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Article

Fuzzy Analytical Hierarchy Process for Supplier Selection: A Case Study in An Electronic Component Manufacturer

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Abstract. Supplier selection has become one of the essential effects on the entire electronic supply chain network to gain competitiveness. In the upstream supply chain, companies are able to achieve a high quality and value of products to reduce the potential risks from both internal and external stakeholders by selecting the right suppliers. The case study company produces a nano sim-card connector in which four different types of raw materials are processed into different parts. Currently, the case study company selects each raw material supplier based on its appraisal record. Nevertheless, the appraisal record is measured by the department of procurement. When candidate suppliers are categorized at the same level, the cost becomes the priority criteria to select the supplier, which increases the potential risks of, for example, the components defect rate, a penalty from clients, and a reduction in orders. This paper proposed a Fuzzy analytic hierarchy process (FAHP) model for the selection of raw material suppliers by collecting data from two of the company's departments (procurement and engineering) and the clients to address qualitative and quantitative elements, uncertainty, and linguistic vagueness based on the company's scenario in two parts. First, the main and sub-criteria can be weighted using a decision-maker (DM) to identify the level of importance. Second, the FAHP model also dealt with personal preferences and judgement so that the right supplier(s) for each raw material could be selected by collecting and computing the data from the respondents. Then, the sensitivity analysis is applied to observe how the decisions change when the model parameters in the top five sub-criteria change. The proposed model can offer better information and solutions for the DM in the case study company to differentiate the crucial main and sub-criteria and select the suitable raw material suppliers effectively.

Keywords: Supplier selection, analytic hierarchy process, fuzzy AHP, manufacturing supply chain.

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1. Introduction

In global competition, the supply chain network of a company has become more complex than before, indicating that organizations have spent more time on identifying and selecting an optimal supply source in their supply chain to achieve a high level of efficiency and effectiveness [1]. The boundaries between businesses have diminished, giving manufacturers the opportunity to seek their supply sources globally [2]. This means that the entire supply chain, from the upstream to the downstream, is closely connected. Also, over the past few decades, gaining global competitiveness has become essential, since manufacturers are able to supply high quality products at a reasonable price [3].

In the real world, information is combined with external factors, such as shortage and delays, and internal factors, such as capacity and product lifecycle; meanwhile, people's judgement always exists vague on handling certain problems, especially in qualitative elements, so that decision-makers (DMs) might not be able to identify information precisely [4-7]. These uncertainties have a high possibility to lead DMs to selecting inappropriate suppliers. Thus, an appropriate supplier selection has become significant enough for companies to spend time considering their strategic processes in different fields in order to reduce potential risks that affect companies' performance.

Recently, environmental awareness in the population has risen, leading to entire supply chains having to consider the environmental aspects in their operation strategy [8, 10]. Notably, in the smartphone industry, most of the well-known brands have already become involved in their entire supply chain to ensure it is green. Moreover, in recent years, organizations have relied on suppliers more than before, which indicates that the frequency of poor decision making in supplier selection will affect the entire supply chain's performance. This makes selection of the upstream supply chain crucial, as the appropriate supplier must provide high-quality products on time.

The case study company of this report is an electronic company that has been manufacturing hardware for its clients from different industries, such as smartphones and automobiles in China. The company produces a variety of electronic components, and this paper focuses on a nano sim-card connector, shown in Fig. 1. Since the first smartphone was launched in the global market, the volume of smartphones has increased to reach 1.37 billion units in 2019 [11], with the competition in the smartphone market has been in full swing. Therefore, smartphone companies need to focus on both hardware and software to maintain customer loyalty and to appeal to potential new customers. Specifically, the hardware parts must be monitored because the software is established on the hardware parts and so they have a high potential to affect the smartphone companies' reputation, market share, and even the smartphone supply chain.

Furthermore, as the first supplier to produce nano sim-card connectors in smartphone companies, and with only a few electronic companies being able to produce the required number of connectors to fulfill orders per year, the case study company covers largest portion of the market share in premium smartphones from three android smartphone companies in Asia. The sim card connector has been scaled down to be 'nano-sized', as in a millimeter-scale (Fig. 2). Thus, the component, the nano sim-card connector from the case study company, has played an essential role that not only produces a stable quality of components to receive the reception from the telecom carriers, but also affects the companies' reputation and performance in the downstream supply chain.

Fig. 1. Nano sim-card connector.

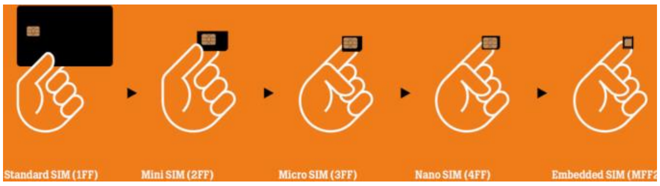

Fig. 2. Evolution of the Sim card from TELE2 [12].

The objective of this research was to identify a suitable raw material supplier via the supplier selection process in the upstream smartphone supply chain, which can be qualified by the manufacturer's decision criteria in the nano sim-card connector. Indeed, the manufacturer needs to consider qualitative and quantitative elements to convert into numbers.

Fuzzy analytic hierarchy process (FAHP) methodology can solve qualitative criteria, while triangular fuzzy numbers (TFN) can deal with uncertainties (linguistics and personal preference). The first part of this research evaluated the five main criteria and 12 sub-criteria selected by the company's departments of engineering and procurement. The second part presents the selection of the correct raw material suppliers for the four primary materials that involve the weight of all criteria from the first part and linguistic vagueness from respondents to compute to rank raw material suppliers. The result of this study offers the data on the structure of the FAHP, which in turn will provide a different aspect in the supplier selection environment or sustainable development guideline in the manufacturer's aspect in the electronic industry.

The main contribution of this paper explores a new perspective that involves two of the company's departments (engineering and procurement) and clients to identify and select the suitable raw material suppliers for producing the nano sim-card connector in the smartphone supply chain, instead of a single source or department. In addition, the personal preference and linguistic vagueness are addressed by the fuzzy set theory (FST), which provides more accurate data to measure and select the suitable supplier. Compared to other research, they focus on a large size of products and commodity. In this paper, we focus on the nano sim card connector (millimeter scale) that is high value-added to be one of hardware in a flagship smartphone. Also, each respondent in a higher position (e.g., supervisor, manager, and senior manager) has been in the electronic field for more than five years which is qualified to be involved in the supplier selection in the nano sim-card connector. Therefore, the new supplier selection can not only provide better information to select a raw material supplier, but also reduces the potential risks, such as the components defect rate, penalty from clients, and order reduction, in the case study company.

