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Neutrosophic MCDM Based Risk: Centric Six Sigma Assessment Approach For Supplier Selection

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Abstract

The rapidly developing and dynamic industrialization, compounded by factors of uncertainty with the inclusion of a variety of risks in the manufacturing process, renders the task of selecting the most suitable supplier complex and challenging. In this study, a risk centric performance evaluation approach that integrates neutrosophic-process failure mode and effects analysis (PFMEA), MCDM technique and Six-Sigma, is proposed to assist the organization in the supplier selection (SS). Firstly, neutrosophic PFMEA is utilized for risk identification and assessment. Secondly, the weights of the organization's selected critical to quality characteristics' (CTQ) for SS are assessed using the neutrosophic-DEMATEL-ANP method, and each CTQs' performance is evaluated in terms of Six Sigma metric. In the subsequent analysis, the overall risk-based performance of suppliers is assessed by the introduction of a mathematical model where risk is integrated with Six Sigma. This model aggregates the risk-based performance values of all CTQs to provide a single performance measure for each supplier. The novelty of the work lies in developing a methodology by leveraging limited data for risk centric performance evaluation of the supplier in accordance with the requirement of ISO 9001:2015.

Keywords: neutrosophic DEMATEL-ANP, risk, uncertainty, PFMEA, supplier selection, performance evaluation, six sigma

1. Introduction and literature review

Selecting the appropriate suppliers holds substantial significance not only in minimizing procurement expenses significantly, but also in fostering product innovation and facilitating efficient production processes. Hence, the process of supplier selection is recognized as a critical aspect within supply chain management (SCM), playing a pivotal role in sustaining a competitive advantage (Yoon et al., 2018).

In recent times, there has been a heightened emphasis on risk within business operations, particularly in the context of supplier selection. This increased concern is a response to the evolving business landscape, where uncertainties and potential disruptions can significantly impact the reliability and performance of the supply chain. Furthermore, ISO 9001:2015 underscores the crucial role of recognizing and addressing potential risks and opportunities within an organization. The standard mandates organizations to conduct a thorough evaluation of both internal and external factors that could pose risks or present opportunities ("ISO 9001:2015(En), Quality Management Systems — Requirements" 2015, 9).

In prior studies, decision-makers have utilized a multi-criteria assessment to evaluate and make selections among suppliers. In the context of performance evaluation, Multi-Criteria Decision-Making (MCDM) based methods are well-known approach which allow decision-makers to assess and prioritize alternatives based on various criteria, considering the inherent uncertainties and risks associated with each option. (Yoon et al., 2018) utilized multi-objective optimization-based simulation to develop a decision model for comprehensive supplier selection, considering diverse quantitative and qualitative risk factors. (Xu et al., 2019) introduced the application of the sorting method, analytic hierarchy process (AHP) Sort II, within a fuzzy context utilizing interval type-2 fuzzy sets (IT2FSs), along with a novel approach for selecting representative points to determine suppliers' priorities. This method aims to enhance the management of ambiguous class assignments by softening transitions between classes, thus aiding in sustainable supplier selection. (Alikhani, Torabi, and Altay 2019) proposed a comprehensive approach using interval type-2 fuzzy sets, integrating quantitative empirical studies and analytical modeling to assess suppliers, considering both desirable and undesirable factors, and addressing sustainability and risk in supplier selection.(Rouyendegh, Yildizbasi, and Üstünyer 2020) proposed an intuitionistic fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) based approach for solving green supplier selection problem.(Sharaf 2020) presented interval-valued based fuzzy MCDM approach for straightforward and computationally efficient supplier selection. (Liu et al., 2021) proposed a novel fuzzy MCDM based decision framework intended to assist vehicle manufacturers in the selection of an innovative supplier, with the aim of enhancing their performance while considering supply risk. While the application of fuzzy sets, interval-valued fuzzy sets, intuitionistic fuzzy sets-based MCDM techniques in previous literature effectively handles data set uncertainty, it falls short in addressing the indeterminacy associated with datasets.(Yazdani et al., 2021) introduced a sustainable supplier evaluation framework using an interval-valued fuzzy neutrosophic (IVFN) model, facilitating decision-making for procurement and supply chain professionals in selecting the optimal supplier within specified timeframes. (Kaur and Prakash Singh 2021) presented mixed integer program to optimize multi-period, multi-item order allocation to suppliers, aiming to concurrently minimize overall cost and the risk of disruption. However, the study does not take into account uncertainty and risk factors concurrently. (Pehlivan and Yalçın 2022) proposed an assessment of sustainable supplier selection within a Turkish discount market chain, employing the single-valued neutrosophic TOPSIS method that relies on normalized Euclidean and Hamming distances.(Mateo-Fornés et al., 2023) introduced a two-stage stochastic programming framework aimed at improving product quality by optimizing supplier selection and cold storage management, thereby reducing deterioration risks and maintaining consistent quality levels over time. (Saputro, Figueira, and Almada-Lobo 2023) proposed a dual-phase solution approach integrating MCDM and multi-objective simulation-optimization (S-O). This work presented a comprehensive framework addressing both qualitative and quantitative aspects of a company's competitive priorities, supply risk, decision scope, and uncertainty. While the utilization of MCDM techniques proves effective in streamlining supplier ranking, there is a notable gap in providing a quantitative approach for ranking or benchmarking suppliers using standardized metrics. This deficiency raises concerns about the potential for customer dissatisfaction due to the lack of clear, measurable criteria for supplier assessment and comparison.

