

1 **A Novel Hybrid Multi-Criteria Group Decision Making Approach for Failure Mode and Effect**
2 **Analysis: An Essential Requirement for Sustainable Manufacturing**

3 Soumava Boral^{1,2}, Ian Howard^{2*}, Sanjay K. Chaturvedi¹, Kristoffer McKee², V.N.A. Naikan¹,

4 ¹ Subir Chowdhury School of Quality and Reliability, Indian Institute of Technology Kharagpur,
5 Kharagpur, India – 721302

6 ² School of Civil and Mechanical Engineering, Curtin University, WA – 6102

7 [*Communicating author =I.Howard@exchange.curtin.edu.au]

8 **Abstract:**

9 Modern manufacturing organizations have started giving paramount importance to sustainable aspects
10 of the manufacturing processes, realising not only that the natural resources are dwindling rapidly but
11 also that they bear significant responsibility to the society and surroundings for the overall future
12 development. Catastrophic failures and the maintenance of complex equipment can generate a large
13 amount of hazardous waste within the organization that can affect the overall production level,
14 environment, along with impacting the health of workers in the long run. Failure mode and effect
15 analysis (FMEA) is an efficient risk analysis tool for processes, products, designs or services and has
16 been adopted by different types of organizations. In this paper, for the first time in the literature, the
17 consequences of failure modes of industrial equipment are considered from the sustainable point of
18 view, which is believed to be a requirement for the establishment of a successful sustainable
19 manufacturing strategy. *Severity* of failure modes are considered from environmental, societal and
20 economic points of view, along with the chances of occurrence and detection. However, due to lack of
21 exact data, these risk factors are evaluated linguistically by cross-functional experts, which made the
22 situation complex. To properly prioritize the failure modes according to their risk levels, a novel hybrid
23 Multi-Criteria Group Decision Making (MCGDM) approach by integrating Interval Type-2 Fuzzy
24 Decision-Making Trial and Evaluation Laboratory (IT2F-DEMATEL) and Modified Fuzzy Multi-
25 Attribute Ideal Real Comparative Analysis (Modified FMAIRCA) methods is proposed. Calculating
26 the causal dependencies among the risk factors and finding out their relative importance are the twofold
27 benefits of the IT2F-DEMATEL approach. Defuzzified criteria weights are further utilized in the
28 proposed modified FMAIRCA approach for risk ranking of failure modes. The effectiveness of the
29 proposed hybrid approach is demonstrated by considering a case-study from a process plant gearbox.
30 Next, the obtained ranking results are compared with the results obtained from other commonly applied
31 fuzzy MCDM methods in the FMEA domain. Stability and robustness of the proposed approach is also
32 highlighted by performing sensitivity analysis.

33 **Index Terms:** Failure mode and effect analysis; Sustainable manufacturing; Interval type-2 fuzzy sets;
34 DEMATEL; Fuzzy MAIRCA; Process plant gearbox.

1 **1. Introduction**

2 A hazard is described as anything that can cause harm to the society, such as injury, death, damage to
3 environment, reputation, property, and economic balance of an organization. Risk is defined as the
4 possibility that harm may occur due to exposure to the hazard. Most organizations try to identify the
5 causes of hazards, estimate their risks, take appropriate proactive measures to eliminate/mitigate/control
6 them and then monitor the control measures regularly. However, risk estimation related to any process,
7 product, service or design is known to be a tedious task due to the involvement of multiple indices
8 which are hard to articulate. As per IEC 31010: 2019, there are several types of risk assessment
9 techniques that include interviews, Delphi, HAZOP (Hazard and Operability Analysis), RCA (Root
10 Cause Analysis), FMEA (Failure Mode and Effect Analysis), FTA (Fault tree analysis), ETA (Event
11 Tree Analysis), etc.

12 Failure mode and effect analysis (FMEA) has been considered as a proactive risk management tool
13 in reliability engineering where systems, processes, designs or services are evaluated systematically to
14 find out their different potential failure modes, problems, errors and subsequent effects on the system
15 level. Subsequently, feasible alternatives are recommended and adopted to eliminate/mitigate the
16 consequences due to those failures modes [1]. From the historical perspective, this tool was first
17 developed as a formal design methodology in the 1960s for meeting the safety and reliability
18 requirements of the aerospace industry [2]. Later, it was adopted by different types of industrial sectors,
19 such as the automotive [3]–[5], nuclear [6], manufacturing [7]–[10], etc. for its simplicity and ease of
20 application. As a whole, a complete FMEA analysis of a system spans from the bottom to the top level
21 in a system hierarchy, where the known potential failure modes are identified by the FMEA team
22 members at the lower level, the effects of which are progressively investigated at the next or higher
23 level of the system hierarchy [1].

24 In the traditional FMEA approach, associated risks of failure modes are generally expressed by
25 developing risk priority numbers (RPNs) obtained through the multiplication of three risk factors (RFs),
26 *viz.*, severity (S), probability of occurrence (O) and probability of detection (D). These RFs are
27 evaluated by cross-functional experts according to a particular scale having scale values between 1 to
28 10, where 10 implies the most severe fault, having the most frequent occurrence, with the least
29 detectable failure mode and 1 implies the reverse (*i.e.*, least severe, least frequent, and highly detectable
30 failure mode). However, this traditional FMEA approach has been criticized due to the following main
31 reasons [1], [11]:

- 32 • RFS are evaluated and rated with respect to different failure modes by the cross-functional
33 experts (team members) using some linguistic terms, like - high, very high, low, etc. Later
34 these linguistic evaluations are converted to a customized crisp scale (usually between 1-
35 10), omitting the existing and inherent vagueness.

- 1 • Total combinations of say 1000 RPNs contain numerical values which are not unique and
- 2 are repeated several times. Histogram plots of these RPNs show that they are heavily
- 3 concentrated at the bottom of the scale. This multiplicity of RPN values may not reveal
- 4 hidden risk implications of each FM.
- 5 • Small variations in ratings of RFs may change the overall risk-ranking of the failure modes.
- 6 • Multiplicative operation is performed to obtain the final RPN value, which is debatable as
- 7 it lacks a strong mathematical foundation.
- 8 • It does not consider the relative importance of each RF during the calculations of RPN.
- 9 • Each RF (*i.e.*, severity) is implicitly defined. But, in actual case it is case-specific.

10 The idea of *sustainability* and *sustainable development* was first propounded after the 1987's
 11 Brundtland Report (World Commission of Environment and Development) by the UN. It defines the
 12 sustainable development as “...*development that meets the needs of the present without compromising*
 13 *the ability of future generations to meet their own needs*”. The U.S. Department of Commerce defined
 14 sustainable manufacturing as “...*the creation of manufactured products that use processes that minimize*
 15 *negative environmental impacts, conserve energy and natural resources, are safe for employees,*
 16 *communities, and consumers and are economically sound*” [12]. Moreover, from the last two decades,
 17 it is evident that manufacturing industries are heavily pushed to consider sustainability aspects as a
 18 major point of concern to save the planet. The Governments have started formulating and enforcing
 19 the statutory regulations (*e.g.*, Clean Air Act (1970), Resource Conservation and Recovery Act (1976)
 20 and Toxic Substance Control Act (1976)), which are mainly based on the environmental impacts of
 21 hazardous waste produced by systems/machinery during their operational, maintenance phases or after
 22 their failure [13]. Apart from these regulations, there are several other standards like ISO 45001 (related
 23 to health and safety), ISO 37001 (anti-bribery management systems), ISO 14064 (greenhouse gases),
 24 and TS 14067 (carbon footprint of products) that have also broadened the concept of sustainable
 25 development to now include economic, social and environmental aspects [14].

26 Generally, different types of hazardous waste (*e.g.*, burnt oil, grease, hazardous gases) are produced
 27 due to the failure of large scale and complex machines, which have a significant impact on the working
 28 surroundings. Apart from that, when a machine operates in a degraded condition, excess energy is
 29 consumed, and sometimes toxic substances are generated that adversely affect the environment [13].
 30 From an economical point of view, a considerable amount of the budget is utilized to repair and maintain
 31 these machines. Furthermore, in degraded condition, poor quality products are produced by these
 32 machines, which are either reused or discarded, leaving a large amount of scrap, causing further
 33 significant economic and ecological damage. Socially, the chances of occurrence of fatal accidents are
 34 increased when failures of critical machines occur as it can affect the workers' mind-set, besides causing
 35 delays and frustration in completing other assigned tasks.

1 It is obvious from the preceding discussion that to make the FMEA approach suitable for sustainable
2 manufacturing practices and industrial need, it is necessary to consider the severities of failure modes
3 from multiple aspects, like economical severity, social severity and environmental severity. These sub-
4 factors are further decoupled into multiple sub-sub factors for more accurate risk-ranking of failure
5 modes. This type of problem is considered as a multi-criteria decision making (MCDM) problem: based
6 on multiple conflicting RFs, the failures modes are ranked based on their criticality. However, in such
7 problems, RFs are rated linguistically by cross-functional experts due to the unavailability of exact
8 information, the fluctuating nature of information and variability in judgement, etc. The Type-1 fuzzy
9 set (T1 FS), proposed by Zadeh [15] is an efficient approach to deal with such natural languages and to
10 provide optimal decisions. It is often combined with MCDM approaches to make more rational
11 decisions. A detailed review of the applications of MCDM approaches, combined with T1 FS for
12 solving FMEA problems is presented in [16]. Subsequently, the concept of type-2 fuzzy set (T2 FS), as
13 an extension of T1 FS was propounded by Zadeh [17]. The main difference between these two types of
14 FSs is that the membership grade of T1 FS is a real number in $[0,1]$, whereas in T2 FS it is a fuzzy
15 number with a support bounded by the interval $[0,1]$. Further, the membership function in T2 FS
16 includes a footprint of uncertainty (FOU) that provides additional degrees of freedom for directly
17 modelling and for handling of uncertainties. In fact, T2 FSs were introduced to capture the fuzziness of
18 the membership function. However, considering the computational complexity of T2 FS, it has only
19 had limited application for real world applications. Interval type-2 fuzzy sets (IT2FSs) are mostly used
20 instead of T2 FS due to their ease of application, less computational effort, more flexibility, and being
21 able to handle the linguistic uncertainties since they can be described by primary and secondary
22 membership. However, it is admitted that both hard and soft computational complexity of IT2FS is
23 higher than that of T1 FS, and hence to keep a balance between computational complexity and
24 acceptable accuracy in the decision making problem, both T1 FS and IT2FS are employed in this paper.

25 A hybrid MCGDM framework is presented in this paper, by combining IT2F-DEMATEL and
26 modified FMAIRCA approaches. The reasons for using IT2F-DEMATEL are twofold: to derive the
27 causal relationships among the RFs, as well as to derive their relative importance. From the causal
28 diagram, it is easy to identify those RFs which have strong influence on others [18]. The relative
29 importance of the RFs is later utilized in our modified FMAIRCA approach for risk-ranking of failure
30 modes. The MAIRCA approach was first developed by Pamučar et al. [19]. The basic idea of this
31 method is to determine the gap between ideal and empirical ponderers. The gap for each criteria of the
32 alternatives are summed up and ranked accordingly thereafter. The best alternative always has the
33 lowest gap value, while the worst has the highest gap value. Following are the major advantages of this
34 MCDM method:

- 35 • Decision makers are unbiased in selecting any alternative. Hence, there is equal probability in
36 selecting the best alternative [20].

- 1 • This method has simple mathematical calculations, solution stability and is easy to combine
2 with other methods [20]–[22].
- 3 • This approach has proven to be more stable than other popular methods, like the Technique for
4 Order Preference by Similarity to Ideal Solution (TOPSIS) and ELimination Et Choix
5 Traduisant la REalité (ELECTRE) [23].

6 From the preceding discussions, and three review works [16], [24], [25], the following points are
7 observed, which are aimed to be presented in this paper:

- 8 • Severity of a failure mode is decoupled into economical, societal and ecological severity. This
9 approach is believed to be helpful in sustainable manufacturing practice within an organization.
10 To illustrate the idea in a well-organized manner, a novel case-study of a process plant gearbox
11 is considered. In that case-study, different components of a gearbox are presented along with
12 their failure modes, causes and effects.
- 13 • After observing the effectiveness of IT2FS, TI FS, DEMATEL, and MAIRCA, a hybrid
14 MCGDM approach is developed by combining IT2F-DEMATEL and modified FMAIRCA.
15 The detailed analysis of RFs is carried out after getting outputs from the IT2F-DEMATEL
16 approach. The modifications in the FMAIRCA method are carried out to improve the traditional
17 method.

18 The rest of the paper is organized as follows: In Section 2, a literature review related to decoupling
19 of RFs in FMEA problems and recent applications of different MCDM approaches for solving FMEA
20 problems are presented. In Section 3, preliminaries of fuzzy numbers, IT2FS, IT2F numbers, and their
21 arithmetic operations are briefly explained. In Section 4, the hybrid approach is presented and in Section
22 5 a case-study is supplemented to highlight the effectiveness of the proposed approach. Section 6
23 presents the validation of the proposed hybrid approach. Finally, in Section 7, the conclusion is given.

24 **2. Literature review**

25 2.1 *Decoupling risk factors in FMEA*

26 To make the FMEA approach more pertinent to the industrial needs, several researchers have considered
27 additional risk factors apart from the traditional ones commonly in use. Garrick [26] considered multiple
28 indices like quality loss of the product, environmental safety, production loss, and ‘*domino effects*’ for
29 estimating risks associated with different industries. In [27], the author considered FMECA as an
30 MCDM problem, and considered four different factors, *viz.*, chance of failure, chance of non-detection,
31 severity and expected cost for risk estimation. Finally, failure modes were ranked according to their risk
32 levels by using the Analytic Hierarchy Process (AHP). Rhee & Ishii [28] proposed a concept of life
33 cost based FMEA, wherein risk was considered from the economical point of view. In [29], severity
34 was detailed into safety, quality, maintenance cost and mean time to repair, considering the overall

1 customer's satisfaction. Von Ahsen [30] and Carmiganani [31] also solved FMEA problems from the
2 economical point of view. In [32] severity was decoupled into damage caused to safety, environment,
3 production costs and maintenance costs. Further, detectability was categorized into sub-levels, such as
4 detailed inspections, generic inspections, switchboard detection and detection by the naked eye.
5 Silvestri et al. [33] proposed the concept of safety improved risk assessment by combining the concept
6 of conventional FMEA with economic considerations. In their work, Das Adhikary et al. [34]
7 considered multiple factors such as human attributes (operator's skill, maintenance personnel skill),
8 factors related to the operating environment, downtime reduction factors (maintainability, spare parts
9 availability) and economic factors (economic loss of a failure) while performing FMEA in a thermal
10 power plant. Recently, Yousefi et al. [35] in their work considered HSE (health, safety and environment)
11 for risk prioritization, considering two additional factors, namely, cost and duration of treatment of
12 workers along with traditional severity, occurrence and detection.