This paper is organized as follows. In the next section, the literature review explores the relevant study for this research, including an overview of the AHP and FAHP methodology in supplier selection. Meanwhile, the current situation for the case study company that produces nano sim-card connectors was evaluated for the supply of the four primary materials (plastic, nickel, phosphor bronze, and stainless-steel) that are utilized. In section 3, the research method and the main and sub-criteria are described, while in section 4, the research results are provided and discussed. In section 5, the sensitivity analysis is presented. Ultimately, section 6 provides the conclusion and suggestion for further research.

1.1. Statement of the Problem

The nano sim-card component produced by the case study company is assembled from four primary materials: plastic, stainless-steel, nickel, and phosphor bronze. Each part is small (millimeter scale) and light (less than 1 g). The case study company, which is in the upstream supply chain, provides approximately ten million sim-card connectors, assembled into a flagship handset, to its clients per year. In the original equipment manufacturing (OEM), once one of the components has issues, the assembly line will be suspended until the issues are solved. Thus, the whole internal supply chain performance would be affected. For instance, the case study company received an issue from clients that the nano sim card connector could not weld onto the printed circuit board because of flatness. This issue was eventually identified when the case study company switched their raw material supplier for stainless-steel in order to reduce the cost and improve the profitability, but this actually caused a tremendous loss and affected its performance.

Indeed, the case study company did employ an appraisal record for their supplier survey to categorize at different levels and allow selection of the raw material supplier. However, in the case of the stainless-steel material supplier selection, all the candidate suppliers were categorized at the same level, and since the supplier survey was only scored by the procurement team, the information might have been inaccurate for selecting the appropriate supplier. To maintain or improve the profitability, the procurement team first considerably reduced the raw material cost. Integrating all the factors, the procurement team in the case study company decided to switch the stainless-steel supplier to decrease the material cost. However, in contrast, this issue caused a negative impact on the further corporation with the client with reduced the orders, a penalty to pay, and the return of all the connectors that were lasered etched with the same code. Also, the smartphone assembly line was suspended until the issue was solved, which caused a downstream delay and affected the performance.

Although the existing technology is able to monitor and improve most of the connector's manufacturing process, the raw materials are ordered from different suppliers which can be defined as an external source. This explains that the raw materials they produce are based on their internal standard operating procedure. Undeniably, most of the raw material suppliers are certificated by an international standard such as ISO and IECQ. Nevertheless, the difference between each raw material supplier is their procedure to produce the raw material, which directly affects the quality of raw materials to be material parts.

Hence, we proposed to collect data from two departments of the case study company and the clients to select the correct supplier(s) for each raw material by utilizing FAHP to improve the selection process, deal with uncertainty, linguistic vagueness, and reduce of the potential risks of the four primary raw materials used in the nano sim-card connector.

2. Literature Review

In globalization, many companies cooperate with both domestic and international suppliers in order to strengthen their efficiency, effectiveness, and profitability. Nowadays, a supply chain has become a more complex network, from raw materials to the end consumers, and consists of all the processes, such as purchasing, manufacturing, risks, and other factors [3]. Also, people's judgement would influence on decision-making. In order to improve the entire supply chain network to be competitive, appropriate suppliers would promote a product to achieve a high quality with customer satisfaction [1]. Hence, supplier selection plays a crucial role in the supply chain to achieve the maximum benefits and a better performance.

Recently, a variety of methodologies have been utilized in multi-criteria decision problem (MCDM) to determine the most suitable decision in its supply chain to achieve its' needs in different fields, such as evaluation based on Distance from Average Solution (EDAS) to measure seven criteria for classifying an appropriate alternative in inventory items [13], simultaneous evaluation of criteria and alternatives (SECA) to recognize the final weight in each alternative's performance and alleviate the deviation in each criterion [14], weighted aggregated sum product assessment (WASPAS) to select the fittest green supplier in the construction industry [15], and Method based on the Removal Effects of Criteria (MEREC) to compute criteria weights from objective [16]. AHP becomes one of the valuable and popular methodologies to determine the weight from main and sub-criteria, and FAHP, combined with fuzzy set theory, is able to address uncertainty in decision making in fuzzy environments [17].

Many researchers have performed supplier selection by utilizing AHP and FAHP for dealing with MCDM in order to select the optimal suppliers in the supply chain, as shown in the relative fields related to the case study company, in Table 1.

Table 1. Literature review for supplier selection study.

Reference	Scope	Methodology
[18]	Semiconductor	AHP
[1]	Global supplier	Fuzzy AHP
[26]	PC	Fuzzy AHP
[3]	PC	Questionnaire, AHP, and multi-objective linear programming
[20]	Electronic industry	Fuzzy preference programming (FPP)
[19]	Manufacturer	AHP
[21]	Washing machine	Fuzzy AHP
[27]	Focal companies	Fuzzy AHP
[22]	Automotive industry	Balanced scorecard and Fuzzy AHP
[9]	Automotive industry	Fuzzy (AHP, TOPSIS, WASPAS, and MABAC)
[24]	Electronic industry	AHP with intuitionistic Fuzzy number
[23]	Automotive industry	Balanced scorecard and Fuzzy AHP

TOPSIS = technique for order preference by similarity to ideal solution; WASPAS = weighted aggregated sum-product assessment; MABAC = multi-attributive border approximation area comparison.

2.1. Analytic Hierarchy Process

The AHP method is one of the systematic approaches to categorize different factors to deal with multi-criterion problems, including subjective and objective evolution [8]. Also, the hierarchy procedure is able to provide consistent measures and alternatives to reduce the difficulty of decision-making. Hence, AHP is able to perform qualitative and quantitative elements to be weighed so that decision-makers (DMs), procurement teams, or top management teams can select the optimal suppliers by numbers.

