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Development of a TQM-based Framework for Product Infant Failure Assessment

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***Abstract*:** Product infant failures have been traced to the product development and production stage. Researchers and practitioners have opined that total quality management (TQM) can be used to properly managed these failures. While their suggestions have helped in this regard, there is limited information on how to scientifically aggregate criteria that can be used to specifically identify the most suitable TQM technique for product infant failure improvement, especially at the development stage. Hence, this study proposes a fuzzy-based multi-criteria framework for this problem. The framework uses intuitionistic fuzzy set to handle vague and imprecise judgment and Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) to rank selected TQM techniques. Real-world data sets were used to evaluate the framework performance, while TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) was used to validate the framework performance. Based on the results obtained, the IFWG-VIKOR and TOPSIS methods rank the most and least suitable TQM practices as TM4 and TM11, respectively. The framework can be used to provides insights into the management of techniques that can address infant product failure issues at the early stage of product development.

***Keywords*:** Product infant failure, Multi-criteria, Total quality management, Fuzzy sets

1. Introduction

Owning to the increased failure rate in new products development process, and the high rate of failures in product development SMEs [1], [2], product developers are gradually turning to the used of total quality management (TQM) technique [3]. TQM is increasingly becoming a major front-line tool for addressing product infant failure and for eliminating defect in production processes [4]. First, it is use in driving quality and reliability of new products during their early development stage, and to deliver better products that meet customers' requirements [5], [6]. Secondly, to improve products competitiveness and organizational productivity as well as to assist in the general survival of the enterprise in a chaotic business environment [7]. Finally, to address product infant failure [8].

TQM is a system and strategy that focuses on product quality and reliability management within an organization [9]. It has also been described as a technique for addressing issues relating to meeting customer's needs within an organization [10]. Its principle is based on the actions, activities and people commitment, especially when these actions and activities are towards the achievement of the top goal, vision, and target of the organization. [11].

Considering the important role of TQM in product quality and reliability, it important that SMEs managers understand the impact of TQM technique for a product development process - especially those with a specialty in product development. They should have the requisite skills on how to predict reliability of new product early at the product development stage, how the product development SMEs in general will performs, especially in a chaotic business environment. Also, they should be able to prioritize the TQM practices by considering their performance outcome; where this will encourage, the making of a system that produces infant failure-free product.

To know an organization TQM technique status, and to address their product development challenges, an acceptable product quality/reliability performance management framework is required. The framework will aid in the prioritization of potential TQM practices for the product quality and reliability enhancement within an organization, and for assisting product development managers to make appropriate decisions about the quality and reliability of their products. Hence, a new product quality/reliability performance management framework based on a new multi-criteria decision-making model has been proposed. The framework seeks to prioritize TQM practices based on some performance outcomes that are used in addressing product infant failure in SMEs.

2. Related work

A number of works of literature have offered suggestions on the underlying relationship of performance and TQM technique [12]–[14]. Recently, researchers have accepted organizational culture as performance indicators for TQM evaluation [15], [16]. Also, other managerial tools and strategies are been considered as moderating factors also, for measuring and prioritizing TQM performances [17]–[20].

In addressing organizational performance and the use of TQM in product development, Shafiq et al. [13], presented empirical evidence which was based on study from a developing country in the Southern part of Asia (Pakistan). A structural equation-based method was used to model the effect of TQM technique on the organizational performance of about 210 textile companies around the country. Findings from the study show that TQM technique is extremely significant and show positive outcome/effect on organizational performances. Also, it supports the divergence view which points to the fact that the positive effect of TQM on organizational performance is not restricted to the company's location in developed nations, but can also be attained in other parts of the world.

Jimoh *et al.*[12], studied and examined the connecting impact of TQM practices on strategic organizational improvement that measures performance among companies in Nigeria. Unlike past studies with a specific account on the connection between TQM practices and performance is mediated by the organizational strategies to ensure continuous improvement. Singh et al. [14], study the implementation of TQM in manufacturing and service companies that focus on the extent of TQM implementation in the different companies that put forward a positive conceptual fit model for the study. The hypotheses showed a positive impact on TQM and organizational performances.