13 From this above review, it is observed that none of the previous researchers have aimed to consider
14 the severity from the triple bottom line (TBL) aspect of sustainability, which is a necessary component
15 to successfully implement the practice of sustainable manufacturing in any organization. Considering
16 this research gap, at first, this paper aims to decouple the severity of failure modes from the economical,
17 societal and ecological point of view.

18 2.2 *Recent applications of MCDM methods in FMEA*

19 MCDM methods have been widely used to prioritize failure modes according to their risk levels in
20 FMEA studies. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method,
21 based on the idea of pairwise comparison has also been found to have its niche in conducting FMEA
22 analysis. It has been combined with other methods, like Shannon's entropy principle and fuzzy logic
23 [6], evidential reasoning [36], soft set theory [37], intuitionistic fuzzy logic [38], AHP [5], D-number
24 [39], rough number [9], Support Vector Machine (SVM), fuzzy inference system and logarithmic fuzzy
25 preference programming [40], and cloud model theory [41], etc. for more rationale decision-making.
26 VlseKriterijumska Optimizacija I Kompromisno Resenje; a Serbian Word (VIKOR), developed as a
27 Multi-criteria Optimization and Compromise Solution, is a compromise ranking method that has been
28 also applied solely or in combination with other approaches, like Decision Making Trial and Evaluation
29 Laboratory (DEMATEL) and AHP [4], fuzzy AHP and Entropy principle [42], Fuzzy Best-Worst
30 Method (FBWM) and fuzzy proximity & fuzzy similarity entropy [8], house of reliability and rough
31 number [43], in the FMEA domain. There are also some articles based on the application of outranking
32 based MCDM methods in FMEA, like ELECTRE combined with interval two-tuple linguistic fuzzy
33 logic [44], ELCTRE-TRI based approach [45], hesitant 2-tuple linguistic qualitative flexible multiple
34 criteria method (QUALIFLEX) [46], Preference Ranking Organization METHod for Enrichment of
35 Evaluations (PROMETHEE) integrated with cloud model [47], etc.

1 Apart from the above approaches, COMplex PROportional ASsessment (COPRAS) was integrated
 2 with the Grey number [34], and the interval valued intuitionistic fuzzy analytic network process (ANP),
 3 [48], to incorporate the inconsistency and vagueness of the decisions as well as to represent the
 4 interactions between failure modes and dependencies of the RFs. Further, the full multiplicative form
 5 of Multi-Objective Optimization by Ratio Analysis (MULTIMOORA) was extended to the fuzzy
 6 domain [49], and integrated with interval valued intuitionistic continuous weighted entropy [50], and
 7 the fuzzy AHP [51] method for making the decision-making approach simpler and robust. An effective
 8 behavioural decision making method derived from prospect theory - TODIM approach (an acronym in
 9 Portuguese for interactive and multi-criteria decision making) was extended to incorporate the linguistic
 10 distribution assessment in the FMEA domain to overcome some drawbacks of the traditional approach
 11 [7]. In [52], the Multi-Attributive Border-Approximation Area Comparison (MABAC) method was
 12 extended to interval-valued intuitionistic fuzzy sets to model the uncertainty and vagueness in a
 13 structured way. Moreover, they developed a linear programming model capable of determining the RF
 14 weight when the prior information available is incomplete. Recently, in [53] a newly developed MCDM
 15 method, Election based on Relative Value Distance (ERVD) was coupled with AHP for performing
 16 FMEA of an induction motor.

17 It is observed from the previous discussions that despite several benefits of IT2FS, so far it has not
 18 been applied in the FMEA domain. MAIRCA, being a new and potential method in the MCDM family,
 19 has not had any application in FMEA. Thus, this paper aims to present a novel hybrid MCGDM
 20 approach by using IT2F-DEMATEL and the modified FMAIRCA in the FMEA domain.

21 3. Preliminaries

22 The triangular fuzzy number and trapezoidal IT2FS are utilized in this proposed work. Therefore, some
 23 basic operations and definitions for both are briefly presented here for the sake of completeness and
 24 benefit of the reader.

25 3.1. Fuzzy Number and Arithmetic Operations

26 A fuzzy number is the special fuzzy set, which is represented as follows [15]:

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)), x \in R\}, \quad (1)$$

27 where x represents the set of values on the real number line and $\mu_{\tilde{A}}(x)$ is the continuous mapping from
 28 R to the closed interval. There are different kinds of fuzzy numbers and among them the triangular
 29 fuzzy number (TFN) is the most popular one due to its lower computational complexity and it has been
 30 used in those problems where a decision maker is not sure about the membership function of an
 31 alternative and/or criteria. A TFN is expressed as $\tilde{A} = (a_l, a_m, a_u)$. The membership function of this
 32 TFN is defined as:

$$0, x < a_l \text{ or } x > a_u \quad (2)$$

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{x - a_l}{a_m - a_l}, & a_l \leq x \leq a_m \\ \frac{a_u - x}{a_u - a_m}, & a_m < x \leq a_u \end{cases}$$

1 Usually $a_l \leq a_m \leq a_u$, and a_l, a_m and a_u are known as the smallest possible value, most promising
2 value and largest possible value, respectively of a TFN \tilde{A} .

3 Basic arithmetic operations on TFN are:

4 Let two TFNs are $\tilde{A} = (a_l, a_m, a_u)$ and $\tilde{B} = (b_l, b_m, b_u)$.

Addition: $\tilde{A} \oplus \tilde{B} = (a_l + b_l, a_m + b_m, a_u + b_u)$ (3)

Subtraction: $\tilde{A} \ominus \tilde{B} = (a_l - b_u, a_m - b_m, a_u - b_l)$ where $a_i > 0, b_i > 0$ (4)

Multiplication: $\tilde{A} \otimes \tilde{B} \cong (a_l \times b_l, a_m \times b_m, a_u \times b_u); a_l \geq 0, b_l \geq 0$ (5)

Division: $\tilde{A} \oslash \tilde{B} = (a_l \div b_u, a_m \div b_m, a_u \div b_l); a_l \geq 0, b_l > 0$ (6)

Multiplication by a crisp value: $\lambda \tilde{A} = (\lambda \times a_l, \lambda \times a_m, \lambda \times a_u); \lambda > 0$ (7)

by a crisp value: $\lambda \tilde{A} = (\lambda \times a_u, \lambda \times a_m, \lambda \times a_l); \lambda < 0$

5 3.2. Interval type-2 fuzzy sets

6 Useful definitions of type-2 fuzzy set theory are described below [18]:

7 **Definition 1:** A type-2 fuzzy set (T2FS) $\tilde{\tilde{A}}$ in the universe of discourse X is represented by Eq. (8) where
8 $\mu_{\tilde{\tilde{A}}}$ is a type-2 membership function,

$$\tilde{\tilde{A}} = \{((x, u), \mu_{\tilde{\tilde{A}}}(x, u)) | \forall x \in X, \forall u \in J_x \subseteq [0, 1], 0 \leq \mu_{\tilde{\tilde{A}}}(x, u) \leq 1\}$$
 (8)

9 where J_x denotes an interval in $[0, 1]$. A type-2 fuzzy set $\tilde{\tilde{A}}$ can also be represented as in Eq. (9)

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_x} \mu_{\tilde{\tilde{A}}}(x, u) / (x, u)$$
 (9)

10 where $J_x \subseteq [0, 1]$ and \int denotes union over all admissible x and u .

11 **Definition 2:** Let $\tilde{\tilde{A}}$ be a T2FS in the universe of discourse X represented by the type-2 membership
12 function $\mu_{\tilde{\tilde{A}}}$. If all $\mu_{\tilde{\tilde{A}}}(x, u) = 1$, then $\tilde{\tilde{A}}$ is called an IT2FS. An IT2FS $\tilde{\tilde{A}}$ can be regarded as a special
13 case of a type-2 fuzzy set, represented as follows:

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_x} 1 / (x, u)$$
 (10)

14 where $J_x \subseteq [0, 1]$.

15 In other words, if all the secondary grades are equal to 1, then T2 FS is known as IT2FS.

16 **Definition 3:** The upper membership function and the lower membership function of an IT2FS are type-
17 1 membership functions, respectively. Refer to Figure 1, which shows a trapezoidal IT2FS $\tilde{\tilde{A}}$ as given
18 in Eq. (11). In other words, when the upper membership function and lower membership function of an
19 IT2FS are of linear type, it can be known as the trapezoidal IT2FS.

$$\tilde{A} = (\tilde{A}_i^U, \tilde{A}_i^L) = \left((a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U; H_1(\tilde{A}_i^U), H_2(\tilde{A}_i^U)), (a_{i1}^L, a_{i2}^L, a_{i3}^L, a_{i4}^L; H_1(\tilde{A}_i^L), H_2(\tilde{A}_i^L)) \right) \quad (11)$$

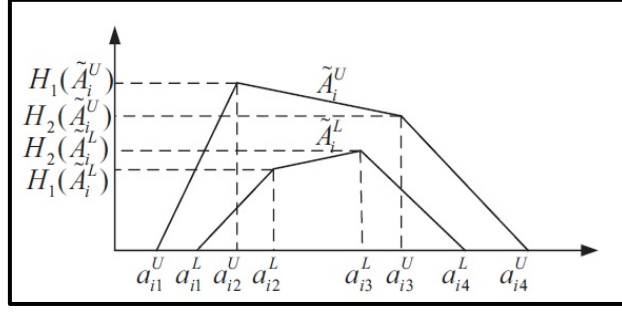


Figure 1. A trapezoidal type-2 fuzzy set [18]

\tilde{A}_i^U and \tilde{A}_i^L are type-1 fuzzy sets, $a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U, a_{i1}^L, a_{i2}^L, a_{i3}^L, a_{i4}^L$ are the reference points of IT2FS \tilde{A}_i . $H_j(\tilde{A}_i^U)$ denotes the membership value of the element $a_{j(j+1)}^U$ in the upper trapezoidal membership function (\tilde{A}_i^U), where $1 \leq j \leq 2$. $H_j(\tilde{A}_i^L)$ denotes the membership value of the element $a_{j(j+1)}^L$ in the lower trapezoidal membership function (\tilde{A}_i^L), where $1 \leq j \leq 2$. $H_1(\tilde{A}_i^U) \in [0,1], H_2(\tilde{A}_i^U) \in [0,1], H_1(\tilde{A}_i^L) \in [0,1], H_2(\tilde{A}_i^L) \in [0,1]$ and $1 \leq i \leq n$.

Arithmetic operations

Let two trapezoidal IT2FSs be,

$$\tilde{A}_1 = \left((a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), (a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)) \right), \text{ and}$$

$$\tilde{A}_2 = \left((a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1(\tilde{A}_2^U), H_2(\tilde{A}_2^U)), (a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1(\tilde{A}_2^L), H_2(\tilde{A}_2^L)) \right).$$

Definition 4 (Addition): The addition operation between the trapezoidal IT2FSs is defined as follows:

$$\begin{aligned} \tilde{A}_1 \oplus \tilde{A}_2 = & ((a_{11}^U + a_{21}^U, a_{12}^U + a_{22}^U, a_{13}^U + a_{23}^U, a_{14}^U \\ & + a_{24}^U; \min(H_1(\tilde{A}_1^U); H_1(\tilde{A}_2^U)), \min(H_2(\tilde{A}_1^U); H_2(\tilde{A}_2^U))), (a_{11}^L + a_{21}^L, a_{12}^L \\ & + a_{22}^L, a_{13}^L + a_{23}^L, a_{14}^L \\ & + a_{24}^L; \min(H_1(\tilde{A}_1^L); H_1(\tilde{A}_2^L)), \min(H_2(\tilde{A}_1^L); H_2(\tilde{A}_2^L)))) \end{aligned} \quad (12)$$

Definition 5 (Subtraction): The subtraction operator between two trapezoidal IT2FSs is carried out as follows:

$$\begin{aligned} \tilde{A}_1 \ominus \tilde{A}_2 = & ((a_{11}^U - a_{24}^U, a_{12}^U - a_{23}^U, a_{13}^U - a_{22}^U, a_{14}^U \\ & - a_{21}^U; \min(H_1(\tilde{A}_1^U); H_1(\tilde{A}_2^U)), \min(H_2(\tilde{A}_1^U); H_2(\tilde{A}_2^U))), (a_{11}^L - a_{24}^L, a_{12}^L \\ & - a_{23}^L, a_{13}^L - a_{22}^L, a_{14}^L \\ & - a_{21}^L; \min(H_1(\tilde{A}_1^L); H_1(\tilde{A}_2^L)), \min(H_2(\tilde{A}_1^L); H_2(\tilde{A}_2^L)))) \end{aligned} \quad (13)$$

Definition 6 (Multiplication): The multiplication operation between two IT2FS is carried out as follows:

$$\begin{aligned} \tilde{\tilde{A}}_1 \otimes \tilde{\tilde{A}}_2 \cong & ((a_{11}^U \times a_{21}^U, a_{12}^U \times a_{22}^U, a_{13}^U \times a_{23}^U, a_{14}^U \\ & \times a_{24}^U; \min(H_1(\tilde{A}_1^U); H_1(\tilde{A}_2^U)), \min(H_2(\tilde{A}_1^U); H_2(\tilde{A}_2^U))), (a_{11}^L \times a_{21}^L, a_{12}^L \\ & \times a_{22}^L, a_{13}^L \times a_{23}^L, a_{14}^L \\ & \times a_{24}^L; \min(H_1(\tilde{A}_1^L); H_1(\tilde{A}_2^L)), \min(H_2(\tilde{A}_1^L); H_2(\tilde{A}_2^L)))) \end{aligned} \quad (14)$$

1 **Definition 7 (Scaling of IT2FSs):** Multiplication and division of a crisp value with a trapezoidal IT2FS
 2 yields the following equations:

$$\begin{aligned} \tilde{\tilde{A}}_1 \times k = & ((a_{11}^U \times k, a_{12}^U \times k, a_{13}^U \times k, a_{14}^U \times k; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), (a_{11}^L \times k, a_{12}^L \times k, a_{13}^L \\ & \times k, a_{14}^L \times k; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L))) \end{aligned} \quad (15)$$

$$\begin{aligned} \frac{\tilde{\tilde{A}}_1}{k} = & \left(\left(a_{11}^U \times \frac{1}{k}, a_{12}^U \times \frac{1}{k}, a_{13}^U \times \frac{1}{k}, a_{14}^U \times \frac{1}{k}; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U) \right), \left(a_{11}^L \times \frac{1}{k}, a_{12}^L \times \frac{1}{k}, a_{13}^L \right. \right. \\ & \left. \left. \times \frac{1}{k}, a_{14}^L \times \frac{1}{k}; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L) \right) \right) \end{aligned} \quad (16)$$

3 **Definition 8 (Expected value of an IT2FSs):** Expected value of a trapezoidal IT2FS $\tilde{\tilde{A}}_1$ is calculated
 4 as follows:

$$E(A) = \frac{1}{2} \left(\frac{1}{4} \sum_{i=1}^4 (a_i^L + a_i^U) \right) \times \frac{1}{4} \left(\sum_{i=1}^2 (H_i(A^L) + H_i(A^U)) \right) \quad (17)$$

5 where $\tilde{\tilde{A}} = \left((a_1^U, a_2^U, a_3^U, a_4^U; H_1(\tilde{A}^U), H_2(\tilde{A}^U)), (a_1^L, a_2^L, a_3^L, a_4^L; H_1(\tilde{A}^L), H_2(\tilde{A}^L)) \right)$.