Chan and Chan [18] proposed that based on multiple criteria, the company had to consider selecting optimal suppliers in order to fulfill their requirements, and that utilizing AHP to identify five main criteria and 21 sub-criteria to compute the final weight for supplier selection was valid for making semiconductor equipment. Ting and Cho [3] mentioned that multinational companies have relied on outsourcing more than before, where an appropriate supplier selection and purchasing decision would influence their entire supply chain whether would be efficient and effective. They demonstrated that AHP is able to identify both quantitative and qualitative criteria to weigh each criterion in the PC industry. Amid et al. [19] stated that DMs can handle MCDM problems by AHP. This helps organizations to manage their supplier chain performance on cost, quality, and service.

2.2. Fuzzy Analytic Hierarchy Process

Although AHP has become one of the effective solutions to deal with MCDM in real situations, DMs and procurement teams have a limitation in the information that they can collect, compute, and memorize in order to calculate all the alternatives in the decision-making environment; plus, they also have their preference and judgement [20]. Chamodrakas et al. [20] mentioned that modern industries face global competition, in which companies obtain vast information in a complex environment to execute the optimal strategy in the market. With these limitations and global competition, an appropriate supplier is able to satisfy a company's requirements in different needs [21, 22]. Additionally, AHP has some existing defects that might make decision-making crisp and imprecise [25], as listed in Table 2. However, a result, those uncertainties can be solved by the FST.

Table 2. Shortcomings of AHP [25].

1.	Judgement is based on personal preference leading to unbalanced scale
2.	Not involve in linguistic vagueness
3.	The result is affected by DMs based on their preference
4.	Measurement by individuals on qualitative attributions has existing bias, heterogeneity, and imprecision

Chan et al. [1] proposed that in global competition it is essential to involve, not only common criteria, such as quality and cost, but also other vital variances are essential to be involved. To this purpose, they utilized the FAHP framework to tackle the data for global supplier selection. Chiou et al. [26] stated that selection of green supplier selection needs to be involved in the MCDM process in order to determine the relative importance. They demonstrated that FAHP could explore the differences in three foreign companies in China and conclude that the groups from three countries can identify the optimal ranking for green supplier selection.

Chamodrakas et al. [20] indicated that in the washing machine field, the main cost of a product is comprised of the cost of materials and components. Those costs occupy a large proportion of revenue, which would affect the performance of a company. They employed Fuzzy preference programming in electronic marketplaces to alleviate the information overload and deal with inconsistency and uncertainty to then select the optimal suppliers in a metal manufacturing company.

Kilincci and Onal [21] utilized FAHP to select optimal supplier selection in order to achieve the customers' needs. Galankashi et al. [22] and Manupati et al. [23] integrated the balanced scorecard with FAHP to weigh each criterion and rank the final score of each supplier in the automobile industry. Nirmala and Uthra [24] integrated nearest weighted intuitionistic interval approximation into the triangular intuitionistic fuzzy number for dealing with vagueness and uncertainty when selecting the optimal vendor suppliers in the supply chain.

Gold and Awasthi [27] proposed that general decision-making tools do not involve sustainability risks, such as the civil society, into the supply chain. They demonstrated that FAHP could provide the appropriate information for DMs to deal with issues and select a proper supplier.

Gupta et al. [9] explained that in assembled machine planning in the automotive industry, companies require not only the location, quality, and material but also highly skilled employees to achieve a high quality and optimization. They utilized FAHP along with other techniques, which were multi-attributive border approximation area comparison, weighted aggregated sum-product assessment), and technique for order preference by similarity to ideal solution, to measure each criteria weight to identify the optimal green suppliers. Other research that is related to FAHP can be found in Kahraman et al. [28-30].

Most research has directly evaluated and analyzed the supplier selection in the OEM (Fig. 3). The role of the OEM is to select a suitable component supplier in order to enhance the supplier chain [18-20]. To be specific, nowadays, in the globally competitive electronic market, connections in the supply chain are suppressed more than before, which requires more criteria and involves uncertainty and preference. Notably, smartphones can be categorized as fashion goods, which indicates that the supply chain in the smartphone has established a higher connection. When the upstream supplier has some issues, the whole supply chain is affected.

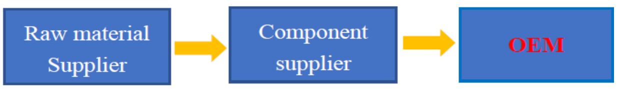

Fig. 3. The role of an OEM in the electronic industry.

The existing appraisal record in the case study company was measured by the company's department of procurement, which might lead to an imprecise decision on the supplier selection due to the presence of some bias and preference. In order to tackle this issue, in this paper, two different departments of the company and the clients were included to identify the main and sub-criteria, whilst the personal preference and linguistic vagueness was also addressed to provide more precise information for selection of the suitable raw material supplier for each of the four primary materials used in the nano sim-card connecter. In this study, one raw material supplier was selected for each material. This is because comparison of the volume of orders per year in the case study company with other electronic components in the electronic and automobile industry, revealed the total weight of each material was less than ten tons, and the average weight per month was less than 600 kilograms, and so one raw material supplier could reliably fulfill the orders from the case study company.

Although it might be possible that the raw material supplier is unable to supply because another client had purchased most of the orders, or the order from the case study company is a small batch in the slack season, an agent whose role is similar to a forwarder is in contract with the raw material supplier, for many small and medium enterprises require a small batch order. Thus, the case study company is still able to order the same material from the agent.

In this study, the role in selecting a suitable supplier moved up one level in the upstream chain to be the component supplier (Fig. 4). We utilized FAHP to identity the main and sub-criteria to select a suitable raw supplier in the nano sim-card connector by collecting data from two departments (procurement and engineering) and the clients. Moreover, FAHP can also measure qualitative and quantitative data and deal with uncertainty and personal preferences to select the right raw material suppliers for the four primary materials (plastic, stainless steel, nickel, and phosphor bronze) in the nano sim-card connecter to achieve a high quality and value-added product, reduce the potential risks, and explore a new perspective in supplier selection to provide precise information for the DM in the case study company.

Fig. 4. The role of the component supplier in this paper.