This paper delves into neutrosophic logic, MCDM method, process failure mode and effects analysis (PFMEA) for integrating risk assessment into the Six Sigma evaluation. The study aims to address the concept of risk-based performance evaluation, highlighting its significance and potential benefits for organizations. It presents a novel technique for Six Sigma assessment centered on risk, to offer a standardized approach for benchmarking suppliers with limited available data, while mitigating issues related to the costs and time associated with experiments and testing for data collection. This strategy, encompassing the techniques mentioned above for evaluating risks and their integration with the quality metric without sufficient data, has not been covered in existing literature. Furthermore, the paper discusses an illustrative example to demonstrate the application and effectiveness of the risk-based approach.

This paper is organized as follows: Section 2 describes the methodology, Section 3 discusses an illustrative example to explain the proposed methodology, Section 4 describes results and discussions and Section 5 concludes the paper with the limitations and future scope of the proposed work.

2. Methodology

The flowchart in Figure 1 presents the proposed framework for this research paper. The research methods, the justification for their selection, and their implementation are outlined in the subsequent steps. The research is carried out in two phases, where the first phase presents the identification and assessment of risk through the neutrosophic PFMEA method. The second phase evaluates the organizations process performance utilizing the risk impact value assessed in Phase 1.

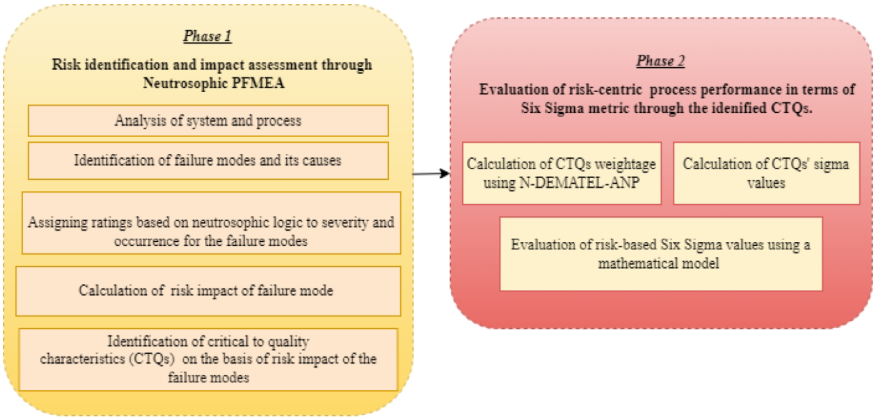

Fig. 1 Methodology.