6 **4. The proposed methodology**

7 The proposed methodology consists of four steps, viz.

- 8 i. Structuring the problem
- 9 ii. Modelling the interactions between criteria by IT2FS-DEMATEL
- 10 iii. Deriving the weights of the criteria by IT2FS-DEMATEL
- 11 iv. Ranking of the alternatives by our proposed FMARICA

12 A detailed view of the above steps is shown in Figure 2 and is elaborated in the succeeding paragraphs.

13 **4.1. Structuring the problem**

14 In this step, the goal and scope of the study is defined. Subsequently, cross-functional experts are chosen
 15 by top management and they decide on criteria, sub-criteria and major alternatives of the problem being
 16 considered. The problem is depicted in a hierarchical structure for ease of decision making. Also,
 17 linguistic variables and their associated IT2FSs values are assigned/chosen.

18 **4.2. Interval type-2 fuzzy DEMATEL**

19 Major steps of IT2FS-DEMATEL are as follows [18]:

- 1 • **Step 1:** Cross-functionals are assigned to fill-out the IT2F influence matrix. For generalization,
 2 it is assumed that k number of influence matrices are obtained from k number of experts, which
 3 are denoted as $\tilde{Y}^{(1)}, \tilde{Y}^{(2)}, \tilde{Y}^{(3)}, \dots, \tilde{Y}^{(k)}$.
 4 • **Step 2:** Calculating the average of the IT2F influence matrix as in Eq. (18).

$$\tilde{Y} = \frac{\tilde{Y}^{(1)} \oplus \tilde{Y}^{(2)} \oplus \tilde{Y}^{(3)} \oplus \dots \oplus \tilde{Y}^{(k)}}{k} \quad (18)$$

5 Here \tilde{Y} represents initial direct relation matrix. This matrix is seen as Eq. (19),

$$\tilde{Y} = \begin{bmatrix} 0 & \tilde{y}_{12} & \dots & \tilde{y}_{1m} \\ \tilde{y}_{21} & & \ddots & \vdots \\ \vdots & & & \\ \tilde{y}_{m1} & \tilde{y}_{m2} & \dots & 0 \end{bmatrix} \quad (19)$$

6 where $\tilde{y}_{ij} = \left((a_{ij}, b_{ij}, c_{ij}, d_{ij}; H_1(\tilde{y}_{ij}^U), H_2(\tilde{y}_{ij}^U)), (e_{ij}, f_{ij}, g_{ij}, h_{ij}; H_1(\tilde{y}_{ij}^L), H_2(\tilde{y}_{ij}^L)) \right)$

- 7 • **Step 3:** In this step, the normalized direct relation matrix is obtained. To do that, the initial
 8 trapezoidal IT2FS direct relation matrix based on the membership function is recognized. It is
 9 observed that heights of IT2FNs do not affect the results and hence they are omitted from the
 10 subsequent calculations. A total of eight $m \times m$ matrices are constructed as follows:

$$\begin{aligned} Y_{a'} &= \begin{bmatrix} 0 & a'_{12} & \dots & a'_{1m} \\ a'_{21} & & \ddots & a'_{2m} \\ \vdots & & & \vdots \\ a'_{m1} & a'_{m2} & \dots & 0 \end{bmatrix} \\ Y_{b'} &= \begin{bmatrix} 0 & b'_{12} & \dots & b'_{1m} \\ b'_{21} & & \ddots & b'_{2m} \\ \vdots & & & \vdots \\ b'_{m1} & b'_{m2} & \dots & 0 \end{bmatrix} \\ &\vdots \\ Y_{h'} &= \begin{bmatrix} 0 & h'_{12} & \dots & h'_{1m} \\ h'_{21} & & \ddots & h'_{2m} \\ \vdots & & & \vdots \\ h'_{m1} & h'_{m2} & \dots & 0 \end{bmatrix} \end{aligned} \quad (20)$$

11 As $Y_{a'}$ contains the greatest element, we use it further for calculating the normalization
 12 coefficients. The normalized direct relation matrix is represented by Eq. (21):

$$\tilde{N} = \begin{bmatrix} \tilde{n}_{11} & \tilde{n}_{12} & \dots & \tilde{n}_{1m} \\ \tilde{n}_{21} & & \ddots & \tilde{n}_{2m} \\ \vdots & & & \vdots \\ \tilde{n}_{m1} & \tilde{n}_{m2} & \dots & \tilde{n}_{mm} \end{bmatrix} \quad (21)$$

13 Elements of the normalized direct-relation matrix are calculated as follows:

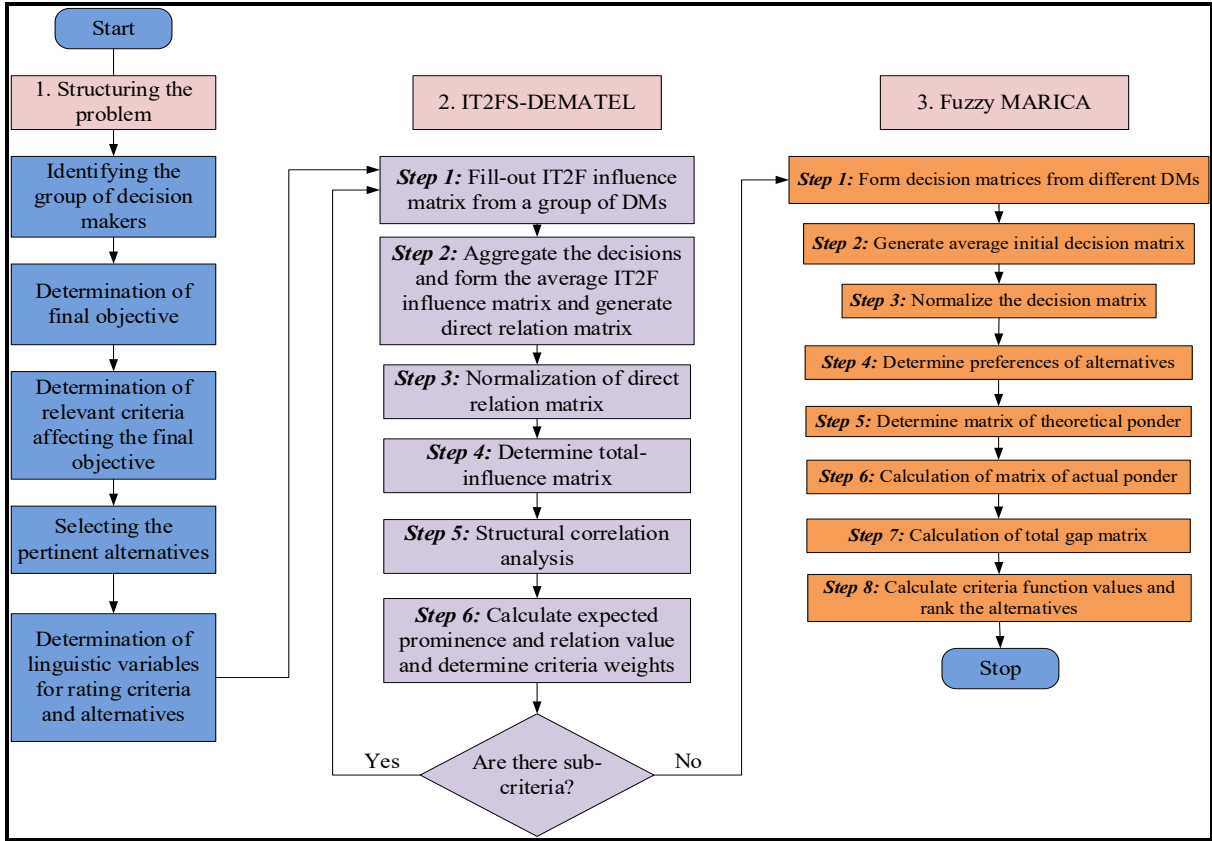


Figure 2. Workflow diagram of proposed MCGDM framework

$$\tilde{n}_{ij} = \frac{\tilde{y}_{ij}}{v} = \left(\left(\frac{Y_{a'_{ij}}}{v}, \frac{Y_{b'_{ij}}}{v}, \frac{Y_{c'_{ij}}}{v}, \frac{Y_{d'_{ij}}}{v}; H_1(\tilde{y}_{ij}^U), H_2(\tilde{y}_{ij}^U) \right) \times \left(\frac{Y_{e'_{ij}}}{v}, \frac{Y_{f'_{ij}}}{v}, \frac{Y_{g'_{ij}}}{v}, \frac{Y_{h'_{ij}}}{v}; H_1(\tilde{y}_{ij}^L), H_2(\tilde{y}_{ij}^L) \right) \right) \quad (22)$$

The normalization coefficient t is calculated as follows:

$$v = \max \left(\max_{1 \leq i \leq m} \sum_{j=1}^m Y_{a'_{ij}}, \max_{1 \leq j \leq m} \sum_{i=1}^m Y_{d'_{ij}} \right) \quad (23)$$

- **Step 4:** Obtain the total relation matrix in a similar fashion as in Step 3, where the normalized direct-relation matrix represented by eight crisp matrices are:

$$N_{a''} = \begin{bmatrix} 0 & a''_{12} & \cdots & a''_{1m} \\ a''_{21} & & \ddots & a''_{2m} \\ \vdots & & & \vdots \\ a''_{m1} & a''_{m2} & \cdots & 0 \end{bmatrix}$$

$$N_{b''} = \begin{bmatrix} 0 & b''_{12} & \cdots & b''_{1m} \\ b''_{21} & & \ddots & b''_{2m} \\ \vdots & & & \vdots \\ b''_{m1} & b''_{m2} & \cdots & 0 \end{bmatrix}$$

$$\vdots$$
(24)

$$N_{h''} = \begin{bmatrix} 0 & h''_{12} & \cdots & h''_{1m} \\ h''_{21} & & \ddots & h''_{2m} \\ \vdots & & & \vdots \\ h''_{m1} & h''_{m2} & \cdots & 0 \end{bmatrix}$$

1 The total relation matrix \tilde{T} is represented as follows:

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \cdots & \tilde{t}_{1m} \\ \tilde{t}_{21} & & \ddots & \tilde{t}_{2m} \\ \vdots & & & \vdots \\ \tilde{t}_{m1} & \tilde{t}_{m2} & \cdots & \tilde{t}_{mm} \end{bmatrix} \quad (25)$$

2 where, $\tilde{t}_{ij} = \left((a'''_{ij}, b'''_{ij}, c'''_{ij}, d'''_{ij}; H_1(\tilde{t}_{ij}^U), H_2(\tilde{t}_{ij}^U)), (e'''_{ij}, f'''_{ij}, g'''_{ij}, h'''_{ij}; H_1(\tilde{t}_{ij}^L), H_2(\tilde{t}_{ij}^L)) \right)$.

3 The elements of the matrix in Eq. (25) are calculated as follows:

$$\begin{aligned} [a'''_{ij}] &= N_{a''} \times (I - N_{a''})^{-1} \\ [b'''_{ij}] &= N_{b''} \times (I - N_{b''})^{-1} \\ &\vdots \\ [h'''_{ij}] &= N_{h''} \times (I - N_{h''})^{-1} \end{aligned} \quad (26)$$

4 • **Step 5:** To conduct the structural correlational analysis, the elements of the total-relation matrix
5 \tilde{t}_{ij} are used. Sum of the columns and sum of the rows of \tilde{T} are denoted by \tilde{R}_j and \tilde{D}_i , and
6 represented by Eq. (27) and Eq. (28), respectively.

$$\tilde{R}_j = \sum_{i=1}^m \tilde{t}_{ij} \text{ where } j = 1, 2, 3, \dots, m \quad (27)$$

$$\tilde{D}_i = \sum_{j=1}^m \tilde{t}_{ij} \text{ where } i = 1, 2, 3, \dots, m \quad (28)$$

7 To draw the causal diagram, expected values of the ordered pairs $(\tilde{D}_i \oplus \tilde{R}_i)$ and $(\tilde{D}_i \ominus \tilde{R}_i)$ are
8 calculated.

9 • **Step 6:** Importance of each criterion is calculated as in Eq. (29):

$$w_i = \sqrt{\left(E(\tilde{D}_i \oplus \tilde{R}_i) \right)^2 + \left(E(\tilde{D}_i \ominus \tilde{R}_i) \right)^2} \quad (29)$$

10 $E(\tilde{D}_i \oplus \tilde{R}_i)$ = Expected prominence and $E(\tilde{D}_i \ominus \tilde{R}_i)$ = expected relation.

11 Finally, the normalized importance degree of each criterion is calculated as in Eq. (30):

$$nw_i = \frac{w_i}{\sum_{i=1}^m w_i} \quad (30)$$

12 Sub attribute weights are calculated in a similar fashion as the calculation of the main attribute
13 weights and finally they are multiplied to get the overall weights.