3. Methodology

The methodology is discussed in two parts in this paper. The first part identifies which main and sub-criteria are essential in the selection of raw material suppliers using the AHP with the FST. The second part then selects the optimal raw material supplier for the four primary materials by combining with the linguistics approximation in the FAHP. Overall, the methodology in this paper is summarized in Fig. 5.

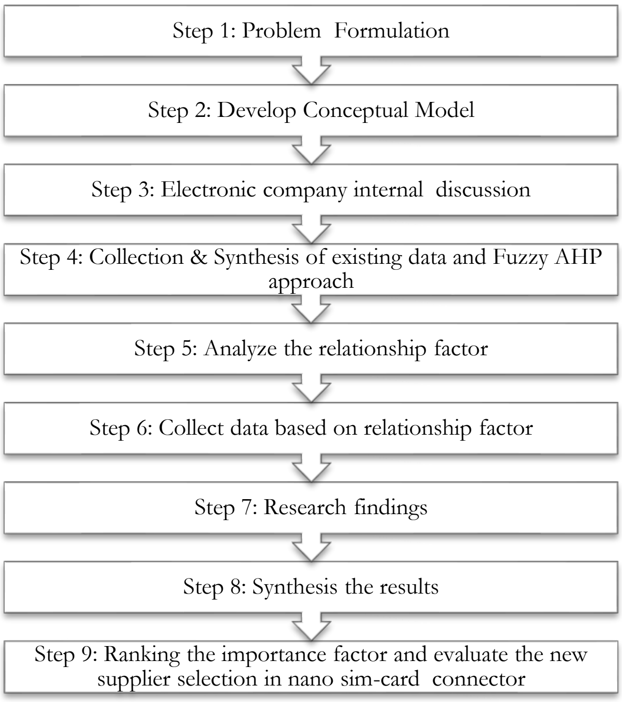

Fig. 5. Research framework for the raw material supplier selection.

3.1. Fuzzy Analytic Hierarchy Process Methodology

The AHP is one of the MCDM approaches to break down the factors into smaller constituent parts [31]. However, in the complex environment of the smartphone industry, more criteria, decisions, preferences, and other uncertainties must be involved in the decision making, which FST is able to deal with.

In order to select suitable main and sub-criteria in the nano sim-card connector by the case study company, several studies in related fields were collected to conform with the company's requirement and current scenario, as shown in Tables 3 and 4.

Five main criteria and 12 sub-criteria that would affect the quality and value of the nano sim-card connector were obtained by collecting several studies and elected by the case study company, as shown in Fig. 6.

Table 3. Main criteria from literature in relative fields.

Main criteria	Literature
Cost	[1, 3, 9, 18, 20, 26-28]
Quality	[1, 3, 9, 18, 20, 21, 26-28]
Reliability	[3, 18, 20, 21]
Risks	[1, 26, 27]
Financial status	[1, 3, 22, 28]
Service/ partnership	[1, 3, 9, 21, 28]

Table 4. Sub-criteria from literature in relative fields.

Sub-criteria	Author
1. Material cost 2. Credit time 3. Ordering cost 4. Transportation cost	[1, 3, 9, 18, 20, 26-28]
1. Quality consistency 2. Defect rate 3. Packaging quality	[1, 3, 9, 18, 20, 21, 26-28]
1. Delivery-delay 2. Delivery-shortage 3. Minimum order requirement	[3, 18, 20, 21]
1. Distance 2. Legal environment 3. Political stability	[1, 26, 27]
1. Cash flow 2. Assets and debts 3. Income	[1, 3, 22, 28]
1. Contract 2. Proactive information 3. Lead time to order. 4. Response after defect 5. Flexibility	[3, 9, 21, 28]

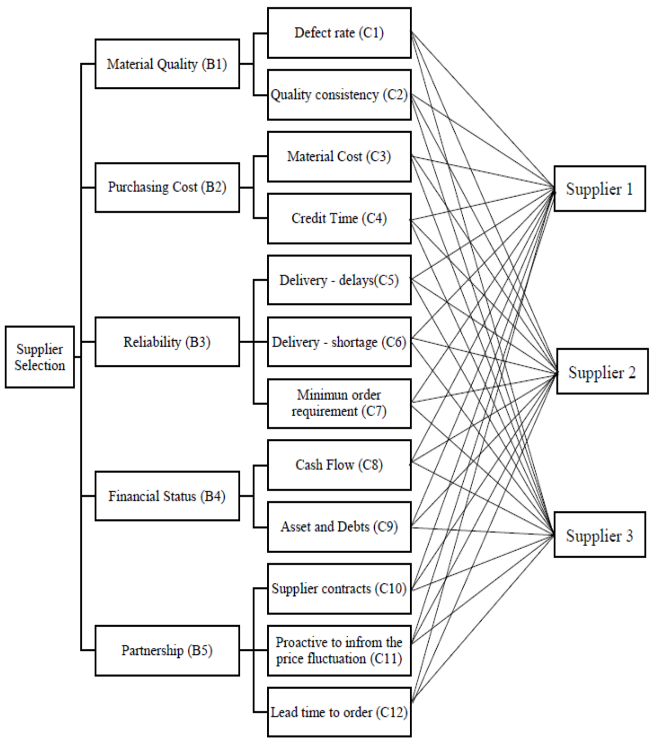

Fig. 6. Criteria for raw material supplier selection.

B1. Material quality: the nano sim-card connector is produced in a millimeter size range that is the essential criterion in the supplier selection process.

- C1: Defect rate - defective rate from the four Materials' part report

- C2: Quality consistency - internal testing report of the quality standards for the raw material

B2. Purchasing cost: the profit can be directly affected by the total raw material acquisition costs.

- C3: Material cost - the latest price is offered by the raw material suppliers
- C4: Credit time - the number of days that the case study company is allowed to wait before paying the invoice

B3. Reliability: the performance of the raw material suppliers in being able to meet the due day. In addition, the purchasing team can receive the precise quantity orders from the raw material suppliers.

- C5: Delivery-delays - delivery schedule report
- C6: Delivery-shortage - raw material delivery report
- C7: Minimum order requirement - the latest minimum order information from the raw material suppliers

B4. Financial status: The clients of the case study company provide a list of which raw material suppliers can be adopted. The accounting statement represents whether they are capable of receiving specific raw material orders from the purchasing team.