2.2 Phase 1: risk identification and assessment through neutrosophic PFMEA method

Among various risk assessment tools that exist in the literature, FMEA differs from others by focusing on pre-emptive identification of potential failures and associated risks before they occur (Qin, Xi, and Pedrycz, 2020). The PFMEA, a structured form of FMEA, prioritizes and implements preventive actions by assessing potential failure modes (FMs), considering severity (S), occurrence likelihood (O), and detectability (D), calculating the Risk Priority Number (RPN). However, the traditional FMEA has certain limitations, including subjectivity in data for S, O, and D rankings due to uncertain information, and the potential for different FMs to share the same RPN. Therefore, the proposed approach employs a neutrosophic logic-based PFMEA to account for subjectivity, vagueness, and indeterminacy inherent in the dataset. Neutrosophic theory, a mathematical framework, handles uncertainty and indeterminacy in data is applied to represent linguistic opinions from experts and literature survey data for severity and occurrence rating. (Smarandache 2005) introduced neutrosophic set with three independent subsets i.e., truth, falsity, and indeterminacy with the non-standard unit interval of] 0-,1+ [. There are several types of neutrosophic sets such as single valued neutrosophic sets (SVNS), multi valued neutrosophic sets, interval neutrosophic sets etc. In the proposed work, SVNS are utilized instead of non-standard subsets, which are more complex and challenging to apply in real-life situations. The basic definition of single valued neutrosophic number (SVNN), deneutrosophication of SVNN to crisp number, and single valued neutrosophic weighted average number (SVNWA) is presented as follows:

Definition 1 (Wang et al., n.d.). Let us assume X is a space of points, with each element denoted by x. A single valued neutrosophic number (SVNN), N can be defined as $N = \{\langle x, T_N(x), I_N(x), F_N(x) | x \in X \rangle\}$, where $T_N(x)$ is a truth-membership function, $I_N(x)$is the indeterminacy-membership function, and $F_N(x)$ is the falsity-membership function. The function $T_N(x), I_N(x) F_N(x) \rightarrow$[0,1] for each point x in X and with the constraint $0 \leq T_N(x) + I_N(x) + F_N(x) \leq 3$.

Definition 2 (Awang, Aizam, and Abdullah, 2019). Let $N = \{\langle x, T_N(x), I_N(x), F_N(x) | x \in X \rangle\}$ is an SVNN, the elements in the neutrosophic matrix is deneutrosophied into crisp number $\chi \in X$ by utilizing the following equation:

$$\chi_N = 1 - \sqrt{\{(1 - T_N(x))^2 + (I_N(x))^2 + (F_N(x))^2\}/3} \tag{1}$$

Definition 3 (Hezam et al., 2022). Let $A_j (j = 1,2, \ldots n) = (T_j, I_j, F_j) \in \text{SVNN}(X)$; $j = 1(1)n$ and $w = (w_1, w_2, w_3 \ldots w_n)^{\mathrm{T}}$ with $w_j \in [0,1]$ and $\sum_{j=1}^{n} w_j = 1$ be the weight of X_j.Then, the SVNWA can be represented by

$$SVNWA(X_1, X_2, X_3, \ldots, X_n) = \oplus_{j=1}^{n} (w_j X_j) = \left(1 - \prod_{j=1}^{n} (1 - T_j)^{w_j}, \prod_{j=1}^{n} (I_j)^{w_j}, \prod_{j=1}^{n} (F_j)^{w_j}\right) \tag{2}$$

Neutrosophic PFMEA technique is utilized for the identification and assessment of FMs and selection of critical to quality characteristics (CTQs) in this approach. The procedure for risk identification and assessment within a process are as follows:

Step 1. The system overview is thoroughly analysed, and a process flow chart of the selected case (Section 3) is constructed to understand the overall system. A brainstorming session is undertaken to identify the FMs and assign ratings to them.

Step 2. The determination of the impact of each failure mode is conducted through the risk impact assessment method, which comprises two components: estimating the S and O of process FMs. Neutrosophic-based ratings are allocated to the S and O of each FM with Table 1 and Table 2 presenting the evaluation using linguistic terms and their corresponding SVNNs.

