 2: Obtain expected values (EV) for initial direct-relation (ID).
The EV of the ITF numbers is calculated by Eq. (3).

$$\mathrm{EV}(A) = \frac{1}{8}\left(a_1 + a_2 + a_3 + a_4 + b_1 + b_2 + b_3 + b_4\right) \tag{3}$$

Step 3: Normalize the ID.
Normalization of the ID is performed using Eq. (4).

$$D = \frac{\mathrm{EV}(A)}{s}, \tag{4}$$

where, $s = \max\left(\max_{1\le i\le n}\sum_{j=1}^{n} z_{ij}, \max_{1\le j\le n}\sum_{i=1}^{n} z_{ij}\right)$ and z_{ij} denotes the element of the ID, with i indicating the rows and j the columns. The normalization step standardizes data, allowing valid comparisons across factors and enhancing consistency and precision in MCDM analysis.

Step 4: Calculate the total-influence matrix, T.
The total-influence matrix is computed according to Eq. (5), where I represents the identity matrix.

$$T = D(I - D)^{-1} \tag{5}$$

Step 5: Construct CD by obtaining structural analysis using (6)–(8).
The causal diagram (CD) is constructed using the horizontal (prominence) axis to represent $(D + R)$ values and the vertical (relation) axis to represent $(D - R)$ values.

$$T = [t_{ij}]_{n\times n}, \quad i, j = 1, 2, \ldots, n \tag{6}$$

$$D = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1=[t_i]_{n\times 1}} \tag{7}$$

$$R = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n=[t_i]_{1\times n}} \tag{8}$$

The prominence axis reflects the overall importance of each factor, while the relation axis indicates the net impact of the factors. Positive $(D - R)$ values correspond to net causers, whereas negative values indicate net receivers.

3 Results of a Case Study on Green Manufacturing

3.1 Implementation

This study conducted a case study of GM to promote environmental sustainability by reducing pollution and minimizing waste. Eight influential factors are recognized concurrently with the literature review [20, 21], as shown in Table 2. The evaluation data is partly adopted from Singh et al. [22] using linguistic terms and intuitionistic trapezoidal fuzzy numbers in Table 1. This GM study is examined under ITF-DEMATEL to clarify the interrelationship of the influential factors and visualize the causal relationship by constructing a CD.

Table 2: Factors of Green Manufacturing

Factor	**Description**
F_1	Leadership dedication and support
F_2	Company policies
F_3	Influence from peer governments
F_4	Social influence from peers
F_5	Customer characteristics
F_6	Green supply chain management
F_7	Government support
F_8	Integration of novel methods

The case study of GM is implemented using five steps of IF-DEMATEL in Section 2.2 as follows.

Step 1: Evaluation of the influential factors is carried out based on the linguistic scales in Table 1.

Step 2: The data with ITF numbers are transformed into expected values (EV) using Eq. (3), as shown in Table 3.

Table 3: The Data with Expected Value, EV(A)

Factors/Factors	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
F_1	0.00	1.00	0.85	0.45	0.45	0.85	0.15	0.85
F_2	0.85	0.00	0.85	0.45	0.45	0.85	0.15	0.15
F_3	1.00	1.00	0.00	0.15	0.85	1.00	0.00	0.45
F_4	0.85	0.45	1.00	0.00	0.45	0.45	0.45	0.45
F_5	1.00	0.15	0.85	0.85	0.00	0.45	0.85	0.85
F_6	1.00	0.15	1.00	1.00	0.15	0.00	0.85	0.45
F_7	1.00	0.85	0.15	0.15	0.85	0.85	0.00	0.45
F_8	0.15	0.45	0.45	0.85	0.15	0.45	0.15	0.00

Step 3: Expected values in Table 3 are normalized using Eq. (4), where each element of EV(A) is divided by 5.85 because it is the highest value of the sum of column and row. The outcome is presented in Table 4.

Table 4: Normalization of ID

Factors/Factors	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
F_1	0.00	0.17	0.15	0.08	0.08	0.15	0.03	0.15
F_2	0.15	0.00	0.15	0.08	0.08	0.15	0.03	0.03
F_3	0.17	0.17	0.00	0.03	0.15	0.17	0.00	0.08
F_4	0.15	0.08	0.17	0.00	0.08	0.08	0.08	0.08
F_5	0.17	0.03	0.15	0.15	0.00	0.08	0.15	0.15
F_6	0.17	0.03	0.17	0.17	0.03	0.00	0.15	0.08
F_7	0.17	0.15	0.03	0.03	0.15	0.15	0.00	0.08
F_8	0.03	0.08	0.08	0.15	0.03	0.08	0.03	0.00

Step 4: The total influence matrix is obtained using Eq. (5). Table 5 presents the total influence and structural analysis of the GM.