- C8: Cash flow - the raw material suppliers' annual cash flow in the annual report
- C9: Assets and debts - the raw material suppliers' balance sheet in the annual report

B5. Partnership: based on globalization, the price can fluctuate each month, which influences the operation cost. Also, the raw material supplier's plan to have a long-term trade with the case study company, which creates a stable supply and demand. In addition, the cycle time that the raw materials are manufactured in is affected by the production schedule

- C10: Supplier contract - the time of fixed cost
- C11: Proactive to inform the price fluctuation – the price fluctuation is updated one month earlier
- C12: Lead time to order - the lead time schedule from production to delivery.

Buckley [32] explained that traditional AHP is not able to present an individual's subjective judgement and uncertainty appropriately. In the conventional AHP questionnaire (Table 5), each linguistic approximation is individual (subjective), which might lead to an imprecise result. Thus, Buckley [32] proposed, that fuzzy theory is able to deal with this situation to provide the appropriate result in real-world decisions (Fig. 7). Hence, TFN in the FAHP evaluation criterion semantic scale (Table 6) would be utilized to create a questionnaire.

Table 5. Semantic scale for AHP evaluation criteria (from [31]).

Evaluation criterion	Meaning
1	Equal importance
3	Weak importance
5	Essential importance
7	Very strong importance
9	Absolute importance
2,4,6, and 8	Intermediate values

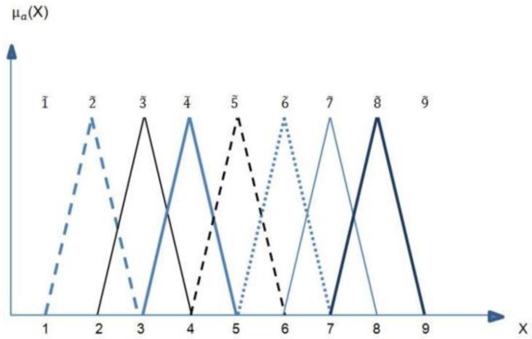

Fig. 7. Fuzzy linguistic (from [32]).

Table 6. Semantic scale for the FAHP evaluation criterion semantic scale.

Fuzzy evaluation criterion	Meaning
$\tilde{1}$ = (1,1,1)	Equal importance
$\tilde{2}$ = (1,2,3)	Intermediate values
$\tilde{3}$ = (2,3,4)	Weak importance
$\tilde{4}$ = (3,4,5)	Intermediate values
$\tilde{5}$ = (4,5,6)	Essential importance
$\tilde{6}$ = (5,6,7)	Intermediate values
$\tilde{7}$ = (6,7,8)	Very strong importance
$\tilde{8}$ = (7,8,9)	Intermediate values
$\tilde{9}$ = (9,9,9)	Absolute importance

After collecting data from the case study company, the elements are compared pairwise to establish a pairwise comparison matrix. Also, utilizing the TFN on a scale of $\tilde{1}$ to $\tilde{9}$ can address the individual's preference and judgement. Nine TFNs ($\tilde{1}$ to $\tilde{9}$) were employed in this study, where $\tilde{1}$ is equal importance, were $\tilde{9}$ is absolute importance in Table 6. In addition, the pairwise comparison has reciprocal property. If a ratio of factor i and factor j is $\tilde{a}_{ij}$, then, element i and j are related by is $1/\tilde{a}_{ij}$. If $\tilde{A} = (\tilde{a}_{ij}) = (L, M, U)$ then reciprocal value is $\widetilde{A^{-1}} = (\widetilde{a_{ij}^{-1}}) = (L, M, U)^{-1} = (\frac{1}{U}, \frac{1}{M}, \frac{1}{L})$. Thus, the elements of the comparison matrix are as shown in Eq. (1),

$$\tilde{A} = (\tilde{a}_{ij}) = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \cdots & 1 \end{bmatrix} \quad (1)$$

After establishing the pairwise comparison（$\tilde{a}_{ij}$, a weight （$\widetilde{W}_{ij}$） from each level of the hierarchy can be measured. Normalization of the geometric Mean of the rows (NGM) was utilized to measure the weight. Next, the eigenvalue $\tilde{\lambda}_{max}$ was used to measure consistency, as shown in Eqs. (2)-(5).

$$\widetilde{W}_{ij} = \sqrt[n]{\prod_j^n \tilde{a}_{ij}} \,/\, \sum_i^n \sqrt[n]{\prod_j^n \tilde{a}_{ij}}\text{ , i,j = 1,2, …, n} \quad (2)$$

$$\tilde{A}\times\widetilde{W} = \tilde{\lambda}_{max}\times \widetilde{W} \quad (3)$$

$$\tilde{A} = \begin{bmatrix} \widetilde{W}_1/\widetilde{W}_1 & \widetilde{W}_1/\widetilde{W}_2 & \cdots & \widetilde{W}_1/\widetilde{W}_n \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{W}_n/\widetilde{W}_1 & \widetilde{W}_n/\widetilde{W}_2 & \cdots & \widetilde{W}_n/\widetilde{W}_n \end{bmatrix} \begin{bmatrix} \widetilde{W}_1 \\ \widetilde{W}_2 \\ \vdots \\ \widetilde{W}_n \end{bmatrix} = \begin{bmatrix} \widetilde{W}_1{}' \\ \widetilde{W}_2{}' \\ \vdots \\ \widetilde{W}_n{}' \end{bmatrix} \quad (4)$$

$$\tilde{\lambda}_{max} = \frac{1}{n}\left(\frac{\widetilde{W}_1{}'}{\widetilde{W}_1} + \frac{\widetilde{W}_2{}'}{\widetilde{W}_2} + \ldots + \frac{\widetilde{W}_n{}'}{\widetilde{W}_n}\right) \quad (5)$$

After obtaining the aggregate judgement matrix from all the pairwise comparisons, the consistency index (C.I) and the consistency ratio (C.R) were determined to judge whether the aggregate judgements were consistent. If not, they were adjusted to avoid imprecise decision making. Saaty [33] suggested that if the C.I < 0.1, the error will affect the optimal acceptance, but, if the C.I < 0.2, the error is acceptable. Also, the R.I is the random consistency index, where the value is given from Table 7. If the C.R $<$ 0.1, the judgement matrix is satisfied, whereas if the C.R > 0.1, it can be considered to be in consistent. The measurements are as shown in Eqs. (6) and (7):

$$\text{C.I}= \frac{\lambda_{max}-m}{m-1} \quad (6)$$

$$\text{C.R}= \frac{C.I}{R.I} \quad (7)$$

Where λ_{max} is the first priority of the pairwise comparison matrix,
m is the number of classes,
R.I is the ratio indexes of the value of R.I.