Gimenez-Espin et al [15], introduced observational proof about the hierarchical culture best for a TQM system. They presented another type of structure which they believe could promote flexibility - the culture is between adhocratic and clique cultures. These culture types have a dual-orientation, which can describe as external and internal within the organization. Using an organizational linear regression methodology to analyze data from 451 companies, the study found that adhocratic structure has a positive effect on TQM, which was contrary to expectations. Also, they observed that a clique culture doesn't have a remarkable effect on TQM, finally, they reported that a mixed culture is suitable culture for a TQM system. Chatterjee et al. [17], used empirical study based on perceived employee's relationship between organizational culture and work-environment-related learning. Their finding was inconclusive; it suggests that some hierarchical structure supports certain learning transfer factors more than others.

Joiner [20], used the relationship between total quality management application and organizational performance, as well as the effect of co-worker and organization support on the application of TQM and the overall performance. The study used an opinion poll survey-based method to collect data from a selected automobile parts and accessories company. The study shows a good relationship between the extent of TQM application and organization performance. They found out that co-worker support has an effect on

TQM implementation and hierarchy performance. Kanapathy *et al.*[21], used a moderation model to study the relationships among quality, innovation, and hierarchy structure. The model is based on the competing values framework (CVF) and total quality management (TQM), was applied amongst 106 ISO 9000-certified manufacturers, senior managers and persons with enough knowledge to collect data. Findings from the study show that innovation is enhanced mainly when soft TQM elements are adopted and partly when hard TQM elements are used, furthermore the study found that the organizational culture has an effect on hard TQM elements than the soft TQM elements.

From the foregoing, several attempts have studied the effect of culture and managerial tools on TQM application and performance. However, there is needs to prioritize the quality practices which include top management, process management, employee quality management, employee knowledge and education, and customer focus. Organizational culture types (such as clan, adhocracy, market, and hierarchy culture) and the other management tools (such as strategic planning, benchmarking and balanced scorecard) are used when implementing TQM. The performance outcomes, which consist of financial performance, customer satisfaction, product/service quality performance and operational performance of the firm [22], can be used in measuring the influence of the adopted quality practices, organizational culture, and the different management tools.

2.1 Product quality/reliability performance assessment framework for TQM practices in product development SMEs

A performance measurement system has been extensively used throughout history for the assessment of organizational success. It is an invaluable and indispensable means of guiding managers and enabling them in making enlightened and informed decisions. Over the years, this system has evolved from the traditional accounting framework that is predominantly based on financial criteria to a more modern and reliable system that measures the systems, including non-financial criteria such that the measurement system now reflects the applied context [23].

Traditional measurement systems that are based on finance in an organization reflect the overall business activities of the organization ([24]. However, they provide only a little or no indication achieved performance or how it can be improved in the future. Also, the information from these systems is believed to be inadequate for the effective management of product improvement technique in a changing and competitive market [24].

Regardless of constantly and exertion association put into structure and update their performance measurement system, there is little proof to recommend that they are mirroring the hierarchical setting just as the changing and focused market condition.[25]. According to Kennerley & Neely [24], modern implementation, measurement system, must reflect the specific situation and goals of the association, while any inability to viably and proficiently deal with the performance system after some time will achieve measurement crises in the whole framework.

This study primary motivation is to design a new product quality/reliability, performance assessment framework for TQM practices, especially for SMEs product development process. Since the outcome is expected to present the internal and external assessment of the technique for product quality and reliability management, it will assist in making internal and external decisions as well as assist corresponding partners in monitoring their performance. The framework is built on premises surrounding the nature of the qualitative and quantitative inquiry of TQM technique during product development in SMEs - it is based on a new multi-criteria model. The model, which is termed IFWG-VIKOR, combines Intuitionistic Fuzzy Weighted Geometric (IFWG) operator and intuitionistic fuzzy VlseKriterijumska Optimizacija I Kompromisno Resenje (IF-VIKOR). Figure 1 shows the framework for the performance measure.