Table 5: Total Influence of GM

Factors/Factors	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
F_1	0.34	0.40	0.45	0.31	0.27	0.43	0.18	0.35
F_2	0.43	0.22	0.41	0.28	0.25	0.39	0.16	0.23
F_3	0.49	0.40	0.33	0.27	0.33	0.45	0.16	0.30
F_4	0.45	0.31	0.44	0.21	0.26	0.35	0.21	0.28
F_5	0.52	0.31	0.47	0.38	0.22	0.40	0.30	0.38
F_6	0.50	0.30	0.47	0.38	0.24	0.31	0.28	0.30
F_7	0.48	0.37	0.34	0.26	0.32	0.42	0.16	0.29
F_8	0.23	0.22	0.27	0.27	0.15	0.25	0.12	0.13

Step 5: In Table 6, the structural analysis is derived using Eq. (6)–(8). Figure 1 illustrates the causal diagram (CD) derived from the structural analysis.

Table 6: Structural Analysis of GM

Factors	$D+R$	$D-R$
F_1	6.17	-0.72
F_2	4.92	-0.17
F_3	5.92	-0.45
F_4	4.91	0.14
F_5	5.03	0.94
F_6	5.80	-0.20
F_7	4.22	1.08
F_8	3.91	-0.62

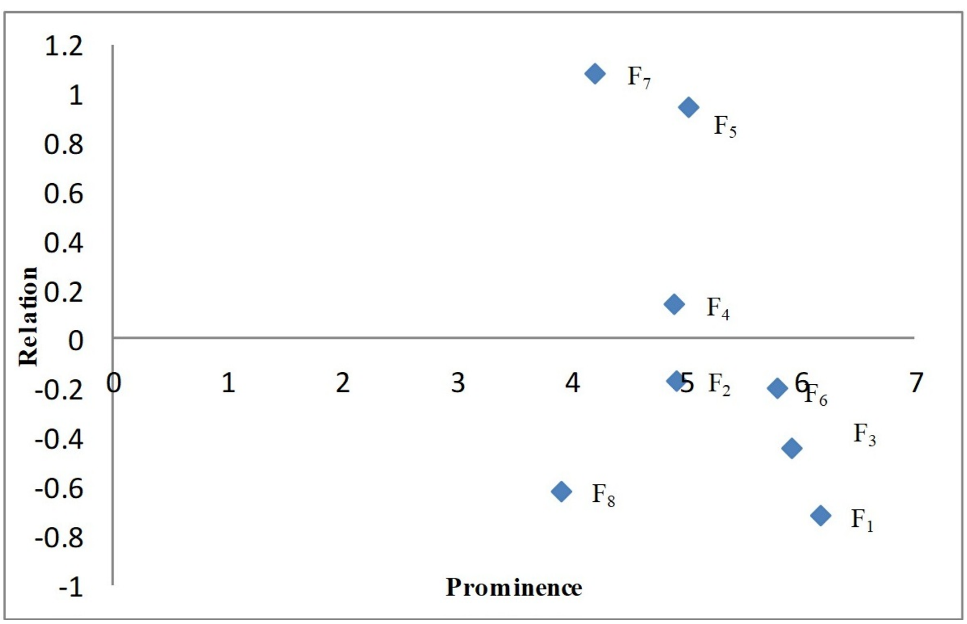

Figure 1: Causal Diagram of GM

3.2 Preliminary Discussion

Table 6 and Figure 1 reveal several interesting findings. Firstly, based on Table 6, it is evident that F_1 (Leadership dedication and support) is the most significant factor, as it gains the highest priority based on the $(D+R)$ value of 6.17. Based on the importance degree $(D+R)$, the ranking order of the GM factors is revealed as $F_1 \succ F_3 \succ F_6 \succ F_5 \succ F_2 \succ F_4 \succ F_7 \succ F_8$. Additionally, F_7 (Government support) holds the highest $(D-R)$ value of 1.08, making it the most influential criterion and indicating that it exerts the greatest impact on GM adoption.