Table 7. Ratio index (R.I) for different values of n (from [33]).

Order (n)	1	2	3	4
R.I	0	0	0.52	0.89
Order (n)	6	7	8	9
RI	1.25	1.35	1.40	1.45

Defuzzification was used to convert the fuzzy values to exact values. The center of gravity method was used to calculate the fuzzy number of membership function to find the exact value of the fuzzy number,

$$G(A) = \frac{\int_U \mu_a(x)\times x dx}{\int_U \mu_a(x) dx}\text{ , and } \int_U \mu_a(x)\, dx \neq 0 \quad (8)$$

When the fuzzy number is the TFN, the center of gravity can be converted to the linear formula using Eq. (9),

$$DF = \frac{(M_i-L_i)+(U_i-L_i)}{3} + L_i\ ,\forall_i \quad (9)$$

Based on the DF, the final score can be ranked to identify the priority of sub-criteria in each hierarchy.

3.1.1. 3.1.1 Sub-weight (TFN)

The sub-weight is denoted as $\widetilde{W}_i = (L_{wi}, M_{wi}, U_{wi})$ from each respondent where $\widetilde{W}_i$ is the assessment criterion of the fuzzy weight, and s is the number of respondents. $\widetilde{W}_i$ can be described as shown in Eq. (10):

$$\begin{aligned} \widetilde{W}_i &= (L_{wi}, M_{wi}, U_{wi}),\ j = 1, 2, \ldots N \\ L_{wi} &= min\{W_{si}\}, \forall j\ , \\ M_{wi} &= ave\{W_{si}\}, \forall j\ , \\ U_{wi} &= max\{W_{si}\}, \forall j\ , \end{aligned} \quad (10)$$

where min is the lowest weigh, ave is the geometric mean, and max is the largest weight from the total numbers of experts

The sub-weight collected from 15 respondents was then used to calculate the final sub-weight (Fig. 8), where $\widetilde{W}_i$ can be listed. It can be described in Eq. (11).

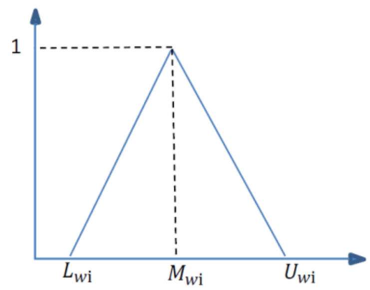

Fig. 8. The TFN $\widetilde{W}_i = (L_{wi}, M_{wi}, U_{wi})$ for membership of the function.

$$f_{\tilde{A}}(\widetilde{W}_i) = \begin{cases} 0 & , \widetilde{W}_i < L_{wi} \\ \frac{\widetilde{W}_i - L_{wi}}{M_{wi} - L_{wi}} & , L_{wi} < \widetilde{W}_i < M_{wi} \\ \frac{U_{wi} - \widetilde{W}_i}{U_{wi} - M_{wi}} & , M_{wi} < \widetilde{W}_i < U_{wi} \\ 0 & , \widetilde{W}_i > U_{wi} \end{cases} \quad (11)$$

3.1.2. Linguistic approximation

Liang and Wang [34] explained that the linguistic variable is able to address each respondent's preference in supplier performance. Five scales can be identified in Fig. 9.

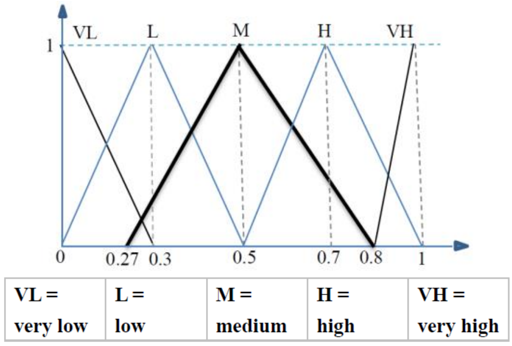

Fig. 9. Five scales of linguistic approximation ([34]).

Based on the respondents' experience and knowledge in a 0–100% ratio scale, a questionnaire can be created to identify each respondent's judgement and preference. After collecting data, the fuzzy synthetic value (X_{ij}^k) was identified. The term X_{ij}^k shows that k respondent is for the i^{th} supplier under the j fuzzy synergy value. Then, $LX_{ij}^k, MX_{ij}^k, and\ UX_{ij}^k$ can be measured by NGM, as shown in Eq. (12):

$$X_{ij}^k = (LX_{ij}^k, MX_{ij}^k, UX_{ij}^k)$$
$$LX_{ij}^k = \sqrt[m]{\prod_j^m LX_{ij}^k} \,/\, \sum_i^m \sqrt[m]{\prod_j^m LX_{ij}^k}$$
$$MX_{ij}^k = \sqrt[m]{\prod_j^m MX_{ij}^k} \,/\, \sum_i^m \sqrt[m]{\prod_j^m MX_{ij}^k}$$
$$UX_{ij}^k = \sqrt[m]{\prod_j^m UX_{ij}^k} \,/\, \sum_i^m \sqrt[m]{\prod_j^m UX_{ij}^k} \quad , \quad (12),$$

where m is numbers of respondents

3.1.3. Fuzzy synthetic decision

The fuzzy synthetic decision combines the fuzzy sub-weight ($\widetilde{W}_i$) and fuzzy synthetic value (X^s) with being as hierarchy in series in order to measure the entire fuzzy synthetic value ($\tilde{V}$). It can be described as shown in Eq. (13);

$$\tilde{V} = \widetilde{W}_i \circ X^{s} \quad (13),$$

where ∘ presents the fuzzy pairwise comparison matrix including fuzzy multiplication and fuzzy addition

Next the score from the $\tilde{V}$ = (L, M, U), where the $DF = \frac{(M-L)+(U-L)}{3} + L$, was used to derived the final weight to rank each supplier of the four raw materials.