Step 3. This step is devoted to estimating risk impact of the FMs. Neutrosophic values are transformed into crisp numbers using the formula presented in (1). The formula for evaluating the risk impact is expressed as follows:

$$Risk\ impact\ of\ failure\ mode (RI) = S * O \tag{3}$$

As the risk impact value increases, the potential hazard associated with the process failure mode also increases(Tian et al., 2019). For the identification of CTQs, consideration is given to the top six FMs with maximum risk impact. The features associated with the FMs are treated as CTQs of the product and are employed for the assessment of manufacturing process performance.

Table 1. Severity rating

Severity	Single valued neutrosophic number
Critical	$< 0.9,0.1,0.1 >$
Major	$< 0.8,0.2,0.15 >$
Significant	$< 0.5,0.4,0.45 >$
Moderate	$< 0.35,0.6,0.7 >$
Minor	$< 0.1,0.8,0.9 >$

Table 2. Occurrence rating

Occurrence	Single valued neutrosophic number
Frequent	$< 0.9,0.1,0.1 >$
Probable	$< 0.8,0.2,0.15 >$
Occasional	$< 0.5,0.4,0.45 >$
Remote	$< 0.35,0.6,0.7 >$
Extremely Unlikely	$< 0.1,0.8,0.9 >$

2.3 Phase 2: evaluation of manufacturing process performance considering risk impact

Initially, the study aims to assess CTQs' weights using a SVNS-based Decision-Making Trial and Evaluation Laboratory- Analytic Network Process (DEMATEL-ANP) approach introduced by (Smarandache 2005). For assessing interrelationships among criteria during weight evaluation, a generalized analytic hierarchy process (AHP) called ANP is employed in the past, although ANP has limitations such as complex computation, assumed reciprocal interdependencies, and equal cluster weightage. To address these issues, the study introduces a hybrid approach by combining DEMATEL with ANP. Due to space constraints, the detailed steps for weightage calculation through neutrosophic DEMATEL-ANP are not provided here. Interested readers are encouraged to refer to source (Awang, Aizam, and Abdullah 2019)for further details. Following the calculation of CTQs' weightage, their performance is assessed subsequently.

Six Sigma serves as a standardized metric for evaluating supplier performance based on a chosen set of CTQs. Six Sigma metrics encompass sigma level, yield, and Defects per Million Opportunities (DPMO) to gauge and improve process performance. For the evaluation of the metric, experts' input is collected to set the rating and target for each CTQ per supplier. Afterward, sigma level of each criterion is evaluated using the following formulas, each tailored to address different scenarios (Song-Kyoo Kim 2008):

For Bigger-the-better case:

$$Z_i = \varphi^{-1}\left(\frac{\alpha_6 . x_i}{\rho_i}\right) \approx \varphi^{-1}\left(\frac{x_i}{\rho_i}\right), x_i \geq 0, \rho_i \geq 0,\ i = 1, \dots, n \tag{4}$$

For Smaller-the-better case:

$$Z_i = \varphi^{-1}\left(\frac{\alpha_6 \cdot \rho_i}{x_i}\right) \approx \varphi^{-1}\left(\frac{\rho_i}{x_i}\right), x_i \geq 0, \rho_i \geq 0, i = 1, \dots, n \tag{5}$$

For Nominal-the-better case:

$$Z_i = \varphi^{-1}\left(\alpha_6\left(1 - \frac{|x_i - \rho_i|}{\rho_i}\right)\right) \approx \varphi^{-1}\left(1 - \frac{|x_i - \rho_i|}{\rho_i}\right), i = 1, \dots, n, \tag{6}$$

where Z_i is the sigma level, x_i is the real value and ρ_i is the target value of i^{th} CTQ.

Next, the sigma levels are converted into respective yield value using the procedure mentioned in (Kumar, 2006). After evaluating the yield of CTQs for each supplier, the subsequent stage involves the calculation of performance based on risk.