Meanwhile, in Figure 1, the prominence axis of the CD denotes the significance of each factor, while the relation axis delineates the factors into cause-and-effect categories. The factors with positive $(D-R)$ values, namely F_4 (Social influence from peers), F_5 (Customer characteristics), and F_7 (Government support), belong to the cause group, also referred to as the net causers. The effect factor group, known as the net receivers, includes F_1 (Leadership dedication and support), F_2 (Company policies), F_3 (Influence from peer governments), F_6 (Green supply chain management), and F_8 (Integration of novel methods), which are characterized by negative $(D-R)$ values.

In order to achieve optimal performance in GM, it is crucial to first prioritize and strengthen the net causer factors, as these factors exert influence on other variables but are themselves less susceptible to change. Conversely, net receivers are more easily adjusted once the primary influencing factors are effectively managed [23]. Therefore, enhancing awareness and engagement in F_4, F_5, and F_7 can lead to substantial improvements in F_1, F_2, F_3, F_6, and F_8, resulting in stronger managerial commitment, more effective corporate policies, and the broader integration of sustainable and innovative practices in manufacturing operations.

3.3 Comparative Analysis

The robustness and analytical capability of the proposed ITF-DEMATEL method are evaluated through a comparative analysis with two existing approaches: the fundamental DEMATEL and the fuzzy DEMATEL. This comparison focuses on the overall ranking order and the causal prominence of each criterion. The ranking results are summarized in Table 7, while the detailed $(D+R)$ and $(D-R)$ values are presented in Table 8.

Table 7: Comparison of Criterion Rankings

Method	Ranking
DEMATEL	$F_1 \succ F_6 \succ F_3 \succ F_4 \succ F_5 \succ F_2 \succ F_7 \succ F_8$
Fuzzy DEMATEL	$F_1 \succ F_6 \succ F_3 \succ F_4 \succ F_2 \succ F_5 \succ F_7 \succ F_8$
The proposed ITF-DEMATEL	$F_1 \succ F_3 \succ F_6 \succ F_5 \succ F_2 \succ F_4 \succ F_7 \succ F_8$

Table 8: Comparison of Causal Prominence

	DEMATEL		Fuzzy DEMATEL		ITF-DEMATEL	
Method / Factors	$D+R$	$D-R$	$D+R$	$D-R$	$D+R$	$D-R$
F_1	5.9658	-1.0044	6.6106	-1.0230	6.1750	-0.7212
F_2	5.1352	-0.3009	5.7549	-0.2456	4.9165	-0.1660
F_3	5.6367	-0.0031	6.2607	-0.0027	5.9183	-0.4461
F_4	5.2246	0.1258	5.8740	0.1401	4.9099	0.1350
F_5	5.1348	0.7371	5.8183	0.7966	5.0273	0.9419
F_6	5.9351	-0.0135	6.5921	-0.0952	5.7952	-0.1955
F_7	4.4103	0.9137	5.0496	0.9473	4.2198	1.0761
F_8	4.3238	-0.4548	4.9389	-0.5175	3.9091	-0.6242

Table 7 shows that all three methods consistently identify F_1 (Leadership dedication and support) as the most important factor influencing green manufacturing (GM) adoption. The stability of F_1 across all approaches confirms its dominant influence, indicating that strong leadership commitment remains the fundamental key to successful GM implementation regardless of the analytical environment or uncertainty modeling technique used. However, notable ranking differences are observed for the remaining factors, particularly in the proposed ITF-DEMATEL results. For example, F_3 (Influence from peer governments) rises to the second rank in the proposed model, surpassing F_6 (Green supply chain management), which holds the second rank in both DEMATEL and fuzzy DEMATEL. Similarly, F_5 (Customer characteristics) moves up to the fourth position, highlighting the increasing impact of consumer environmental awareness in shaping manufacturing sustainability. In contrast, F_4 (Social influence from peers) and F_7 (Government support) are ranked lower under the ITF-DEMATEL model, suggesting that their influence becomes relatively less dominant once uncertainty and hesitancy in expert evaluations are better captured.

Further insight can be drawn from Table 8, which compares the $(D + R)$ and $(D - R)$ values among the three models. The $(D + R)$ values represent the total prominence or overall importance of each factor, while the $(D - R)$ values indicate the causal relationship, where positive values denote causes (net causers) and negative values denote effects (net receivers). The proposed ITF-DEMATEL exhibits a wider dispersion of $(D - R)$ values compared to the other two methods, implying a clearer separation between influencing and influenced factors. Specifically, F_4 (Social influence from peers), F_5 (Customer characteristics), and F_7 (Government support) have positive $(D - R)$ values, categorized as causal factors, while the remaining factors are classified as effect factors.