4. Experimental Results

The proposed FAHP model was applied to the supplier selection in the smartphone component manufacturer, so as to identify two parts by collecting data from 15 respondents in the departments of engineering and procurement and the clients. The DM at the company needed to analyze the weight of the main criteria and sub-criteria to identify the right raw material supplier in each material. The company would be able to achieve the maximum benefits and reduce potential risks (e.g., components defect rate, a penalty from clients, and others). Those respondents were familiar with the FAHP concept and, in addition, each member went through FAHP independently and individually. Hence, 13 respondents were deemed to be valid for use the FAHP model, in which the weight of the obtained main and sub-criteria are shown in Table 8.

According to the FAHP analysis, we found that the foremost essential criteria were material quality (B1), reliability (B3), and partnership (B5). Also, the most important sub-criteria under each foremost criteria were the defect rate (C1), quality consistent (C2), delivery delays (C5), and being proactive in informing of price fluctuations (C11). Compared to other studies, the cost is still mainstream [3, 21, 25, 35]. Nevertheless, the role of this paper is a component supplier in the smartphone supply chain, where not only the quality would affect the entire supply chain but also other criteria (e.g., delays and price fluctuation information) play an essential role in the company's performance.

Table 8. Weight of the main and sub-criteria for supplier selection after defuzzification.

Main criteria and Sub-criteria	Weight
B1: Material quality	0.41
C1: Defeat rate	0.50
C2: Quality consistent	0.50
B2: Purchasing cost	0.06
C3: Material cost	0.47
C4: Credit time	0.53
B3: Reliability	0.20
C5: Delivery delays	0.58
C6: Delivery shortage	0.31
C7: Minimum order requirement	0.11
B4: Financial Status	0.14
C8: Cash flow	0.37
C9: Asset and debts	0.63
B5: Partnership	0.18
C10: Supplier contract	0.30
C11: Proactive to inform the price	0.51
fluctuation	0.19
C12: Lead time to order	

Considering the entire supply chain, when one issue is detected in the assembly line in the OEM, the assembly line will be suspended, and so this loss would affect the whole supply chain until the issue is solved. In this case, the potential risks (penalty and order reduction from clients) directly impact negatively upon the case study company's operation, even though the purchasing cost (B2) is not the mainstream in this paper. Also, based on the sub-weight ($\widetilde{W}_i$), the first part that the DM is able to recognize is the top five sub-criteria for the company to involve in their supplier selection, with the result shown in Table 9.

Table 9. Sub-weight from thirteen respondents.

	Sub-weight					
	Min	Avg	Max	Error	DF	Rank
C1	0.05	0.16	0.39	0.34	0.43	2
C2	0.04	0.17	0.42	0.39	0.47	1
C3	0.01	0.03	0.07	0.06	0.08	10
C4	0.02	0.03	0.05	0.03	0.06	12
C5	0.05	0.10	0.26	0.21	0.28	3
C6	0.01	0.05	0.16	0.14	0.17	6
C7	0.01	0.02	0.09	0.09	0.10	8
C8	0.01	0.04	0.09	0.07	0.09	9
C9	0.02	0.08	0.25	0.22	0.26	4
C10	0.01	0.04	0.20	0.19	0.21	5
C11	0.02	0.07	0.14	0.12	0.16	6
C12	0.01	0.03	0.08	0.07	0.08	10

Each respondent has a different preference in scoring raw material suppliers, in which the linguistic approximation is able to deal with this situation. The results (Fuzzy synthetic value) obtained for each raw material are shown in Table 10. For instance, in the current supplier selection for the stainless steel and phosphor bronze raw materials in the case study company, before switching to new raw material suppliers, the frequency of serious issues (e.g., flatness, the times for insertion/withdrawal, pin elasticity of height, etc.) that led to being suspended in the assembly line in the OEM, paid the penalty, or reduced orders from clients was three times in two years. After switching to the new suppliers (stainless-steel: supplier 1 and phosphor bronze: supplier 2 in Table 11), the frequency of similar issues decreased to zero such that the case study company dwindled the potential risks in the downstream supply chain, improved the value of quality of the connector, and maintained its status as the first supplier. In this case, we can assume that the other two raw material parts (plastic and nickel) might have the possibility to cause a different issue that affects the OEM and the case study company's performance. The new supplier selection results in Table 11 represent when plastic and nickel have a high possibility to reduce the potential risks to not only enhance further corporation but also to maintain supplier status, as the first supplier to clients. Hence, the new supplier selection is able to maintain and improve both the quality and value of the nano sim-card connector and reduce the potential risks in the production line in the internal factory and assembly line in the OEM.

Table 10. Raw material suppliers result.

		$\widetilde{R}$		DF	Rank
Plastic:					
Supplier 1	0.170	0.585	1.744	0.833	1
Supplier 2	0.162	0.566	1.692	0.807	2
Supplier 3	0.085	0.346	1.161	0.531	4
Supplier 4	0.132	0.475	1.473	0.693	3
Nickel:					
Supplier 1	0.106	0.396	1.302	0.601	4
Supplier 2	0.166	0.581	1.737	0.828	2
Supplier 3	0.175	0.601	1.787	0.854	1
Supplier 4	0.137	0.480	1.499	0.705	3
Phosphor bronze:					
Supplier 1	0.151	0.524	1.596	0.757	2
Supplier 2	0.167	0.574	1.730	0.824	1
Supplier 3	0.105	0.408	1.324	0.612	3
Stainless-steel:					
Supplier 1	0.172	0.589	1.743	0.835	1
Supplier 2	0.153	0.536	1.626	0.772	2
Supplier 3	0.123	0.453	1.431	0.669	3

Table 11. Nano sim-card connector result.

	Raw material supplier selection	
	Current decision	Proposed model
Stainless-steel:		
Supplier 1	3	1
Supplier 2	2	2
Supplier 3	1	3
Phosphor bronze:		
Supplier 1	2	2
Supplier 2	3	1
Supplier 3	1	3
Plastic:		
Supplier 1	3	1
Supplier 2	2	2
Supplier 3	4	4
Supplier 4	1	3
Nickel:		
Supplier 1	4	4
Supplier 2	3	2
Supplier 3	2	1
Supplier 4	1	3

5. Sensitivity Analysis

The sensitivity analysis provides a new perspective in raw material supplier selection by changing each weight of synthetic value in the top five sub-criteria. Ultimately, based on the result, the relationship in each sub-criterion can be analyzed for the case study company to select the suitable raw material supplier for each raw material.