The presence of risk can significantly affect the quality of a process by introducing variability, defects, and errors, often stemming from resource limitations and noncompliance with regulations. The impact of risk on process performance is heightened in intricate processes, compounded by supplier-related issues that can impact quality and reliability over time. Therefore, the integration of risk management into the evaluation of process performance is crucial. This ensures the identification of uncertainties and the proactive implementation of measures to address these risk factors, ultimately assuring a steady and resilient standard of quality for the end product or service.

As per the literature provided in introduction section, the formulation linking the performance value and the risk is found to be limited. In the context of this (Xu et al., 2020) assessed performance of several types of e-waste management improvement strategies considering risk. Based on this, the expected performance values, considering the risk impact of the failure mode, is proposed using the following formulation:

$$Expected\ process\ performance = \sum_{i=1}^{n}\left((1 - RI_i) * Y_i * w_i\right) \tag{7}$$

where, RI_i- Risk impact of the i^{th}failure mode

Y_i- Yield of the i^{th}CTQ

w_i-Weightage of the i^{th}CTQ

n- Number of CTQs

3. Illustrative example

The presented methodology is demonstrated through an illustrative example focusing on supplier selection for products manufactured using the Fused Filament Fabrication (FFF) process. The FFF, a prevalent additive manufacturing technique, entails layer-by-layer deposition of molten thermoplastic material to form three-dimensional objects. The organization seeks to appraise the process performance of each supplier in the fabrication process, while considering potential risks to identify the most suitable supplier. The assessment encompasses risk identification, evaluating the impact of risks on the manufacturing process, and identifying areas for improvement. The team aims to select the best option from three different suppliers (S1, S2, S3) through the proposed method.

3.1. Phase 1: risk identification and assessment through neutrosophic PFMEA method

The main objective of PFMEA is to recognize and examine potential FMs and their related risks within the process. The execution of PFMEA is segmented into three components: system details, process details, and PFMEA table.

3.2. System details

In this section, a comprehensive analysis of the FFF system is provided. The system is broken down into sub-systems, with further subdivisions for detailed analysis. The hierarchical structure includes the following components:

- Controller Board: Functioning as the system's core, it manages electronic functions, temperature regulation, and motion control;
- Filament: Serving as the thermoplastic feedstock, filaments come in various categories with distinct physical properties, requiring different temperatures for printing. Common diameters are 1.75 mm and 2.85 mm;
- Frame: The support structure for the FFF system, it sustains all mechanical and electrical components involved in the fabrication process;
- Motion Component: Responsible for the movement and positioning of the print head and bed, utilizing components such as stepper motors, belts, threaded rods, and end stops;
- Power Supply Units: Providing the necessary current to the FFF system;
- Print Bed Surface: The flat surface where the fabricated product is built, possessing adhesive properties for temporary bonding during fabrication;

- Feeder System: Supplies filament into the FFF system for product construction;
- Extruder: This component, categorized as Bowden or Direct drive, includes sub-components such as gears, heat cartridge, thermocouple, nozzle, and cooling fan. The extruder motor turns gears to push filament into the nozzle. Sub-components of the extruder:
    - Gears (Hobbed Gear and Idler Gear): Transfers motion from one shaft to another;
    - Heat Cartridge: Provides heat for melting the filament;
    - Thermocouple: Reads the temperature of the heated filament;
    - Nozzle: Heats and melts the filament to a semi-molten stage, available in various sizes;
    - Cooling Fan: Cools the heated filament material on the print bed surface.

After discussing the FFF system and its sub-systems, it becomes crucial to delve into the FFF process details.

3.3. Process details

The FFF process comprises several steps, illustrated in Figure 2. It initiates with the creation of a CAD model, followed by conversion to an .STL file. The model undergoes slicing into layers, and process parameters are established. The printing machine is calibrated, and during production, filament is fed, liquefied, and extruded from the nozzle to deposit molten material layer by layer. Motion control facilitates material spreading across the print bed. The deposited material is then cooled and bonded. Post-production involves inspection, potential calibration, support removal, testing, and finishing to ensure market readiness. With the FFF system and process details explained, the subsequent section introduces the excerpts of PFMEA table demonstrating the identified FMs and the corresponding risk impact value.