This enhanced causal differentiation reflects the superior capacity of ITF-DEMATEL to manage vagueness and hesitancy in human judgments. The incorporation of ITF sets enables a more comprehensive representation of expert uncertainty, resulting in more precise and meaningful causal structures. Consequently, the proposed method not only reinforces the robustness of key factor F_1 but also improves the interpretability and granularity of relationships among GM factors, providing experts with a more reliable analytical framework for sustainable manufacturing strategy formulation.

The findings of this study are consistent with prior research emphasizing leadership commitment as a dominant driver of green manufacturing. For instance, Singh et al. [22] and Gandhi et al. [3] also reported that managerial dedication and strategic support are critical in enabling sustainable production practices. Similarly, Govindan et al. [20] identified top management involvement as a key determinant influencing the successful adoption of green initiatives. However, compared with these earlier studies that employed conventional or fuzzy-based MCDM techniques, the proposed ITF-DEMATEL provides a more nuanced causal interpretation. This improvement stems from its ability to integrate both intuitionistic and trapezoidal fuzzy representations, effectively capturing hesitation and uncertainty in expert judgments. The enhanced causal clarity observed in this study aligns with recent methodological extensions, such as the fuzzy–Choquet DEMATEL of Abdullah et al. [7] and the hybrid Monte Carlo–DEMATEL model by Akbar et al. [6], further validating the robustness and flexibility of the proposed ITF-DEMATEL approach in complex decision environments.

4 Conclusion

In this study, GM problem is evaluated based on the proposed MCDM tool of DEMATEL with ITF sets. The factors of GM are prioritized and the cause–effect relationships among the factors are identified. A diagram (Figure 1) is presented to depict the relationships between the causal and effect factors. The factors F_7, F_5, and F_4 are classified as the cause group, while the effect group consists of F_1, F_2, F_3, F_6, and F_8. In addition, the results indicate that F_1 is the most important factor with the highest $(D+R)$ value of 6.17. Based on the importance degree $(D+R)$, the ranking order of GM factors is identified as $F_1 \succ F_3 \succ F_6 \succ F_5 \succ F_2 \succ F_4 \succ F_7 \succ F_8$. Conversely, F_7 holds the highest $(D-R)$ value of 1.08, indicating that it is the most influential factor, meaning that F_7 exerts the greatest impact on GM. This research will be beneficial for stakeholders who are considering the adoption of GM practices. For future research directions, GM evaluation has significant room for improvement. For instance, GM can be evaluated within other uncertainty frameworks, such as fuzzy sets or Fermatean fuzzy sets, to better capture the ambiguity and indeterminacy inherent in sustainability assessments. In addition, various MCDM approaches can be applied to rank and identify the most significant GM factors, including methods such as AHP, VIKOR, PROMETHEE, and others.

Acknowledgments

We would like to thank the College of Computing, Informatics and Mathematics, Universiti Teknologi MARA for granting permission and providing support to complete this work. This study is funded by the Geran Penyelidikan MyRA Lepasan PhD with file no. 600-RMC/GPM LPHD 5/3 (139/2021) and a grant from Universiti Teknologi Malaysia (PAS Grant Q.J130000.2754.04K22) under the Ministry of Higher Education of Malaysia.

References

[1] Sarker, M. S. I. and Bartok, I. Global trends of green manufacturing research in the textile industry using bibliometric analysis, *Case Studies in Chemical and Environmental Engineering*, 9 (2024).

[2] Waheed, A., Qingyu, Z., Yasir, R., Muhammad, S. T. and Muhammad, W. Z. Impact of green manufacturing on consumer ecological behavior: Stakeholder engagement through green production and innovation, *Sustainable Development*, 28(5) (2020), 1395–1403.

[3] Gandhi, N. S., Shashank, J. T. and Jitesh, J. T. Ranking of drivers for integrated lean-green manufacturing for Indian manufacturing SMEs, *Journal of Cleaner Production*, 171 (2018), 675–689.

[4] Singh, M., Singh, K. and Singh, S. A. Analytical hierarchy process and TOPSIS for selecting best parameters of green manufacturing, *Measuring Business Excellence*, 24(3) (2020), 345–365.