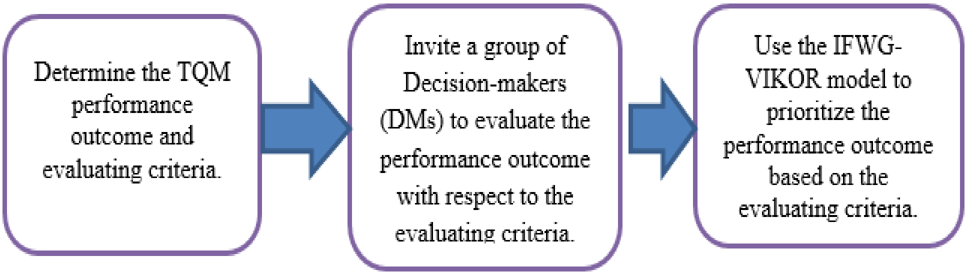

Figure 1: A product quality/reliability performance assessment framework for TQM practice in product development SMEs

3. Materials and Method

3.1. Evaluating theory of the IFWG-VIKOR

The intuitionistic fuzzy set (IFS) was put forward by Atanassov [26] to address fuzziness in the decision-making process, it is an extension of the traditional fuzzy set originally suggested by Zadeh in 1965. IFS concept, which has found several applications in the different fields of engineering management, is used for solving multi-criteria group decision-making (MCGDM) problems. In this paper, the IFS concept is integrated into the traditional VIKOR method, then into an IFWG operator – this operator is used for aggregating experts' opinions-. Definition 1 presents details of IFS, while Definition 2 show the IFWG operator, while Sections 3.2 contains a discussion of the IF-VIKOR method.

Definition 1: [27]

If an *IFS A* is a universal discourse$X = \{x\}$, then the *IFS A* can be defined as follows:

$A = \{\langle x, \mu_A(x), v_A(x)\rangle | x \in X\}$ (1)

Where $\mu_A: X \to [0,1]$ membership function and $v_A: X \to [0,1]$ non-membership function.

If the set is bounded by $0 \le \mu_A(x) + v_A(x) \le 1, \mu_A(x), v_A(x) \in [0,1], \forall x \in X$. Then based on this set boundary, the intuitionistic index of *x* can be expressed as Equation (2), this expression is based on hesitation concept.

$\pi_A(x) = 1 - (\mu_A(x) + v_A(x))$ (2)

This degree will arise only when there is a relative lack of knowledge, personal error or uncertainty of any form, particularly when: $1 - \mu_A(x) - v_A(x) = 0$. For every element $x \in X$ in *A*, the *IFS A* belongs to the fuzzy set, where $0 \le \pi_A \le 1$; hence, the intuitionistic fuzzy number(s) (IFN(s)) is given as $\alpha = (\mu_A, v_A, \pi_A)$ or as $\alpha = (\mu_A, v_A)$.

Definition 2: [28].

If $\alpha_i = (\mu_{\alpha_i}, v_{\alpha_i})$ represent the *IFN* for all $(i = 1,2,3, \dots, p)$, then the Intuitionistic Fuzzy Weighted Geometric (IFWG) operator of the dimension *n* is a mapping IFWG: $\Omega^n \to \Omega$, such that,

$$IFWG(d_1 d_2 d_3, \dots, d_n) = \left(\prod_{i=1}^{n} (\mu_{ij})^{w_i}, 1 - \prod_{i=1}^{n} (1 - v_{ij})^{w_i} \right)$$

where $w_i = (w_1, w_2, w_3, \dots, w_n)^T$ is the weighting vector of $\alpha_i (i = 1, 2, 3, \dots, n)$ with $w_i \in [0, 1]$ and $\sum_{i=1}^{n} w_i = 1$.

The IFWG operator is a mathematical model used to join and summarize the information gathered from different sources when making real-time decisions.