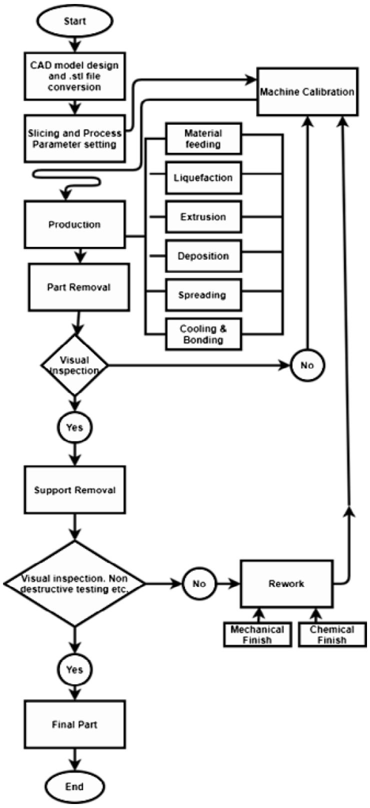

Fig. 2 Process flow chart of FFF.

3.4. Process FMEA table

As discussed in Section 2, the PFMEA is utilized in the identification and assessment of risk to further calculate expected risk-based process performance. A detailed analysis of the FFF system, sub-system, and process steps are presented. In this section, based on the analysis of the previous sub-sections and collected data, PFMEA for FFF process is developed. An extensive brainstorming session is carried out to identify the FMs and their risk impact value. The severity and occurrence have been developed on a neutrosophic scale, with details placed in Table 1 and Table 2 (Section 2). The risk impact of the FMs are calculated using the (3) mentioned in Section 2. After conducting, PFMEA for all the three suppliers, six FMs with highest risk impacts are identified. The features of these FMs are considered as the CTQs of the product and are utilized for yield calculation. The excerpt of the PFMEA table mentioning the CTQs, FMs and risk impact of the FMs for all three suppliers is presented in Table 3.

Table 3. Failure modes and their risk impacts across the suppliers.

CTQs	FMs	Risk impact (S1)	Risk impact (S2)	Risk impact (S3)
Dimensional Accuracy (DA)	Deviation of the printed object's dimensions from the intended or specified dimensions (FM1)	0.1	0.2	0.1
Surface Finish (SF)	Undesired characteristics or defects on the surface of the printed object (FM2)	0.2	0.1	0.1
Material Strength (MS)	Insufficient structural integrity or does not meet the specified material strength requirements (FM3)	0.15	0.15	0.2
Print Resolution (PR)	Lack of the intended level of detail and precision (FM4)	0.14	0.1	0.2
Printed Object Transparency (POT)	Lack of the intended level of see-through or translucency as desired in the design (FM5)	0.13	0.14	0.15
Aesthetics (AT)	Deviations from the intended visual or artistic qualities as desired in the design (FM6)	0.05	0.13	0.15

3.5. Phase 2: evaluation of risk centric process performance in terms of Six Sigma metric through identified CTQs

Firstly, the weights of the identified CTQs' are calculated using neutrosophic DEMATEL-ANP method and placed in Table 4. The CTQs' performance in terms of sigma level for the three suppliers are evaluated using Equations (4), (5) and (6) and converted to corresponding yield value as mentioned in Section 2. The aggregated performance evaluation of the supplier is facilitated by calculating the weighted sum of CTQs' yield value, where each CTQ's yield value is multiplied by its corresponding weight and then added. The aggregated performance values in terms of yield and sigma level are presented in Table 5. Next, the expected process performance considering risk impact associated with each CTQ is evaluated using (7) (Section 2) and placed in Table 5.

Table 4. Weights obtained from neutrosophic DEMATEL-ANP.

CTQs	Weights
Dimensional Accuracy	0.164
Surface Finish	0.158
Material Strength	0.108
Print Resolution	0.110
Printed Object Transparency	0.311
Aesthetics	0.145

Table 5. Suppliers performance measures with and without consideration of risk.