1 **4.3. Proposed fuzzy MAIRCA**

2 Following steps are necessary to carry out the FMARICA procedure:

- 3 • **Step 1:** Define the initial decision matrices, where m alternatives are initially evaluated with
4 respect of the n number of criteria in linguistic terms. Later, these values are converted to TFN
5 by following any suitable and agreed scale, such as in Table 7, shown later in Section 4. Initial
6 decision matrices are represented by Eq. (31):

$$\begin{aligned}
 \tilde{D}^1 &= \begin{bmatrix} \tilde{d}_{11}^{(1)} & \tilde{d}_{12}^{(1)} & \tilde{d}_{13}^{(1)} & \cdots & \tilde{d}_{1n}^{(1)} \\ \tilde{d}_{21}^{(1)} & \tilde{d}_{22}^{(1)} & \tilde{d}_{23}^{(1)} & \cdots & \tilde{d}_{2n}^{(1)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{d}_{(m-1)1}^{(1)} & \tilde{d}_{(m-1)2}^{(1)} & \tilde{d}_{(m-1)3}^{(1)} & \cdots & \tilde{d}_{(m-1)n}^{(1)} \\ \tilde{d}_{m1}^{(1)} & \tilde{d}_{m2}^{(1)} & \tilde{d}_{m3}^{(1)} & \cdots & \tilde{d}_{mn}^{(1)} \end{bmatrix} \\
 \tilde{D}^2 &= \begin{bmatrix} \tilde{d}_{11}^{(2)} & \tilde{d}_{12}^{(2)} & \tilde{d}_{13}^{(2)} & \cdots & \tilde{d}_{1n}^{(2)} \\ \tilde{d}_{21}^{(2)} & \tilde{d}_{22}^{(2)} & \tilde{d}_{23}^{(2)} & \cdots & \tilde{d}_{2n}^{(2)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{d}_{(m-1)1}^{(2)} & \tilde{d}_{(m-1)2}^{(2)} & \tilde{d}_{(m-1)3}^{(2)} & \cdots & \tilde{d}_{(m-1)n}^{(2)} \\ \tilde{d}_{m1}^{(2)} & \tilde{d}_{m2}^{(2)} & \tilde{d}_{m3}^{(2)} & \cdots & \tilde{d}_{mn}^{(2)} \end{bmatrix} \\
 &\vdots \\
 \tilde{D}^k &= \begin{bmatrix} \tilde{d}_{11}^{(k)} & \tilde{d}_{12}^{(k)} & \tilde{d}_{13}^{(k)} & \cdots & \tilde{d}_{1n}^{(k)} \\ \tilde{d}_{21}^{(k)} & \tilde{d}_{22}^{(k)} & \tilde{d}_{23}^{(k)} & \cdots & \tilde{d}_{2n}^{(k)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{d}_{(m-1)1}^{(k)} & \tilde{d}_{(m-1)2}^{(k)} & \tilde{d}_{(m-1)3}^{(k)} & \cdots & \tilde{d}_{(m-1)n}^{(k)} \\ \tilde{d}_{m1}^{(k)} & \tilde{d}_{m2}^{(k)} & \tilde{d}_{m3}^{(k)} & \cdots & \tilde{d}_{mn}^{(k)} \end{bmatrix}
 \end{aligned} \tag{31}$$

7 where $\tilde{d}_{ij}^{(k)} = (d_l^k, d_m^k, d_u^k)$; $d_l \leq d_m \leq d_u$; $i = 1, 2, 3, \dots, m$; $j = 1, 2, 3, \dots, n$; $k =$ number of
8 decision makers.

- 9 • **Step 2:** Aggregation of decisions provided by the decision makers and construct the average of
10 the initial decision matrix as follows:

$$\tilde{D}^F = \begin{bmatrix} \tilde{d}_{11}^{(f)} & \tilde{d}_{12}^{(f)} & \tilde{d}_{13}^{(f)} & \cdots & \tilde{d}_{1n}^{(f)} \\ \tilde{d}_{21}^{(f)} & \tilde{d}_{22}^{(f)} & \tilde{d}_{23}^{(f)} & \cdots & \tilde{d}_{2n}^{(f)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{d}_{(m-1)1}^{(f)} & \tilde{d}_{(m-1)2}^{(f)} & \tilde{d}_{(m-1)3}^{(f)} & \cdots & \tilde{d}_{(m-1)n}^{(f)} \\ \tilde{d}_{m1}^{(f)} & \tilde{d}_{m2}^{(f)} & \tilde{d}_{m3}^{(f)} & \cdots & \tilde{d}_{mn}^{(f)} \end{bmatrix} \tag{32}$$

11 where $\tilde{d}_{ij}^{(f)} = \frac{(\tilde{d}_{ij}^{(1)} + \tilde{d}_{ij}^{(2)} + \dots + \tilde{d}_{ij}^{(k)})}{k}$

- 12 • **Step 3:** Decision matrix \tilde{D}^F is normalized for each of the criterion. Here a different type of
13 normalization technique, instead of the technique given in [19] is used to reduce the efforts of
14 hard computation and to improve the accuracy of numeration. Furthermore, for large number of

1 criteria, it is difficult for the decision makers to identify the cost and benefit type of criterion,
 2 which is discarded after using this technique. Eq. (33) is used in the fuzzy domain for carrying
 3 out the normalization of aggregated data:

$$\begin{aligned}
 n_{ij}^l &= \frac{d_{ij}^l}{\sqrt{\sum_{i=1}^m [(d_{ij}^l)^2 + (d_{ij}^m)^2 + (d_{ij}^u)^2]}} \\
 n_{ij}^m &= \frac{d_{ij}^m}{\sqrt{\sum_{i=1}^m [(d_{ij}^l)^2 + (d_{ij}^m)^2 + (d_{ij}^u)^2]}} \\
 n_{ij}^u &= \frac{d_{ij}^u}{\sqrt{\sum_{i=1}^m [(d_{ij}^l)^2 + (d_{ij}^m)^2 + (d_{ij}^u)^2]}}
 \end{aligned} \tag{33}$$

4 The normalized decision matrix looks like the following:

$$\tilde{N} = \begin{bmatrix} \tilde{n}_{11} & \tilde{n}_{12} & \tilde{n}_{13} & \cdots & \tilde{n}_{1n} \\ \tilde{n}_{21} & \tilde{n}_{22} & \tilde{n}_{23} & \cdots & \tilde{n}_{2n} \\ \vdots & & \vdots & & \vdots \\ \tilde{n}_{(m-1)1} & \tilde{n}_{(m-1)2} & \tilde{n}_{(m-1)3} & \cdots & \tilde{n}_{(m-1)n} \\ \tilde{n}_{m1} & \tilde{n}_{m2} & \tilde{n}_{m3} & \cdots & \tilde{n}_{mn} \end{bmatrix} \tag{34}$$

5 • **Step 4:** Next, the preferences to the selection of alternatives are defined as in Eq. (35). It is
 6 ensured that each of the alternatives are given equal preference for selection as the optimum one.

$$P_{D_i} = \frac{1}{m}; \sum_{i=1}^m P_{D_i} = 1 \tag{35}$$

7 where, m =number of alternatives.

8 • **Step 5:** For the sake of ease in calculation, criteria weights are considered as fuzzy numbers,
 9 where $\tilde{w}_i = (w_i^l, w_i^m, w_i^u)$; $w_i^l = w_i^m = w_i^u$. It is also possible to convert the IT2 criteria weight
 10 to the T1 criteria weight by using any type reduction approach [54]. The fuzzy matrix of
 11 theoretical ponder (\tilde{T}_p) is determined by the following equation:

$$\tilde{T}_p = \begin{bmatrix} \frac{1}{m} \times \tilde{w}_1 & \frac{1}{m} \times \tilde{w}_2 & \frac{1}{m} \times \tilde{w}_3 & \cdots & \frac{1}{m} \times \tilde{w}_n \\ \frac{1}{m} \times \tilde{w}_1 & \frac{1}{m} \times \tilde{w}_2 & \frac{1}{m} \times \tilde{w}_3 & \cdots & \frac{1}{m} \times \tilde{w}_n \\ \vdots & & \vdots & & \vdots \\ \frac{1}{m} \times \tilde{w}_1 & \frac{1}{m} \times \tilde{w}_2 & \frac{1}{m} \times \tilde{w}_3 & \cdots & \frac{1}{m} \times \tilde{w}_n \\ \frac{1}{m} \times \tilde{w}_1 & \frac{1}{m} \times \tilde{w}_2 & \frac{1}{m} \times \tilde{w}_3 & \cdots & \frac{1}{m} \times \tilde{w}_n \end{bmatrix} \tag{36}$$

12 where, $\tilde{t}_{p_{ij}} = \frac{1}{m} \times \tilde{w}_j$, where $i = 1,2,3, \dots, m$ and $j = 1,2,3, \dots, n$.

- 1 • **Step 6:** Calculation of matrix elements of actual ponder \tilde{T}_r which is calculated by following Eq.
 2 (37). Each element is denoted by $\tilde{t}_{r_{ij}}$:

$$\tilde{T}_r = (\tilde{N} \otimes \tilde{T}_p) \quad (37)$$

- 3 • **Step 7:** Total gap matrix (G) is calculated by using the notion of fuzzy Euclidean distance for
 4 each criterion from the theoretical and actual ponder matrix as shown in Eq. (38). By using this,
 5 the necessity of de-fuzzification for calculating the criteria function is eliminated. Each of the
 6 elements G is denoted by g_{ij} :

$$[G]_{m \times n} = \left[\sqrt{\frac{1}{3} \left[(t_{p_{ij}}^l - t_{r_{ij}}^l)^2 + (t_{p_{ij}}^m - t_{r_{ij}}^m)^2 + (t_{p_{ij}}^u - t_{r_{ij}}^u)^2 \right]} \right]_{m \times n} \quad (38)$$

- 7 • **Step 8:** Final values of criterion functions for each of the alternatives are calculated by summing
 8 up the gap values as represented by Eq. (39):

$$Q_i = \sum_{j=1}^n g_{ij} \text{ where } i = 1, 2, 3, \dots, m \quad (39)$$

9 The alternative with the lowest gap distance is selected as the best one, whereas the alternative
 10 with the highest gap distance is considered as the worst one.

11 5. Case Study

12 5.1. Description of the problem

13 A gearbox used in a steel processing plant (light medium and merchant mill section) is considered as a
 14 potential case study of the proposed approach. The block diagram of the considered gearbox is shown
 15 in Figure 3. In this section of the plant, the final shapes and sizes to the red-hot cast blooms are given.

16 A total of seven gearboxes are arranged sequentially to produce the final output. These gearboxes
 17 operate in a harsh industrial environment, where ambient temperature, humidity, dust level and
 18 surrounding vibration are significantly higher than normal. Each of these gearboxes are critical in terms
 19 of operational and production points of view. The failure of anyone of them not only damages the
 20 quality of the final billet with a large economical loss but can also cause a major accident by severely
 21 injuring the operator(s) and may even lead to their death. Due to the strict sustainable regulations from
 22 the government and to facilitate the sustainable manufacturing practices, the organization is aiming to
 23 analyse the failure modes of the different components of the gearboxes, their effects on economical,
 24 social and environmental aspects.

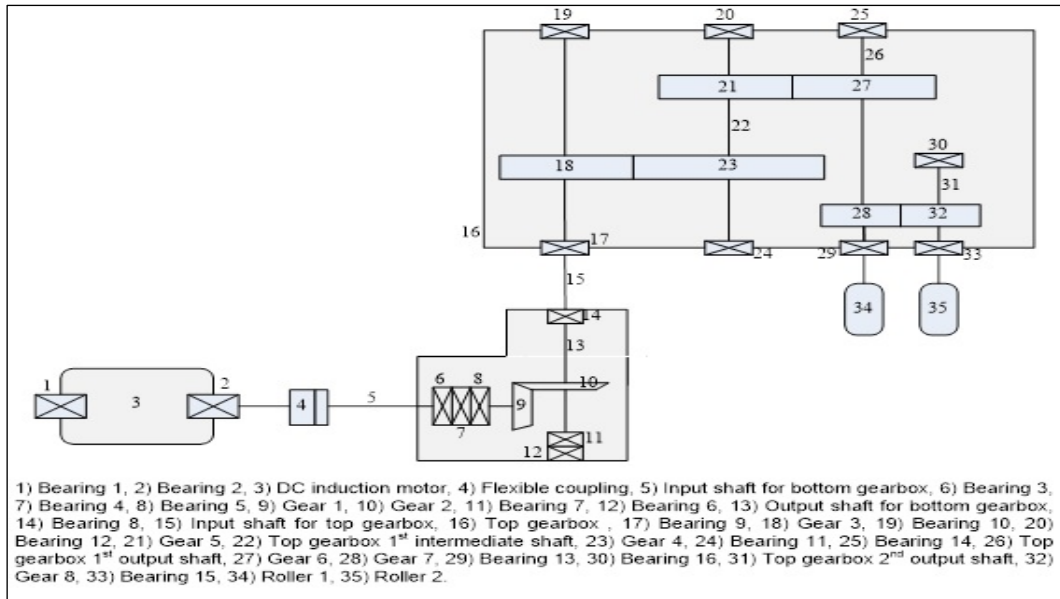


Figure 3. Schematic diagram of considered gearbox [55]

5.2. Structuring the problem

Three cross-functional experts were identified by the organization: one from top management (DM1), and another two are the chief workshop manager (DM2) and a workshop engineer (DM3), respectively. For the sake of simplicity in mathematical calculations, equal weightages are assigned to these experts. However, different weightages to the cross-functional experts can be given as shown in [1]. Later, these experts are asked to identify the most commonly occurring failure modes, their causes, effects (refer Table 1) and risk factors (refer Figure 4).

5.3. Evaluating the causal dependencies and relative importance among risk factors by IT2F-DEMATEL

To show the procedure of calculating causal dependencies and local priorities among risk factors by IT2F-DEMATEL, the severity, probability of occurrence and probability of detection were primarily considered as potential candidates.

Step 1: The degrees of causal dependencies among factors are elicited by cross-functional experts, as shown in Appendix A.1 to A.5, where linguistic variables are used showing causal relationships among risk factors and are provided in Table 2.

Step 2: The average influence matrix is constructed by employing Eq. (18) and Eq. (19). The generated initial direct relation matrix is provided in Appendix B.1.

Step 3: The normalized initial direct relation matrix is obtained by using Eq. (20) – Eq. (23). In this case, the normalized coefficient is 1.433. This matrix is given in Appendix B.2.