3.2 IF-VIKOR Method

VIKOR is a leading decision-making tool that has found application in engineering management and for solving MCGDM problems. It is used to select the most suitable alternative for a MCGDM problem when information about the problem is presented in a decision matrix format. The information can either in crisp or linguistic form. In addressing fuzziness in the decision-making process, the IFS concept can be integrated into the VIKOR to form the Intuitionistic fuzzy-VIKOR (IF-VIKOR). An IF-VIKOR uses the intuitionistic fuzzy number (IFN) to solve and analyze decision problems. With the aid of IFN, the linguistic responses gained from experts in the field are converted and interpreted to improve and make the VIKOR method robust, while dealing with vague data or response.

To aggregate experts' judgment information in an IF decision matrix, an aggregation operator is considered before alternatives evaluation. In this article, however, the IFWG operator is used to aggregate experts' judgments - the aggregated responses are used to determine alternatives' utility (Equation 4) and regret (Equation 5) values. These values are used to evaluate the alternatives VIKOR index (Equation 8), but consideration is given to the contribution factor (v). This factor determines the contribution of an alternative's utility and regrets values when computing its VIKOR index. (Ighravwe & Oke (2017) reported that when v = 0.5, good ranks can be generated for the alternatives to a problem.

$$S_j = \sum_{i=1}^{n} \frac{w_i \left\{ f_i^* - f_{ij} \right\}}{f_i^* - f_i^-} \quad (4)$$

$$R_j = \max \left(\frac{w_i \left\{ f_i^* - f_{ij} \right\}}{f_i^* - f_i^-} \right) \quad (5)$$

$$f_i^* = \max \left\{ f_{ij} \right\} \quad (6)$$

$$f_i^- = \min \left\{ f_{ij} \right\} \quad (7)$$

$$Q_j = \frac{v\left\{S_j^* - S_j\right\}}{S_j^* - S_j^-} + \left\{1 - v\right\} \frac{v\left\{R_j^* - R_j\right\}}{R_j^* - R_j^-}$$

(8)

The proposed model steps are summarized as follows:

Step 1: Select experts (E_i) with the required experience and expertise on the subject for a multi-criteria decision problem. To improve a model's accuracy, experts should be selected from academic and industry.

Step 2: Use a linguistic scale to collect information from experts (see Table 1). With the information in Table 1, linguistic terms can be converted to the IFN values - this creates the opportunity to construct the intuitionistic fuzzy decision matrix $Z = (r_{ij})_{mxn}$, see Equation (9).

$$Z_{mxn}(x_{ij}) = \begin{bmatrix} (\mu_{11}, v_{11}) & (\mu_{12}, v_{12}) & \cdots & (\mu_{1n}, v_{1n}) \\ (\mu_{21}, v_{21}) & (\mu_{22}, v_{22}) & \cdots & (\mu_{2n}, v_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ (\mu_{m1}, v_{m1}) & (\mu_{m2}, v_{m2}) & \cdots & (\mu_{mn}, v_{mn}) \end{bmatrix} \quad (9)$$

Table 1**:** Linguistic scale and its IFN for performance data collection

Linguistic terms	IFN
Insignificant (IS)	(0.4, 0.1)
Moderately Affect (MA)	(0.5, 0.2)
Averagely Affect (AA)	(0.6, 0.2)
Affect (A)	(0.7, 0.4)
Greatly Affect (GA)	(0.8, 0.2)

Step 3: Use Equation 3 to aggregate experts' judgments in the intuitionistic fuzzy decision matrix $Z = (r_{ij})_{mxn}$.

Step 4: Use Equations (4) and (5) to determine the alternatives' utility and regrets values, respectively, based on the aggregated responses.

Step 5: Use a contribution factor to combine the utility and regret values to determine the alternatives' VIKOR index (Equation 8).

Step 6: Rank the alternatives using utility, regret and VIKOR index values.