[5] Kumar, S. and Barman, A. G. Fuzzy TOPSIS and fuzzy VIKOR in selecting green suppliers for sponge iron and steel manufacturing, *Soft Computing*, 25(8) (2021), 6505–6525.

[6] Akbar, M. A., Naseem, A., Ahmad, Y. and Zaman, U. K. Production risk analysis and prioritization in manufacturing industry: A hybrid approach using Monte Carlo simulation and DEMATEL analysis, *Ain Shams Engineering Journal*, 15(7) (2024), 102756.

[7] Abdullah, L., Zulkifli, N., Liao, H., Enrique, H. V. and Abdullah, A. B. An interval-valued intuitionistic fuzzy DEMATEL method combined with Choquet integral for sustainable solid waste management, *Engineering Applications of Artificial Intelligence*, 82 (2019), 207–215.

[8] Al-Quran, A. A., Hashim, H. and Abdullah, L. A hybrid approach of interval neutrosophic vague sets and DEMATEL with new linguistic variable, *Symmetry*, 12(2) (2020), 275.

[9] Awang, A., Aizam, N. A. H. and Abdullah, L. An integrated decision-making method based on neutrosophic numbers for investigating factors of coastal erosion, *Symmetry*, 11(3) (2019), 328.

[10] Mukhtar, N. I. and Sulaiman, N. H. Triangular fuzzy number-based conjoint analysis method and its application in analyzing factors influencing postgraduates program selection, *Malaysian Journal of Mathematical Sciences*, 15(2) (2021), 283–291.

[11] Ahmad, S. A. S., Mohamad, D., Sulaiman, N. H., Shariff, J. M. and Abdullah, K. A distance and set theoretic-based similarity measure for generalized trapezoidal fuzzy numbers, *AIP Conference Proceedings*, 1974(1) (2018), 020043.

[12] Mutalib, S. M. A., N. R. and Mohamad, D. Forecasting fuzzy time series model based on trapezoidal fuzzy numbers with area and height similarity measure concept, *AIP Conference Proceedings*, 1974(1) (2018), 020040.

[13] Ramli, N., Alam, N. M. F. H. N. B., Mutalib, S. M. A. and Mohamad, D. Comparison of fuzzy time series forecasting model based on similarity measure concept with different types of interval length, *AIP Conference Proceedings*, 2266(1) (2020), 050011.

[14] Sulaiman, N. H. and Kamal, N. L. A. M. A subsethood-based entropy for weight determination in interval-valued fuzzy soft set group decision making, *AIP Conference Proceedings*, 1974(1) (2018), 020062.

[15] Alam, N. M. F. H. N. B., Ramli, N. and Mohd, A. H. Intuitionistic fuzzy set-based time series forecasting model via delegation of hesitancy degree to the major grade de-i-fuzzification and arithmetic rules based on centroid defuzzification, *Journal of Physics: Conference Series*, 1988(1) (2021), 012014.

[16] Atanassov, K. Intuitionistic fuzzy sets, *Fuzzy Sets and Systems*, 20(1) (1986), 87–96.

[17] Nehi, H. M. and Hamid, R. M. Intuitionistic fuzzy numbers and its applications in fuzzy optimization problem, *Proceedings of the 9th WSEAS International Conference on Systems* (2005), 1–5.

[18] Ye, J. Expected value method for intuitionistic trapezoidal fuzzy multifactors decision-making problems, *Expert Systems with Applications*, 38(9) (2011), 11730–11734.

[19] Fontela, E. and Gabus, A. The DEMATEL observer, *DEMATEL 1976 Report*, Battelle Geneva Research Center, Geneva, Switzerland (1976).

[20] Govindan, K., Devika, K. and Madan, S. Evaluation of green manufacturing practices using a hybrid MCDM model combining DANP with PROMETHEE, *International Journal of Production Research*, 53(21) (2014), 6344–6371.

[21] Gandhi, S., Sachin, K. M., Pradeep, K. and Dinesh, K. A combined approach using AHP and DEMATEL for evaluating success factors in implementation of green supply chain management in Indian manufacturing industries, *International Journal of Logistics Research and Applications*, 19(6) (2016), 537–561.

[22] Singh, P., Mittal, V. and Sangwan, K. Development and validation of performance measures for environmentally conscious manufacturing, *International Journal of Services and Operations Management*, 14 (2013), 197–220.

[23] Hori, S. and Sakurai, Y. Designing methods of human interface for supervisory control systems, *Control Engineering Practice*, 7(11) (1999), 1413–1419.