Table 1. Different failure modes of the components of the gearbox, their causes and effects

Components	Notations	Failure Modes	Failure causes	Failure effects	
Gear	FM1	Wear of Teeth	<ul style="list-style-type: none"> - Due to excessive load on tooth profile. This load is larger than the endurance limit of the material, - improper mounting of gears, - poor lubricating condition, - improper heat treatment of gear material, -impurities in the lubricating oil. 	Economical	<ul style="list-style-type: none"> - Delay in timely delivery of the final product, - Production of out-of-design final product, - For excessive wear, other costs are incurred, like procurement cost, ordering cost, lost production, etc.
				Social	<ul style="list-style-type: none"> - Excessive wear leads to increased noise and vibration, increase of smear by lubricant, which can harm the operators physically, - Lost production time is compensated with excess labour hours to meet the output target, - Worker's mind-set is changed due to repetitive failure and interruption.
				Environmental	<ul style="list-style-type: none"> - Produce harmful and toxic gases due to burning of lubricants, - Proper disposal of burnt lubricating oil, waste material and their recycling are a major problem.
	FM2	Broken Teeth	<ul style="list-style-type: none"> - Unexpected heavy load on gears. - fatigue breakage from cyclic loading, - excessive wear of teeth and thinning of teeth, etc. 	Economical	Excessive lead time, out-of-design final product preparation, and other procurement and installation related costs.
				Social	<ul style="list-style-type: none"> - Can obstruct the smooth movement of red-hot cast bloom and subsequently those blooms can fall out of the pathway, which will harm the operator, - excess working hours for the operators, and change of their mind-set, etc.
				Environmental	- Same as FM1.
	FM3	Pitting of Gear	<ul style="list-style-type: none"> - Improper consideration of hardness, texture and load. Actual born load generally exceeds the endurance limit, - excessive hardening or crispiness of gear surface, 	Economical	-Same as FM1 and FM2
				Social	-Same as FM1 and FM2
				Environmental	-Same as FM1 and FM2

			- use of improper lubricating oil, etc.		
	FM4	Axial Shift of Gear	- Improper mounting due to lack of knowledge of the operator, - sudden excessive load, -improper design of teeth profile, etc.	Economical	-It can incur huge economic losses, in terms of lost production, higher lead time, damage of final product, etc.
				Social	- Can harm the operator physically and fatal accident may occur.
				Environmental	- Same as FM1, - at the initial stage, more energies are required to move the other meshing gears, etc.
	FM5	Scoring of gears	- poor quality of lubricating oil, with improper viscosity, - poor matching of material, -improper cooling of lubricating oils, larger loads, etc.	Economical	- Same as FM1
				Social	- Scoring of gear can lead to other types of failures, like wear, breakage of teeth or axial shifts and can cause similar types of damages as mentioned above.
				Environmental	- Same as FM1 and FM4.
Bearing	FM6	Brinelling	- shock or excessive loads due to improper mounting, - excessive static or impact load during operation, - improper installation and handling, etc.	Economical	- Can damage other components of the bearing which will lead to total replacement, - excessive vibration can damage the final dimension of the cast blooms, etc.
				Social	- At the later stage, due to excessive vibration, can lead to fatal accident, - replacement of bearing will cause increased lead-time, affects the worker's mind-set to a great extent, etc.
				Environmental	- Can damage the lubrication oil, which in turns damage the other parts, and can produce some toxic gases at the burnt condition, - draw excessive energy for operation, etc.
	FM7	Cage defect	- Excessive vibration caused due to damage of other components,	Economical	- Same as FM6

			<ul style="list-style-type: none"> - contamination and insufficiency of lubricating oil, - fluctuation in the rotating speed due to shocks coming from cast blooms, - improper alignment of balls, etc. 	Social	- Same as FM6
				Environmental	- Same as FM6
	FM8	Crack on raceways	<ul style="list-style-type: none"> - Excessive interference, - excessive load and shock load, - flaking progression, - generation of heat due to creep, - poor taper angle of tapered shaft, etc. 	Economical	- Same as FM6
				Social	- Same as FM6
				Environmental	- Same as FM6
	FM9	Crack of rollers	- Almost similar causes like FM8	Economical	- Same as FM6
				Social	- Same as FM6
				Environmental	- Same as FM6
	Shaft	FM10	Bent shaft	<ul style="list-style-type: none"> - Mostly due to improper installation and setup activities, - heavy shock loads during operation, - thermal expansion or contraction caused due to other reasons, etc. 	Economical
Social					<ul style="list-style-type: none"> - can lead to fatal accidents of the operators, - affects the working mentality of the operator, - overtime work to meet the output target, etc.
Environmental					<ul style="list-style-type: none"> - Generates a lot of waste material which in turn creates a proper disposal problem, - creates excessive heat and burns the lubricating oil. Burnt lubricating oil generates toxic gases, etc.
FM11		Crack of shaft	<ul style="list-style-type: none"> - metallurgical abnormalities, - cyclic fatigue, 	Economical	- Similar to FM10
				Social	- Similar to FM10

			- excessive torque, - increased stress due to misalignment, etc.	Environmental	- Similar to FM10
	FM12	Fracture of shaft	- Heavy loads, - cyclical stress, - poor design, etc.	Economical	- Similar to FM10
				Social	- Similar to FM10
				Environmental	- Similar to FM10

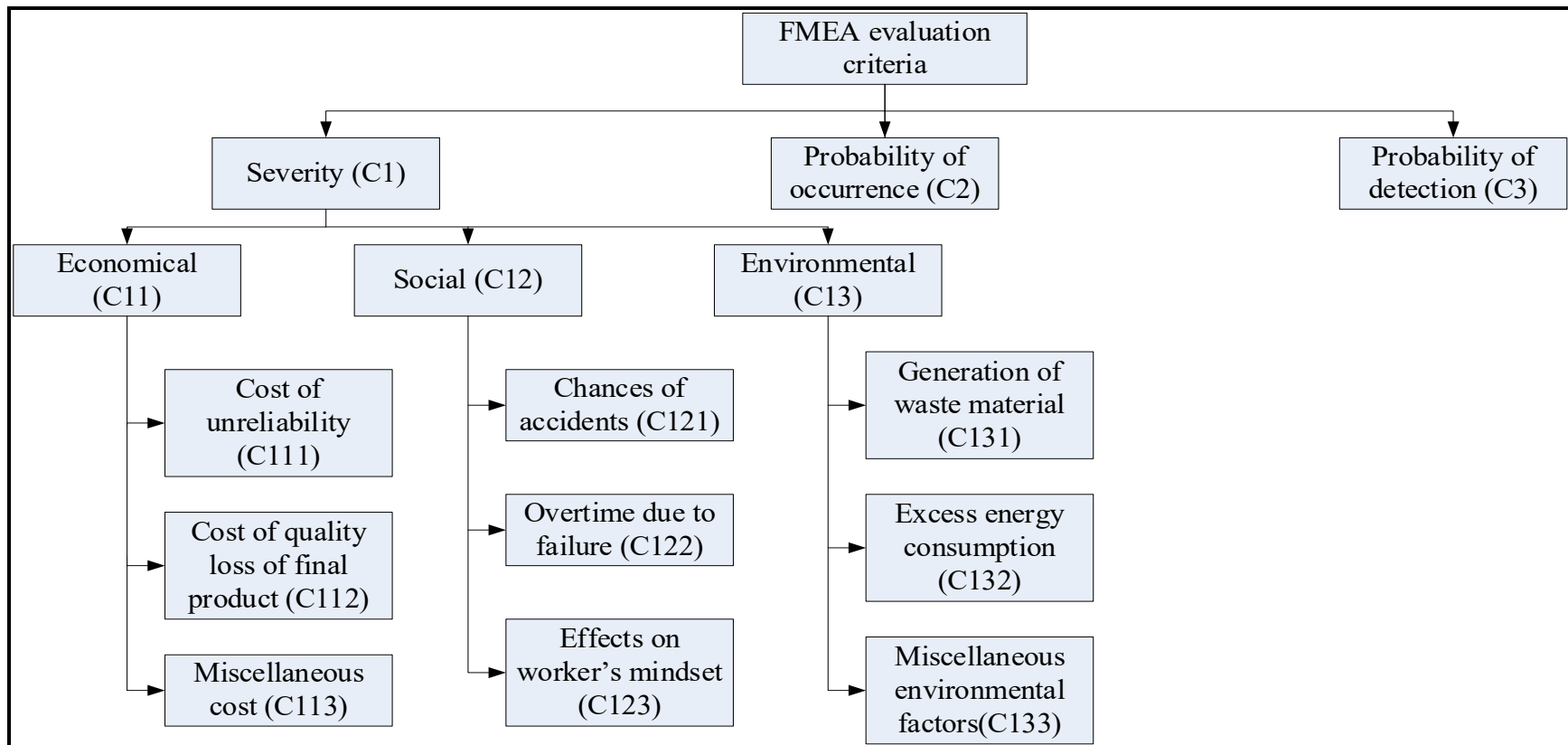


Figure 4. Factors considered for FMEA

1
2
3
4

1

Table 2. Linguistic variables for causal relationships among attributes

Linguistic variable	IT2FN
Very-very low (VVL)	((0,0.1,0.1,0.2;1,1), (0.05,0.1,0.1,0.15;0.9,0.9))
Very low (VL)	((0.1,0.2,0.2,0.35;1,1), (0.15,0.2,0.2,0.3;0.9,0.9))
Low (L)	((0.2,0.35,0.35,0.5;1,1), (0.25,0.35,0.35,0.45;0.9,0.9))
Medium (M)	((0.35,0.5,0.5,0.65;1,1), (0.4,0.5,0.5,0.6;0.9,0.9))
High (H)	((0.5,0.65,0.65,0.8;1,1), (0.55,0.65,0.65,0.75;0.9,0.9))
Very high (VH)	((0.65,0.8,0.8,0.9;1,1), (0.7,0.8,0.8,0.85;0.9,0.9))
Very-very high (VVH)	((0.8,0.9,0.9,1;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))

2 **Step 4:** Total relation matrix is provided in Appendix B.3 and is being calculated by using Eq. (24) –
3 Eq. (26).

4 **Step 5:** Next, the structural correlation analysis is performed, by employing Eq. (27) and Eq. (28) .
5 Thus, \tilde{R} and \tilde{D} values are obtained, respectively, as provided in Table 3.

6

Table 3. Sum of rows and columns of total relation matrix

	\tilde{D}	\tilde{R}
S	((1.0760,1.7811,1.7811,3.0022;1.000,1.000), (1.290,1.781,1.781,2.419;0.900,0.900))	((0.9435,1.6393,1.6393,2.8626;1.000;1.000), (1.150,1.639,1.639,2.295;0.900,0.900))
O	((0.3138,0.6791,0.6791,1.3961;1.000,1.000), (0.426,0.679,0.679,1.073;0.900,0.900))	((0.2938,0.6445,0.6445,1.3474;1.000,1.000), (0.400,0.644,0.644,1.034;0.900,0.900))
D	((0.7966,1.3582,1.3582,2.3268;1.000,1.000), (0.959,1.358,1.358,1.868;0.900,0.900))	((0.9492,1.5345,1.5345,2.5152;1.000,1.000), (1.125,1.535,1.535,2.031;0.900,0.900))

7 **Step 6:** Further, the values of $E(\tilde{D}_j \oplus \tilde{R}_j)$ and $E(\tilde{D}_j \ominus \tilde{R}_j)$ are computed by using Eq. (17). The local
8 priorities are calculated by using Eq. (29) – Eq. (30) and are presented in Table 4-Table 5, respectively.

9

Table 4. $\tilde{D} \oplus \tilde{R}$ values

	$\tilde{D} \oplus \tilde{R}$	$\tilde{D} \ominus \tilde{R}$
S	((2.0195,3.4204,3.4204,5.8647;1.000,1.000), (2.4402,3.4204,3.4204,4.7136;0.900,0.900))	((-1.7865,0.1417,0.1417,2.0587;1.000,1.000), (-1.005,0.142,0.142,1.269;0.900,0.900))
O	((0.6076,1.3236,1.3236,2.7435;1.000,1.000), (0.8261,1.3236,1.3236,2.1078;0.900,0.900))	((-1.0336,0.0346,0.0346,1.1023;1.000,1.000), (-0.608,0.035,0.035,0.673;0.900,0.900))
D	((1.7458,2.8927,2.8927,4.8420;1.000,1.000), (2.0837,2.8927,2.8927,3.8989;0.900,0.900))	((-1.7185, -0.1763, -0.1763,1.3777;1.000,1.000), (-1.072, -0.176, -0.176,0.743;0.900,0.900))

10

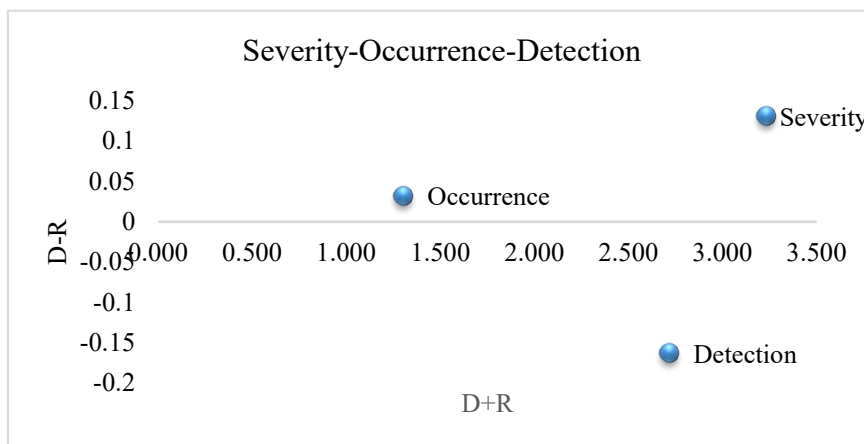
Table 5. Final weights of S-O-D factors

	D+R	D-R	Weights	Normalized weight
S	3.231	0.13095	3.234	0.446
O	1.303	0.032303	1.303	0.180
D	2.716	-0.16325	2.721	0.375

1 In a similar way, the relative importance of the sub-factors is computed. Finally, we calculate
 2 the overall weights of all the considered factors, as presented in Table 6, as subsequently utilized in the
 3 next step of ranking the failure modes.