4. Result and Discussion

4.1. Numerical illustration

The ranking of TQM practices during product development in SMEs is a crucial decision-making problem. This problem gives insight into the most important and appropriate TQM practice(s) to focus on while addressing infant product failure in a new product development process. In this section, the proposed TQM framework, which is based on a new multi-criteria model termed IFWG-VIKOR, used to prioritize TQM practices with respect to some selected performance outcomes for addressing product infant failure in product development SMEs.

The case study for the framework application is based on a product development SMEs in South Africa. They recently adopted a set of TQM practices to address their infant product failure, early at the product development stage. However, due to the huge cost of implementing different TQM practices during product development, they are forced to select and focus on the most important and appropriate TQM practice for their product. Details of the TQM practices and the selected performance outcomes are given in Table 2.

Table 2: TQM practices and the selected performance outcomes

Code	TQM practices	Code	Performance outcomes
TM_1	Top management involvement	PC_1	Financial performance
TM_2	Process management	PC_2	Customer satisfaction
TM_3	Employee quality management	PC_3	Product/service quality performance
TM_4	Employee knowledge and education	PC_4	Operational performance
TM_5	Customer focus		
TM_6	Customers involvement		
TM_7	Clan culture		
TM_8	Adhocracy culture		
TM_9	Market culture		
	Hierarchy culture		
TM_{10}	Strategic planning		
TM_{11}	Benchmarking		
TM_{12}	Balanced scorecard		

To address this issue, the proposed IFWG-VIKOR model steps are implemented for the **prioritization** of TQM practices. Hence, a five-man expert panel with expert knowledge and experience in product development was set-up. They were drawn from the academia and industry, they all have more than ten (10) years' experience, and are all familiar with educational research and the use of MCDM model. The experts are assigned equal weights of 0.2.

Following the proposed IFWG-VIKOR model steps, the experts were asked to rate and give their judgment on the TQM practices on selected performance outcomes. Tables 3 and 4 show the linguistic and IFN ratings, respectively.

Table 3: Experts' judgment on the selection

	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5
	PC_1					PC_2				
TM_1	IA	A	MA	MA	IS	IS	IS	AA	GA	MA
TM_2	MA	GA	AA	AA	IS	MA	GA	AA	AA	MA
TM_3	AA	IS	A	A	AA	AA	IS	A	A	AA
TM_4	A	MA	IS	GA	A	A	MA	GA	GA	A
TM_5	GA	AA	MA	IS	GA	A	GA	AA	MA	A
TM_6	AA	A	IS	IS	MA	AA	IS	AA	A	AA
TM_7	A	GA	MA	MA	AA	MA	GA	AA	AA	MA
TM_8	IS	GA	MA	MA	AA	AA	IS	A		MA
TM_9	IS	IS	A	MA	AA	AA	A	MA	IS	AA
TM_{10}	IS	MA	GA	MA	AA	A	GA	AA	MA	A
TM_{11}	MA	MA	GA	AA	IS	AA	IS	GA	A	MA
TM_{12}	AA	AA	IS	A	MA	A	MA	GA	GA	AA
	PC_3					PC_4				
TM_1	GA	AA	MA	IS	A	IS	MA	GA	GA	A
TM_2	IS	A	AA	MA	GA	MA	AA	MA	A	GA
TM_3	AA	IS	A	A	MA	AA	IS	A	A	AA
TM_4	A	MA	GA	GA	AA	A	MA	GA	GA	A
TM_5	AA	A	IS	MA	A	MA	IS	AA	AA	MA
TM_6	A	GA	MA	AA	GA	AA	IS	A	A	AA
TM_7	AA	IS	GA	A	MA	A	MA	GA	GA	A
TM_8	GA	AA	MA	IS	GA	A	A	AA	IS	A
TM_9	A	A	AA	MA	A	GA	GA	A	AA	GA
TM_{10}	IS	MA	A	AA	GA	AA	AA	GA	A	AA
TM_{11}	GA	AA	MA	IS	GA	IS	GA	AA	AA	IS
TM_{12}	A	A	AA	MA	A	AA	IS	A	A	MA

Table 4: Aggregated values for the TQM techniques with respect to the performance outcome