Suppliers	Sigma level	Yield	Risk based performance
S1	2.6	0.86	0.73
S2	2.3	0.78	0.67
S3	2.8	0.90	0.77

4. Results and discussion

The figure displayed in Figure 3 illustrates the impact of considering risk on process performance, comparing two lines denoted in blue and orange. The blue line, indicative of process performance without considering in risk, serves as a benchmark for the inherent process performance of the suppliers (specifically, S1, S2, S3). This line represents the optimal scenario where risks are not taken into account, and processes operate at their best, demonstrating variations in adherence to specifications. On the other hand, the orange line in Figure 3, representing process performance with the consideration of risk impact, considers potential adverse consequences of the FMs that could affect the final product's quality. The suppliers ranking on the basis of risk-based performance values is as follows: S3 > S1 > S2. By integrating risk impact, the graph presents a more realistic perspective of process performance, acknowledging potential deviations from desired outcomes. In summary, the visual representation in the graph elucidates the interplay between process performance and risk impact, enabling organizations to evaluate how risks influence manufacturing processes.

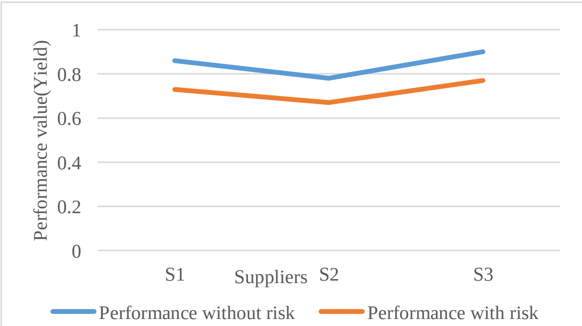

Fig. 3 Performance measure in terms of yield with and without consideration of risk impact.

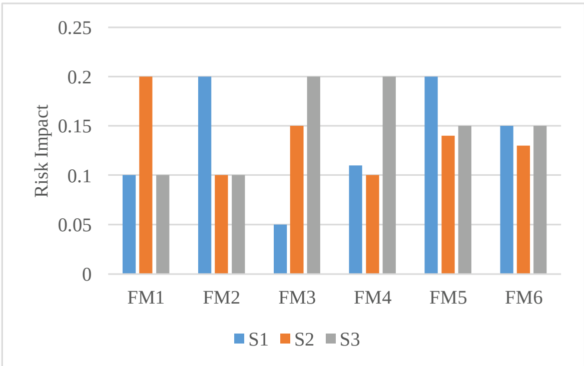

Fig. 4 Impact of risk in each supplier.

The graph depicted in Figure 4 illustrates the impact of various FMs across three suppliers. Analyzing the graph provides valuable insights into the relative significance of each FMs and their potential influence on manufacturing processes. The graph displays the variation in risk impact values for each FMs, with FMs plotted on the horizontal axis and the risk impact scale on the vertical axis. Interpretation of the graph facilitates the identification of key risk FM with substantial impacts on fabricated product for each supplier. This information contributes to understand the overall resilience and robustness of manufacturing processes.

4. Conclusion

This study introduces a novel approach to evaluate performance with a focus on risk, integrating neutrosophic PFMEA, MCDM techniques, and Six Sigma. The proposed method aims to support organizations in the process of selecting suppliers. Overcoming the limitations of traditional PFMEA, this approach provides a unique method to analyse risks, establishing a connection between risk and performance metric. The proposed method aligns with ISO 9001:2015 standard's clause 6.1 for risk-based quality assessment and holds promise in the context of Industry 4.0. The practical application of the introduced methodology is demonstrated through an illustrative example focused on the selection of suppliers for products manufactured using FFF.

Comparative analysis reveals that the identified risks significantly influence overall process performance. The graph plotting risk impact of each FM helps in identifying the influence of FM on manufactured product.

Organizations adopting this approach can improve their risk identification and assessment processes, allocate resources strategically, and make informed decisions to mitigate risks and enhance customer satisfaction. The future studies might expand the application of this approach to various industries and processes, consider additional criteria for risk assessment, and refine the weighting methodology for increased accuracy and reliability.

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