4 **Table 6.** Calculated weights of considered factors by IT2FS-DEMATEL

Factors	Weights	Sub factors	Sub-factor weights	Sub-sub factors	Sub-sub factor weights	Overall weights
Severity	0.446	Economical	0.361	Cost of unreliability	0.436	0.070
				Cost of quality loss	0.261	0.041
				Miscellaneous cost	0.303	0.049
		Social	0.324	Chances of accidents	0.302	0.044
				Overtime due to failure	0.304	0.044
				Effects on workers mind-set	0.394	0.057
		Environmental	0.315	Generation of waste material	0.389	0.055
				Excess energy consumption	0.313	0.044
				Miscellaneous environmental factors	0.298	0.042
		Probability of occurrence	0.180	----	----	----
Probability of detection	0.375	----	----	----	----	0.375

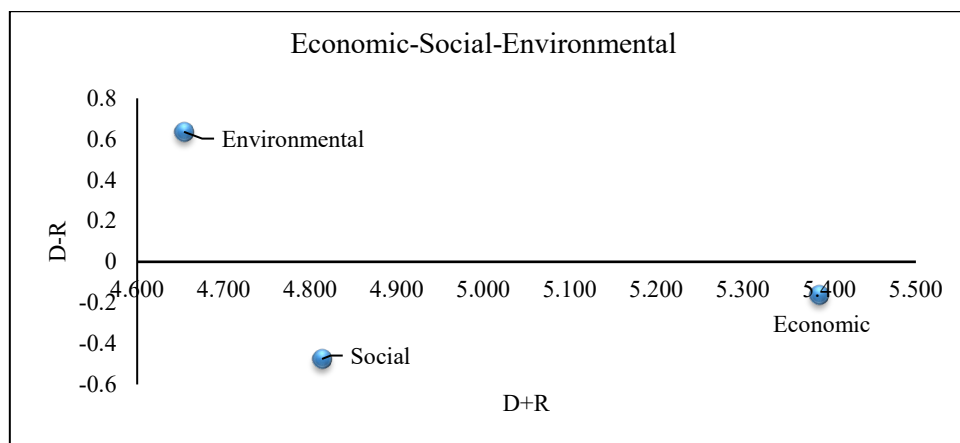


5
 6 **Figure 5.** Causal diagram of Severity-Occurrence-Detection

7 The causal diagram between severity (C1), occurrence (C2) and detection (C3) is represented
 8 by Figure 5. The cause group is known as the influencing factors and the effect group is known as the

1 influenced factors. From the results, it is recommended to the decision makers that they must give their
 2 attention to the cause group, which subsequently controls the effect group. In this case study, decision
 3 makers are advised to give their utmost priority to the severity (C1) and occurrence (C2) factors.
 4 Referring to Figure 5, severity (C1) is decoupled into several sustainable indices, economical (C11),
 5 societal (C12) and environmental (C13) sub-factors, which should be considered for further
 6 improvement of the system. On the other side, chances of occurrence (C2) can only be decreased if
 7 proper maintenance procedures are followed. It is also necessary that the plant is equipped with,
 8 wherever feasible, technologically advanced modern fault detection instrumentation with automated
 9 fault diagnosis arrangements. Further, it is observed from Table 5 that severity (C1) has the highest
 10 prominence value (3.231) and relation value (0.1309). It implies that severity (C1) is the most
 11 influencing factor above the other two factors. Whereas, a high relation value implies that it is not
 12 influenced by other factors and sub-factors. Hence, in this situation, it is always preferable to give
 13 attention to improve other factors for overall system improvement. The only member in the effect group
 14 is detection (C3), whose ($D - R$) value is quite low (-0.1632). This implies that chances of
 15 improvement with this factor are the highest.

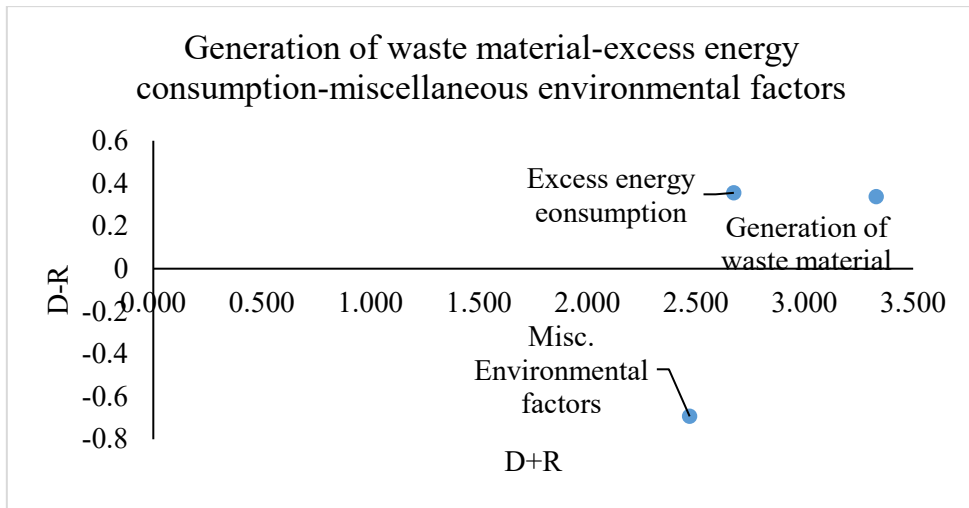
16 Similarly, the causal dependencies among other RFs under severity (C1) are computed and
 17 shown in Figure 6 to Figure 9. Like previous analysis, C1 is decoupled and as it also belongs to the
 18 cause group (or influencing factor), it is necessary to analyse it further. From Figure 6, it is observed
 19 that the economical aspect (C11) has the highest prominence value (5.388), but a lower relation value
 20 (-0.1607). Furthermore, it belongs to the effect group along with the social aspects (C12), which is
 21 influenced by the environmental aspects (C13), whose prominence value (4.654) is lower than the
 22 economic aspects but has the highest relation value (0.6359). In such a scenario, the advice is to give
 23 the utmost importance to environmental aspects (C13), as it is the strongest influencing one.



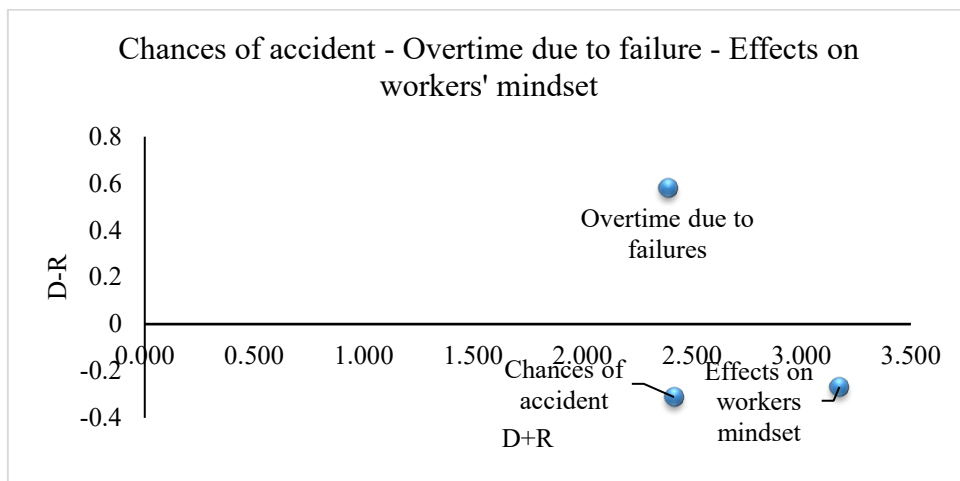
24
 25 **Figure 6.** Causal diagram of Economic-Social-Environmental criteria

26 As environmental aspects belong to the cause group, it is further analysed for better inferences.
 27 From Figure 7, it is observed that generation of waste material (C131) has the highest prominence value
 28 (3.330) and lower relation value (0.3367). It also belongs to the cause group along with excess energy

1 consumption (C132), which has less prominence value (2.674) and highest relation value (0.3557).
 2 These imply that generation of waste material (C131) is the most worrying sub-factor rather than excess
 3 energy consumption (C132), when the severity is considered from an environmental point of view.
 4 Other miscellaneous environmental factors (C133) include generation of toxic gases, fumes, dusts, etc.
 5 when the gearbox is operated in degraded conditions.



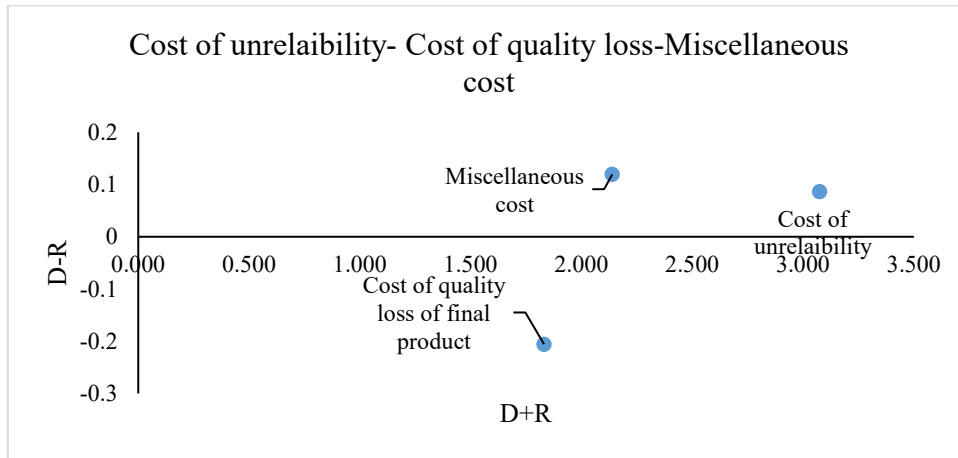
6
 7 **Figure 7.** Causal diagram of Generation of waste material-excess energy consumption-miscellaneous
 8 environmental factors



9
 10 **Figure 8.** Causal diagram of Chances of accident - Overtime due to failure - Effects on workers'
 11 mind-set

12 From Figure 8, from the societal point of view, it is observed that effects on workers' mind-
 13 set due to failure (C123) has the largest prominence value (3.173) with largest local priority (0.394),
 14 although it belongs to the effect group. It is due to that fact that each worker is normally given set task(s)
 15 during their working hours. However, when a gearbox encounters a catastrophic failure, their mind-set
 16 and efficiency changes. Overtime due to failure (C122) belongs to the cause group, as it influences the
 17 chances of accidents due to improper vigilance and machinery failure. Chances of accidents has the

1 least relation value (-0.3112) and implies that it can be further improved by preventing failure of the
 2 machinery.



3
 4 **Figure 9.** Causal diagram of cost of unreliability-cost of quality loss of final product-miscellaneous
 5 cost

6 From an economical point of view, cost of unreliability (C111) and miscellaneous cost (C113)
 7 belongs to the cause group and have local priorities of 43.6% and 30.3 %, respectively, as shown in
 8 Figure 9. Cost of unreliability (C111) is increased with number of failures, which can be controlled if
 9 the detection level is high enough and complemented by proactive maintenance efforts. Miscellaneous
 10 cost includes several factors such as inventory costs, procurement costs, etc. whose data are not easy to
 11 get, hence they are depicted linguistically. The only factor that belongs to the effect group is cost of
 12 quality loss of final product (C112), whose ($D - R$) value is least (-0.2056) and can only be improved
 13 if the other two indices, C11 and C113 are improved.

14 After calculating relative importance and causal dependencies of all factors and sub-factors, the
 15 next step is to rank the failure modes according to their level of risks.

16 **5.4. Ranking of failure modes**

17 The following steps are involved in risk-ranking of failure modes:

18 **Step 1:** Linguistic decision matrices are obtained from cross-functional experts placed in Appendix C.
 19 Using Table 7, the initial decision matrix is obtained.

20

1

Table 7. Fuzzy evaluation scores for alternatives

Linguistic terms	Fuzzy score
Very Poor (VP)	(0,0,1)
Poor (P)	(0,1,3)
Medium Poor (MP)	(1,3,5)
Fair (F)	(3,5,7)
Medium Good (MG)	(5,7,9)
Good (G)	(7,9,10)
Very Good (VG)	(9,10,10)

2 **Step 2:** Using Eq. (32), the aggregated decision matrix is obtained.

3 **Step 3:** Next, the initial decision matrix is normalized by using Eq. (33)-(34) as given in Table 8.