	PC_1	PC_2	PC_3	PC_4
TM_1	(0.327, 0.271)	(0.407, 0.254)	(0.431, 0.354)	(0.549, 0.369)
TM_2	(0.391, 0.241)	(0.437, 0.284)	(0.489, 0.312)	(0.522, 0.353)
TM_3	(0.474, 0.392)	(0.474, 0.392)	(0.432, 0.392)	(0.474, 0.392)
TM_4	(0.485, 0.385)	(0.597, 0.406)	(0.553, 0.315)	(0.597, 0.406)
TM_5	(0.460, 0.254)	(0.511, 0.406)	(0.430, 0.394)	(0.381, 0.267)
TM_6	(0.336, 0.271)	(0.452, 0.338)	(0.551, 0.315)	(0.474, 0.392)
TM_7	(0.447, 0.315)	(0.391, 0.241)	(0.450, 0.338)	(0.597, 0.406)
TM_8	(0.411, 0.272)	(0.432, 0.392)	(0.460, 0.254)	(0.460, 0.416)
TM_9	(0.396, 0.316)	(0.394, 0.296)	(0.497, 0.440)	(0.622, 0.344)
TM_{10}	(0.431, 0.272)	(0.511, 0.406)	(0.510, 0.332)	(0.535, 0.353)
TM_{11}	(0.388, 0.241)	(0.450, 0.338)	(0.460, 0.254)	(0.378, 0.228)
TM_{12}	(0.396, 0.330)	(0.553, 0.315)	(0.497, 0.440)	(0.432, 0.392)

Based on the information in Table 4, Equations (4) to (6) were used to generate the utility, regret and VIKOR index values of the different TQM techniques. Table 5 shows the results for the techniques' utility, regret and VIKOR index values. This information is further analyzed and presented using a bar chart as shown in Figure 1. From the chart, it is not hard to see that the TQM practices TM_4 and TM_{11} respectively, are the most and least important practices for addressing product infant failure.

Table 5: Utility, regret, and VIKOR index values for the TQM techniques

Criteria	S_i	R_i	Q_i	Ranking
TM_1	1.350	0.282	0.860	11
TM_2	1.221	0.195	0.468	6
TM_3	0.735	0.278	0.625	8
TM_4	0.244	0.191	0.105	1
TM_5	1.175	0.287	0.819	10
TM_6	1.009	0.191	0.376	3
TM_7	1.047	0.237	0.573	7
TM_8	1.141	0.283	0.791	9
TM_9	0.832	0.229	0.465	5
TM_{10}	0.784	0.165	0.191	2
TM_{11}	1.653	0.290	1.000	12
TM_{12}	0.759	0.225	0.425	4

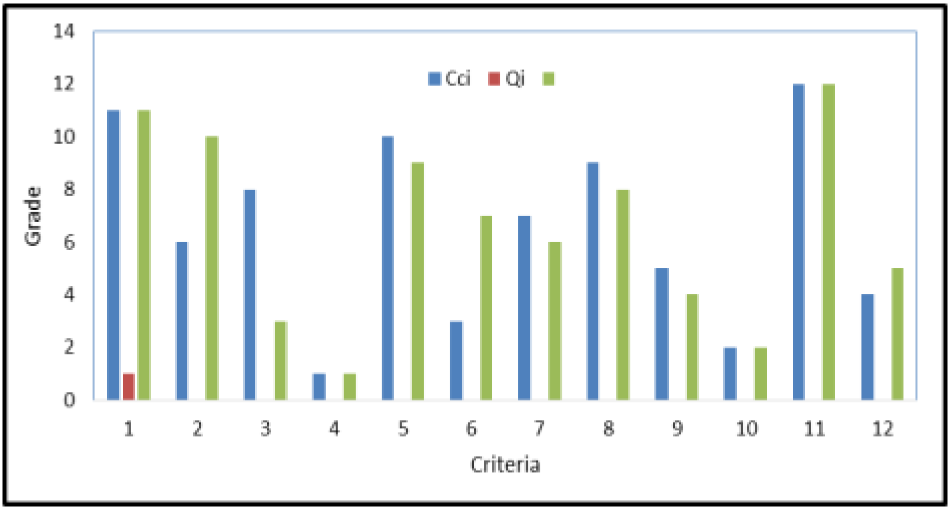

Figure 1: Rankings, for the TQM techniques with respect to PC for the utility, regret and VIKOR index values