4

Table 8. Fuzzy normalized decision matrix

Failure Modes	C111	C112	C113	C121	C122
Wear of Teeth	(0.117,0.159,0.193)	(0.019,0.067,0.125)	(0,0.021,0.075)	(0,0.025,0.088)	(0.053,0.117,0.181)
Broken Teeth	(0.159,0.193,0.207)	(0.01,0.048,0.106)	(0.011,0.053,0.118)	(0.013,0.063,0.139)	(0.245,0.299,0.32)
Pitting of Gear	(0.062,0.104,0.145)	(0.01,0.038,0.087)	(0.043,0.096,0.16)	(0.013,0.063,0.139)	(0.181,0.245,0.299)
Axial Shift of Gear	(0.173,0.2,0.207)	(0.106,0.164,0.221)	(0.043,0.096,0.16)	(0.088,0.164,0.239)	(0.021,0.075,0.139)
Scoring of gears	(0.007,0.035,0.076)	(0.01,0.048,0.106)	(0.011,0.053,0.118)	(0.013,0.063,0.139)	(0.203,0.267,0.309)
Brinelling	(0.076,0.117,0.159)	(0.048,0.106,0.164)	(0,0.032,0.096)	(0.013,0.063,0.139)	(0.139,0.203,0.267)
Cage defect	(0.159,0.193,0.207)	(0.106,0.164,0.221)	(0.246,0.299,0.321)	(0.05,0.113,0.189)	(0.064,0.117,0.181)
Crack on raceways	(0.173,0.2,0.207)	(0.106,0.164,0.221)	(0.182,0.246,0.289)	(0.013,0.063,0.139)	(0.011,0.053,0.117)
Crack of rollers	(0.159,0.193,0.207)	(0.144,0.202,0.25)	(0.139,0.203,0.257)	(0.013,0.063,0.139)	(0.032,0.075,0.139)
Bent shaft	(0.131,0.173,0.2)	(0.183,0.241,0.279)	(0.053,0.118,0.182)	(0.164,0.239,0.315)	(0.011,0.053,0.117)
Crack of shaft	(0.145,0.18,0.2)	(0.164,0.221,0.26)	(0.246,0.299,0.321)	(0.139,0.214,0.29)	(0.021,0.075,0.139)
Fracture of shaft	(0.173,0.2,0.207)	(0.221,0.269,0.289)	(0.011,0.053,0.118)	(0.315,0.365,0.378)	(0.011,0.053,0.117)
C123	C131	C132	C133	C2	C3
(0.173,0.228,0.264)	(0.086,0.144,0.201)	(0.033,0.074,0.123)	(0.043,0.1,0.186)	(0.048,0.109,0.182)	(0.097,0.141,0.186)
(0.155,0.209,0.255)	(0.105,0.163,0.22)	(0.057,0.107,0.156)	(0.014,0.071,0.157)	(0.061,0.133,0.206)	(0.171,0.208,0.223)
(0.191,0.246,0.273)	(0.038,0.086,0.144)	(0.016,0.057,0.107)	(0.014,0.071,0.157)	(0.085,0.157,0.23)	(0.141,0.186,0.216)
(0.1,0.155,0.209)	(0,0.019,0.067)	(0.139,0.189,0.222)	(0.043,0.1,0.186)	(0.048,0.109,0.182)	(0.037,0.082,0.126)
(0.173,0.228,0.264)	(0.029,0.067,0.124)	(0.008,0.041,0.09)	(0.029,0.1,0.186)	(0.061,0.133,0.206)	(0.082,0.126,0.171)
(0.137,0.191,0.237)	(0.057,0.105,0.163)	(0.008,0.041,0.09)	(0.057,0.129,0.214)	(0.157,0.23,0.303)	(0.037,0.082,0.126)
(0.009,0.046,0.1)	(0.239,0.277,0.287)	(0.123,0.172,0.213)	(0.086,0.157,0.243)	(0.012,0.061,0.133)	(0.186,0.216,0.223)
(0.046,0.1,0.155)	(0.019,0.067,0.124)	(0.156,0.205,0.238)	(0.014,0.071,0.157)	(0.278,0.339,0.363)	(0.201,0.223,0.223)
(0.009,0.046,0.1)	(0.239,0.277,0.287)	(0.172,0.222,0.246)	(0.086,0.157,0.243)	(0.085,0.157,0.23)	(0.156,0.193,0.216)
(0,0.018,0.064)	(0.057,0.105,0.163)	(0.189,0.23,0.246)	(0.086,0.157,0.243)	(0.061,0.133,0.206)	(0.082,0.126,0.171)
(0.082,0.137,0.191)	(0.067,0.124,0.182)	(0.172,0.222,0.246)	(0.1,0.186,0.271)	(0.012,0.061,0.133)	(0.082,0.126,0.171)
(0.1,0.155,0.209)	(0.22,0.268,0.287)	(0.205,0.238,0.246)	(0.243,0.328,0.386)	(0,0.024,0.085)	(0.186,0.216,0.223)

5 **Step 4:** Next, using Eq. (35), the matrix of preference according to the available alternatives is obtained.

6 In this case-study, the value is $(\frac{1}{m}) = 0.0833$.

- 1 **Step 5:** Matrix of theoretical ponder is obtained by using Eq. (36).
- 2 **Step 6:** Next, the matrix of actual ponder is calculated according to Eq.(37).
- 3 **Step 7:** The total gap matrix is calculated by using Eq. (38) as provided in Table 9.

4 **Table 9.** Total gap matrix

Failure Modes	C111	C112	C113	C121	C122	C123	C131	C132	C133	C2	C3
Wear of Teeth	0.0049	0.0032	0.0040	0.0035	0.0032	0.0037	0.0039	0.0034	0.0031	0.0133	0.0269
Broken Teeth	0.0047	0.0032	0.0038	0.0034	0.0026	0.0038	0.0038	0.0033	0.0032	0.0130	0.0250
Pitting of Gear	0.0052	0.0033	0.0037	0.0034	0.0028	0.0036	0.0042	0.0034	0.0032	0.0127	0.0256
Axial Shift of Gear	0.0047	0.0029	0.0037	0.0031	0.0034	0.0040	0.0045	0.0030	0.0031	0.0133	0.0287
Scoring of gears	0.0056	0.0032	0.0038	0.0034	0.0027	0.0037	0.0043	0.0035	0.0031	0.0130	0.0273
Brinelling	0.0052	0.0031	0.0039	0.0034	0.0029	0.0039	0.0041	0.0035	0.0030	0.0116	0.0287
Cage defect	0.0047	0.0029	0.0029	0.0032	0.0032	0.0045	0.0034	0.0030	0.0029	0.0140	0.0248
Crack on raceways	0.0047	0.0029	0.0031	0.0034	0.0034	0.0043	0.0043	0.0029	0.0032	0.0101	0.0245
Crack of rollers	0.0047	0.0027	0.0033	0.0034	0.0034	0.0045	0.0034	0.0029	0.0029	0.0127	0.0254
Bent shaft	0.0049	0.0026	0.0036	0.0028	0.0034	0.0046	0.0041	0.0029	0.0029	0.0130	0.0273
Crack of shaft	0.0048	0.0027	0.0029	0.0029	0.0034	0.0041	0.0040	0.0029	0.0029	0.0140	0.0273
Fracture of shaft	0.0047	0.0025	0.0038	0.0024	0.0034	0.0040	0.0034	0.0028	0.0024	0.0145	0.0248

- 5 **Step 8:** Table 10 shows the criteria function values as given in Eq. (39). As stated earlier, the failure
- 6 mode with the highest gap value is the worst one and *vice-versa* as per the proposed modified
- 7 FMAIRCA method.

8 **Table 10.** Defuzzied gap values and ranking of failure modes

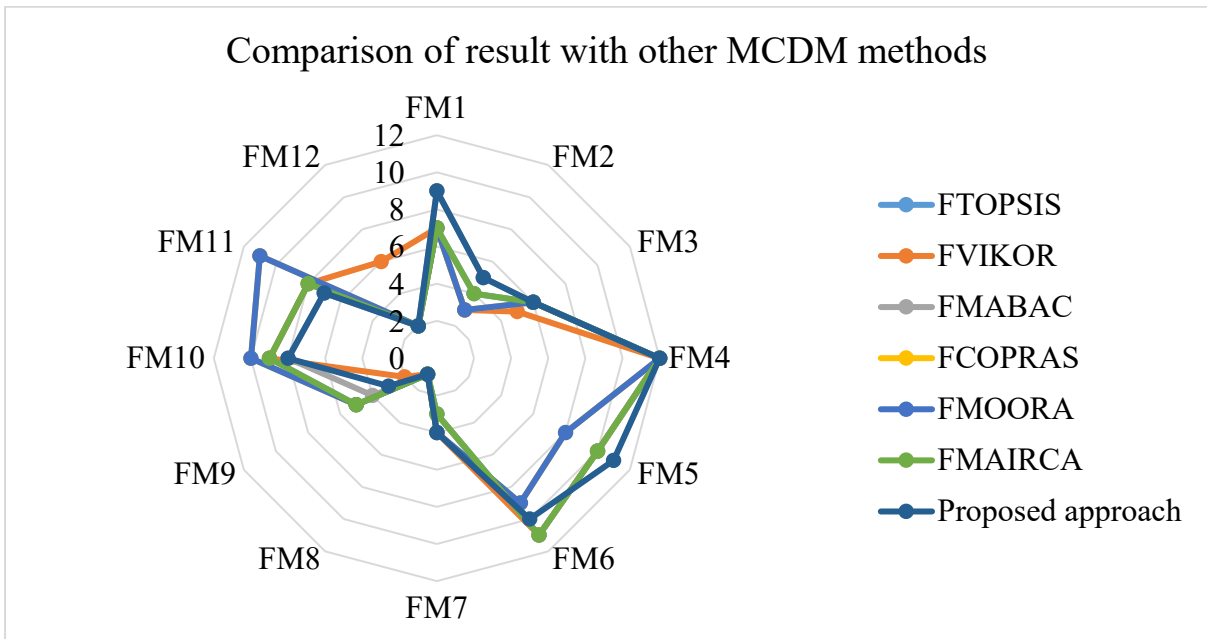
Failure Modes	Criteria function values	Ranking of failure modes by proposed hybrid approach
Wear of Teeth	0.0732	10
Broken Teeth	0.0700	5
Pitting of Gear	0.0711	6
Axial Shift of Gear	0.0744	12
Scoring of gears	0.0738	11
Brinelling	0.0733	9
Cage defect	0.0696	4
Crack on raceways	0.0669	1
Crack of rollers	0.0693	3
Bent shaft	0.0722	8
Crack of shaft	0.0719	7
Fracture of shaft	0.0688	2

1 **6. Validation and discussions of the result**

2 In this section, the obtained risk-ranking of failure modes are validated. It is divided into two parts. In
 3 the first part, the obtained ranking result is compared with the fuzzy extensions of different MCDM
 4 methods, available in the FMEA literature. Secondly, a sensitivity analysis is carried out by varying the
 5 criteria weights to different levels and observing subsequent variations in failure mode rankings.

6 **6.1 Comparison of failure modes ranking with other MCDM methods**

7 In the FMEA domain, to arrive at a consensus about the ranking of failure modes as per their risk levels,
 8 it is often preferred to compare the result with other established methods. From the very recent review
 9 article of Liu et al. [16], it is observed that the most frequently used fuzzy MCDM methods in the
 10 FMEA domain are fuzzy extensions of TOPSIS, VIKOR, COPRAS, MOORA, and MABAC. Thus, the
 11 ranking result obtained in this work is compared with them. Along with that, the obtained result is also
 12 compared with the fuzzy extension of the MAIRCA method proposed by [19]. A comparative
 13 presentation of the failure modes ranking is presented in Figure 10.



14

15 **Figure 10.** Failure modes ranking by different MCDM approaches

16 From the risk ranking of failure modes by using the fuzzy extensions of the previously mentioned
 17 MCDM methods, it is observed that each time, cracks on raceways (FM8) is identified as the most
 18 critical failure mode. Further, it is observed that the fracture of the shaft (FM12) is identified as the
 19 second critical failure mode by all other fuzzy MCDM methods, except FVIKOR [56], where it is
 20 ranked as the sixth critical failure mode. This is probably due to choosing the value of ν (0.5 in our
 21 case), which is known as the weight for the strategy of maximum group utility, whereas $(1 - \nu)$ is the
 22 weight of the individual regret.

Prior to making a final decision, it is necessary to check the reliability of the ranking result, which is generally measured by using Spearman's rank correlation coefficient. From Table 11, it is observed that all the rank correlation coefficients are higher than 0.80, with a mean value of 0.91, which implies that strong correlations are present between the proposed approach and other established MCDM approaches [57]. Therefore, it is concluded that the proposed risk-ranking of failure modes are credible and confirmed.

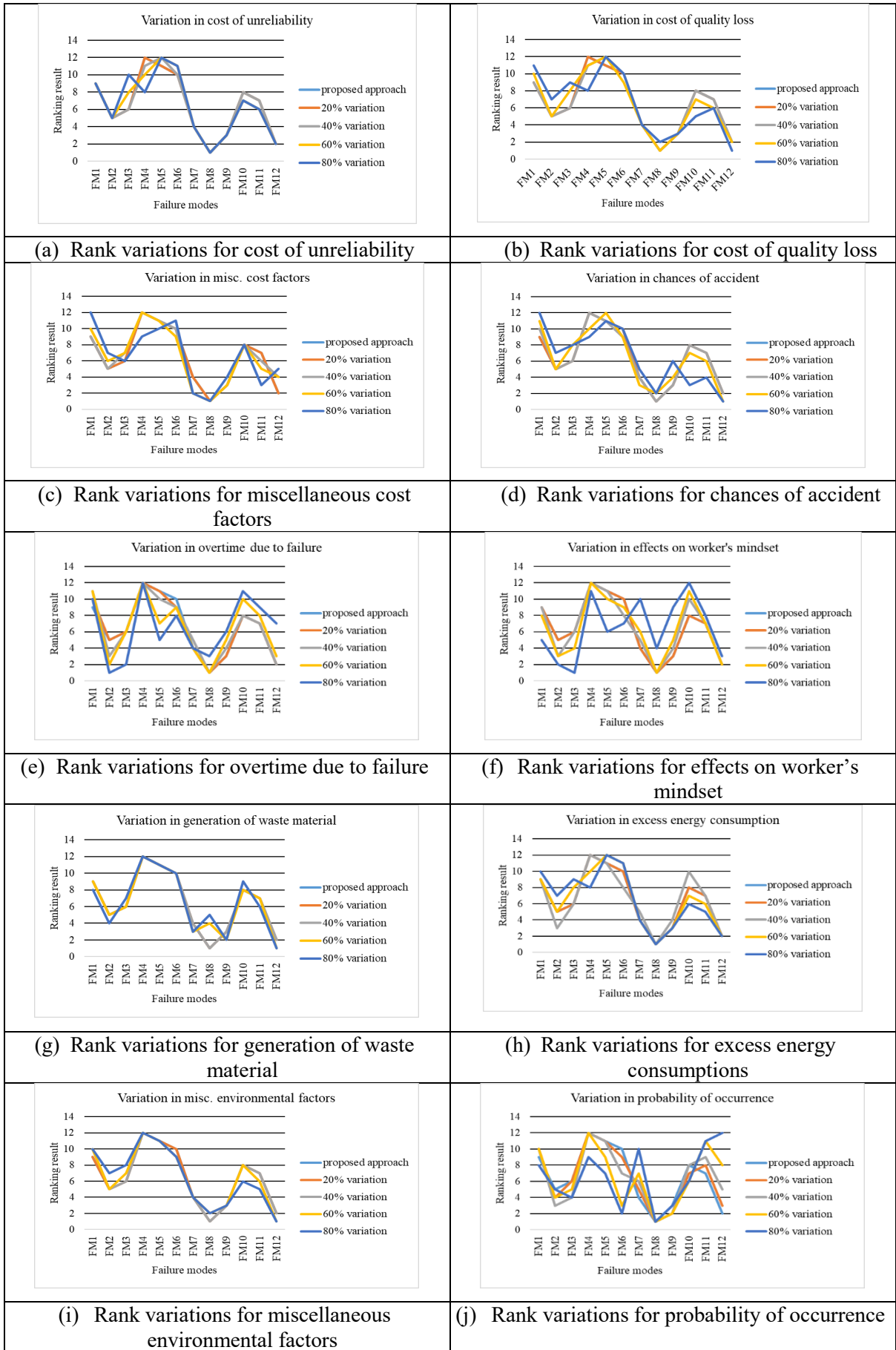
Table 9. Rank correlation among MCDM methods

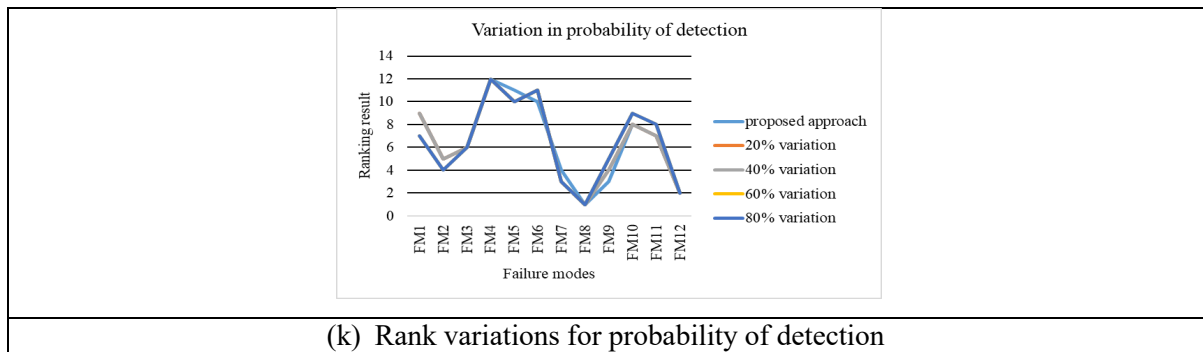
	FTOPSIS	FVIKOR	FMABAC	FCOPRAS	FMOORA	FMAIRCA	Average
Spearman's rank correlation coefficient	0.9510	0.8951	0.9860	0.8531	0.8531	0.9510	0.9148

6.2 Sensitivity analysis

During FMEA, it is often required to change evaluations of criteria and alternatives. When the evaluations of criteria are changed, relative importance of risk factors are also changed. These changes affect the ranking results of failure modes. Therefore, it is necessary to observe the sensitivity of the model used to rank the failure modes, as well as to identify the important criteria which mainly cause the changes to failure mode rankings.