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), which is an established MCDM tool is used to validate the proposed model results. Using the information in Table 3, the TQM techniques coefficients were generated; Table 6 shows the results obtained. These results show that the TOPSIS and the IFWG-VIKOR models ranked the most and least important TQM practices the same.

To further analyzed result, it is presented using a line graph as shown in Figure 2, here a detailed ranking of the efficiency of the two models for evaluating TQM practice used in addressing product infant failure are presented. The ranking pattern for the TOPSIS model and that of VIKOR in the line graph diagram shows that the TQM practice TM4 is the most important TQM practice for addressing product infant failure while TM11 is the least important TQM practice based on the evaluating performance outcome.

Table 6: Comparison of results for validation of the model

Criteria	Q_i	Ranking	TOPSIS CC_i	Ranking
TM_1	0.860	11	0.368	11
TM_2	0.468	6	0.404	10
TM_3	0.625	8	0.606	3
TM_4	0.105	1	0.847	1
TM_5	0.819	10	0.410	9
TM_6	0.376	3	0.475	7
TM_7	0.573	7	0.508	6
TM_8	0.791	9	0.430	8
TM_9	0.465	5	0.603	4
TM_{10}	0.191	2	0.610	2
TM_{11}	1.000	12	0.160	12
TM_{12}	0.425	4	0.601	5

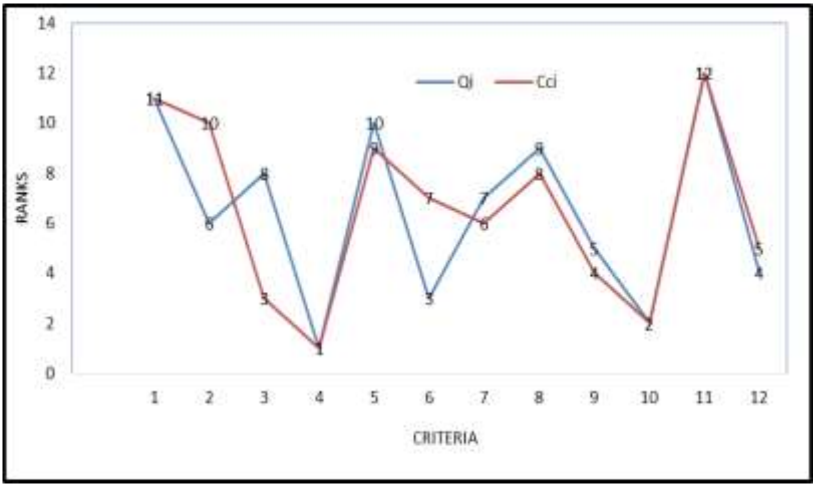

Figure 2: Comparison of result for proposed method validation

From the results, the study can conclude that the proposed method is robust, effective and feasible for addressing decision-making issues under uncertainties. It provides insights into the management of techniques that can address infant product failure issues at the early stage of product development.

5. Conclusions

This study has presented a new performance framework for product infant failure. It was built using qualitative and quantitative inquiry of TQM technique during product development in SMEs. With an IFWG-VIKOR, the framework was used to prioritize TQM techniques including quality practices, organizational culture, and the different managerial tools. Hence, it provides a means of measuring the influence of TQM practices. And it will assist product development managers to make an appropriate decisions tool, especially when considering products infant failure. To ensure the efficiency and feasibility of the proposed IFWG-VIKOR model and framework for solving MCDM problems and the prioritization of TQM techniques, framework performance was evaluated using real-world data. Furthermore, TOPSIS method was used to validate the proposed framework performance. The results obtained showed that both methods ranked the same techniques as most and least important.

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