In this section, a total of 44 scenarios are considered for sensitivity analysis, which can be divided into four phases, where each phase is comprised of 11 scenarios. For each scenario, the relative importance of a single criterion was increased to different levels (in this case 20%, 40%, 60%, and 80%), while the other criteria were decreased by the same level. Further, the normalization procedure was performed to maintain the condition, $\sum_{i=1}^n w_i = 1$. Variations in failure mode rankings for different levels of variation for each criterion are shown in Figure 11. After further verifications, it is observed from Table 12 that the proposed approach provides consistent rankings for most of the critical failure modes in each of the considered four phases. As TOPSIS is the mostly commonly applied MCDM method in the FMEA domain, result obtained by our proposed approach is compared with the fuzzy extension of TOPSIS.





(k) Rank variations for probability of detection

1 **Figure 11.** Variations of criteria weights and their effects on failure modes rankings

2 **Table 12.** Consistency in ranking result

Ranking	Fuzzy extension of MAIRCA [19]	FTOPSIS	Proposed approach
1 st critical FM	Crack on raceways: 35 times. Fracture of shaft: 7 times Others: 2 times	Crack on raceways: 33 times. Fracture of shaft: 8 times Others: 2 times	Crack on raceways: 35 times. Fracture of shaft: 7 times Others: 3 times
2 nd critical FM	Fracture of shafts: 28 times, Crack on raceways: 5 times	Fracture of shafts: 25 times, Crack on raceways: 6 times	Fracture of shafts: 28 times, Crack on raceways: 5 times
3 rd critical FM	Cage defect: 24 times Crack on rollers: 11 times, Others: 9 times	Cage defect: 22 times Crack on rollers: 11 times Others: 11 times	Crack on rollers: 26 times Cage defect: 7 times Others: 11 times
4 th critical FM	Crack on rollers: 21 times Cage defect: 9 times, Others: 14 times	Crack on rollers: 20 times Cage defect: 11 times, Others: 13 times	Cage defect: 25 times, Crack on rollers: 6 times, Others: 13 times

3 From the above discussion, it is concluded that as the crack on bearing raceways (FM8) retains its
4 position for 80% of the scenarios, it can be considered as the most critical failure mode. Moreover, it is
5 observed that for most of the RFs, this FM8 failure mode is dominant above the fracture of a shaft
6 (FM12). For 64% of scenarios, the fracture of a shaft (FM12) maintains its second position and can be
7 considered as the second most critical failure mode. Furthermore, even considering up to 60% variation
8 in criteria weights, any drastic changes in these ranking results are not observed and the results also
9 show significant correlation ($\approx 90\%$) with the results obtained by the IT2FS-DEMATEL and
10 FMAIRCA approach. This high correlation signifies that the obtained ranking of failure modes using
11 the new proposed methodology are confirmed and credible.

12 7. Conclusions

13 In an environment of sustainable manufacturing, it is required that all the processes associated with it
14 become sustainable. Keeping these concerns in mind, in this study we have proposed an extended
15 FMEA approach by considering how a failure mode of a machine can impact on the environmental,
16 societal and economical aspects, necessitating their severity assessment integration within FMEA in
17 order to reflect their benefits on sustainable manufacturing. With the increasing number of indices

1 available for describing the severity, it becomes difficult for organizations to manage their exact values.
2 In such circumstances, subjectively assessed experts' opinions are often utilized, but they themselves
3 bear a vagueness that can lead to erroneous selection of critical failure mode(s). To overcome such
4 eventualities, this study has proposed a hybrid MCGDM approach by combining IT2F-DEMATEL and
5 modified FMAIRCA methods. The approach utilizing IT2F-DEMATEL has not only been used to
6 calculate the causal dependencies but also the local priorities among the risk factors. Later, modified
7 FMAIRCA has been utilized to rank the failure modes. Further, to validate the effectiveness of our
8 approach, a case-study of a large and complex process plant gearbox was investigated. The reasons for
9 considering this gearbox for comparing and validating our approach is its criticality in terms of giving
10 the final shape and size of the red-hot cast blooms in the steel process plant. Any failure may cause
11 damage to the finished goods and might jeopardize the safety of the operators. If so, organizations are
12 compelled to reprocess it, which is not at all desirable due to the consequent generation of hazardous
13 waste that may adversely affect not only the environment but also have economical and societal
14 concerns.

15 Future extension of this research work includes a detailed study on identifying other risk factors of
16 failure modes and an integrated strategy coupled with the practice of sustainable manufacturing.
17 Researchers may extend this framework by examining the effectiveness of other newly developed
18 weight calculations methods, such as SWARA, factor relationship (FARE) etc. Whereas, the application
19 potential of other ranking methods, such as CODAS, EDAS can be examined in FMEA. Last but not
20 least, for more credible decision making, this framework can be extended to include recently advanced
21 theories, such as neutrosophic sets, 2-tuple linguistic fuzzy sets, Z-numbers, etc.

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Appendix A.1. Dependency degree obtained from DMs for main attributes – severity, occurrence and detection

DM1	S	O	D	DM2	S	O	D	DM3	S	O	D
S		M	VH	S		VL	VVH	S		L	VH
O	L			O	M			O	VL		
D	H			D	VH			D	H		

Appendix A.2. Dependency degree obtained from DMs for economic, social and environmental factors

DM1	Ec	So	En	DM2	Ec	So	En	DM3	Ec	So	En
Ec		H	M	Ec		M	H	Ec		H	M
So	M		VH	So	VH			So	H		
En	H	M		En	M	H		En	H	M	

Appendix A.3. Dependency degree obtained from DMs for chances of accident, overtime due to failure and effects on worker’s mind-set

DM1	CA	ODF	EWM	DM2	CA	ODF	EWM	DM3	CA	ODF	EWM
CA			VH	CA			H	CA			M
ODF	VL		H	ODF	H		M	ODF	L		M
EWM	M	H		EWM	H	M		EWM	VL	L	

Appendix A.4. Dependency degree obtained from DMs for cost of unreliability, cost of quality loss and misc. cost

DM1	CoUR	CoQL	MsCo	DM2	CoUR	CoQL	MsCo	DM3	CoUR	CoQL	MsCo
CoUR		VH	M	CoUr		H	H	CoUr		M	VH
CoQL	L			CoQ	H			CoQ	M		
MsCo	H			MsCo	VH			MsCo	H		

Appendix A.5. Dependency degree obtained from DMs for generation of waste material, excess energy consumption and misc. environmental factors

DM1	GWM	EEC	MsEF	DM2	GWM	EEC	MsEF	DM3	GWM	EEC	MsEF
GWM		VH	M	GWM		H	H	GWM		VH	M
EEC	M		L	EEC	L		M	EEC	H		H
MsEF	M			MsEF	H			MsEF	L		

Appendix B.1. Initial Direct Relation Matrix for S-O-D

	Severity	Occurrence	Detection
Severity	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$	$((0.217,0.350,0.350,0.500; 1,1), (0.267,0.350,0.350,0.450; 0.9,0.9))$	$((0.700,0.833,0.833,0.933; 1,1), (0.750,0.833,0.833,0.883; 0.9,0.9))$
Occurrence	$((0.217,0.350,0.650,0.500; 1,1), (0.267,0.350,0.350,0.450; 0.9,0.9))$	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$
Detection	$((0.550,0.700,0.700,0.833; 1,1), (0.600,0.700,0.700,0.783; 0.9,0.9))$	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$

Appendix B.2. Normalized initial direct-relation matrix for S-O-D

	Severity	Occurrence	Detection
Severity	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$	$((0.1914,0.3720,0.3720,0.6981; 1,1), (0.249,0.372,0.372,0.556; 0.9,0.9))$	$((0.488,0.581,0.581,0.651; 1,1), (0.523,0.581,0.581,0.616; 0.9,0.9))$
Occurrence	$((0.151,0.244,0.244,0.349; 1,1), (0.186,0.244,0.244,0.314; 0.9,0.9))$	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$
Detection	$((0.384,0.488,0.488,0.581; 1,1), (0.419,0.488,0.488,0.547; 0.9,0.9))$	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$	$((0,0,0,0; 1,1), (0,0,0,0; 0.9,0.9))$

Appendix B.3. Total relation matrix for S-O-D

	Severity	Occurrence	Detection
Severity	$((0.2662,0.5234,0.5234,1.0011; 1,1), (0.340,0.523,0.523,0.771; 0.9,0.9))$	$((0.151,0.244,0.244,0.349; 1,1), (0.186,0.244,0.244,0.314; 0.9,0.9))$	$((0.6184,0.8857,0.8857,1.3030; 1,1), (0.701,0.886,0.886,1.091; 0.9,0.9))$
Occurrence	$((0.1914,0.3720,0.3720,0.6981; 1,1), (0.249,0.372,0.372,0.556; 0.9,0.9))$	$((0.0289,0.0908,0.0908,0.2435; 1,1), (0.046,0.091,0.091,0.175; 0.9,0.9))$	$((0.0935,0.2163,0.2163,0.4545; 1,1), (0.130,0.216,0.216,0.343; 0.9,0.9))$
Detection	$((0.4859,0.7440,0.7440,1.1634; 1,1), (0.561,0.744,0.744,0.968; 0.9,0.9))$	$((0.0734,0.1817,0.1817,0.4058; 1,1), (0.104,0.182,0.182,0.304; 0.9,0.9))$	$((0.2373,0.4325,0.4325,0.7576; 1,1), (0.293,0.433,0.433,0.597; 0.9,0.9))$

Appendix C. Linguistic decision matrix

Failure Modes		C111	C112	C113	C121	C122	C123	C131	C132	C133	C2	C3
Wear of Teeth (FM1)	DM1	MG	MP	P	P	F	G	F	F	F	P	MG
	DM2	G	P	P	VP	MP	MG	F	MP	P	MP	F
	DM3	MG	MP	VP	P	MP	G	F	P	P	F	MG
Broken Teeth (FM2)	DM1	G	P	P	P	G	G	F	MP	P	F	VG
	DM2	VG	MP	MP	P	VG	MG	MG	F	P	MP	G
	DM3	G	P	P	MP	G	MG	F	F	MP	MP	G
Pitting of Gear (FM3)	DM1	F	VP	F	P	MG	G	MP	MP	P	F	G
	DM2	MP	P	MP	P	MG	G	F	P	P	F	MG
	DM3	MG	MP	P	MP	G	G	P	MP	MP	MP	G
Axial Shift of Gear (FM4)	DM1	VG	F	P	F	MP	MG	P	G	P	P	MP
	DM2	G	MG	F	MP	MP	F	VP	G	F	MP	F
	DM3	VG	F	MP	F	P	F	P	F	P	F	MP
Scoring of gears (FM5)	DM1	P	P	P	P	G	MG	P	MP	P	F	F
	DM2	MP	P	P	P	G	G	P	P	MP	MP	F
	DM3	P	MP	MP	MP	MG	G	F	P	MP	MP	MG
Brinelling (FM6)	DM1	MG	MP	P	P	F	G	F	MP	P	F	MP
	DM2	F	F	P	P	MG	MG	F	P	F	MG	MP
	DM3	F	MP	P	MP	MG	F	P	P	MP	MG	F
Cage defect (FM7)	DM1	G	F	G	F	P	P	VG	G	F	P	VG
	DM2	VG	MG	G	P	F	P	VG	F	F	MP	VG
	DM3	G	F	VG	MP	F	MP	G	MG	P	P	G
Crack on raceways (FM8)	DM1	VG	MG	G	P	P	MP	MP	G	MP	G	VG
	DM2	VG	F	F	P	MP	F	MP	MG	P	G	VG
	DM3	G	F	G	MP	P	MP	P	G	P	VG	VG
Crack of rollers (FM9)	DM1	G	MG	F	P	P	MP	VG	G	F	F	G
	DM2	VG	G	F	P	P	P	VG	G	P	MP	MG
	DM3	G	F	G	MP	F	P	G	G	F	F	VG
Bent shaft (FM10)	DM1	G	G	F	MG	P	P	F	G	F	MP	F
	DM2	MG	MG	MP	MG	P	P	F	VG	P	F	F
	DM3	G	G	MP	F	MP	VP	P	G	F	MP	MG
Crack of shaft (FM11)	DM1	MG	G	G	F	MP	F	F	G	MP	MP	F
	DM2	G	G	VG	MG	P	F	MP	G	F	P	F
	DM3	VG	F	G	F	MP	F	F	G	F	P	MG
Fracture of shaft (FM12)	DM1	VG	VG	P	VG	P	F	VG	VG	F	P	VG
	DM2	VG	G	P	G	P	MG	G	G	G	VP	VG
	DM3	G	G	MP	VG	MP	F	G	VG	G	P	G