Based on the sub-weight, the weight is a fixed value that would not be changed in Table 12. Collecting the data from the medium in very high (VH) from linguistic approximation is to compute the maximum weight of synthetic value in each sub-criterion. Adjusting the weight of sub-criteria from linguistic approximation is able to receive the new supplier selection ranking.

Table 12. Top five sub-weight after defuzzification.

Sub-criteria	Weight	Sub-criteria	Weight
C2	0.47	**C9**	0.26
C1	0.43	**C10**	0.21
C5	0.28		

In second supplier in four raw materials, when Quality (C1 and C2) increases (Plastic: 11%, Nickel: 12%, Phosphor bronze: 27%, and Stainless-steel: 18%), the second supplier becomes the priority in supplier selection in Table 13. The other three materials also have the same trend when second supplier improves quality, first supplier would be replaced in a new supplier selection. Although the other three sub-criteria (C5, C9, and C10) achieve the maximum weight of the synthetic value, the synthetic decision results show that each criterion does not affect the rank in each material supplier selection.

Table 13. Sensitivity analysis with respect to Quality in Plastic.

	C1	C2	C5	C9	C10	Overall
Plastic:						
Supplier 1	0.34	0.41	0.22	0.17	0.15	1.29
Supplier 2	0.34	0.41	0.21	0.18	0.15	1.30
Supplier 3	0.15	0.24	0.15	0.11	0.05	0.70
Supplier 4	0.24	0.32	0.19	0.13	0.11	0.99
Nickel:						
Supplier 1	0.18	0.23	0.11	0.17	0.04	0.73
Supplier 2	0.37	0.43	0.21	0.19	0.14	1.34
Supplier 3	0.35	0.39	0.22	0.21	0.16	1.33
Supplier 4	0.26	0.29	0.12	0.18	0.08	0.93
Phosphor bronze:						
Supplier 1	0.34	0.41	0.18	0.19	0.14	1.26
Supplier 2	0.35	0.36	0.21	0.17	0.16	1.25
Supplier 3	0.23	0.24	0.15	0.12	0.09	0.83
Stainless-steel:						
Supplier 1	0.35	0.338	0.21	0.19	0.12	1.25
Supplier 2	0.39	0.39	0.19	0.18	0.11	1.26
Supplier 3	0.27	0.31	0.17	0.15	0.07	0.97

Ultimately, traditionally, the sensitivity analysis is to understand the influence of changing the weight of main and sub-criteria on suppliers' ranking. Nevertheless, it is not appropriate to adjust the weight of main and sub-criteria, for it can be categorized as one of the high value-added components in the smartphone. Quality has direct effects on the user experience in the smartphone industry. Changing the weight of quality has high potential risks to affect the entire supply chain, leading to rework to fix the issue in OEM, pay the penalty, reduce orders, and even reduce to be a second source. Hence, the sub-weight is a fixed value after defuzzification, for the main and sub-criteria are selected by the respondents (Department of procurement and engineering and the client) as a standard to examine the performance of the raw material suppliers in the four primary materials.

The sensitivity analysis is for changing the weight of linguistic approximation in the top five sub-criteria compared to each raw material supplier. When the raw material suppliers improve their performance (e.g., quality improvement, delay reduction, etc.), the judgment from the respondents will dynamically adjust the synthetic value to understand the relationship between each criterion and rank the suitable raw material supplier. Based on the actual results in four raw materials, the rank of supplier 1 and 2 is slightly different. It can be assumed that the supplier 2 might improve performance in the future, leading to a new supplier selection.

In Quality (C1 and C2), when a second supplier improves their quality performance (Plastic: 11%, Nickel: 12%, Phosphor bronze: 27%, Stainless-steel: 18%), the second supplier becomes the first supplier in each raw material. Nevertheless, in Reliability (C5), Financial status (C9), and Partnership (C10), although the second supplier achieves the maximum weight of synthetic value in each sub-criterion, the results in each material still remain the same. In this case, it indicates that in the smartphone supply chain, the quality is the priority to be considered first because of the size of components (millimeter scale). When the second supplier surpasses the first supplier in quality, reducing the defect rate in the factory, improving the quality consistency, and diminishing rework times in OEM, a new supplier selection will be created to replace the existing one. Although, other sub-criteria are essential, which the case study company must monitor, the second raw material supplier has continued to improve those criteria to gain more orders from clients in the competitive market in the electronic industry; meanwhile, the first raw material supplier remains or improves the performance to appeal to more clients. Hence, it can be defined that the other three sub-criteria are essential for all raw material suppliers to reach a high level of performance. Quality (C1 and C2) becomes a determinant of whether to be the first raw material supplier in raw material supplier selection.

6. Conclusion

In the smartphone supply chain, each chain is relatively tied to each other. Specifically, the collaboration between manufacturer and material supplier is an essential link that has a high potential to affect the entire supply chain performance in the market. The right material supplier can help the manufacturer reduce the failure of coordination in delays, defect rate, and a penalty from the clients; the final products can also be launched smoothly. In this paper, the right material suppliers for four primary materials were selected by employing FAHP in two parts.

Firstly, the DM in the case study company can assess data to recognize the importance of the main criteria (material quality, reliability, and partnership) and the top five sub-criteria (quality consistent, defect rate, delays, asset and debts, and supplier contract). These are

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considered the business scenarios in the case study company, and were collected from several studies in a relative field, and selected by two departments and client.

Secondly, the vagueness of human consideration in personal preference and judgement can be captured by utilizing FAHP from collecting a linguistics approximation survey to select the right supplier. The proposed model contributes to the DM in the case study company to identify the right raw material supplier for each of the four primary materials to improve the value and quality of connectors and reduce the potential risks (e.g., component quality, delays, penalty, etc.) in the supply chain.

Furthermore, sensitivity analysis provides several answers in different scenarios when the linguistic approximation in the top five sub-criteria is adjusted. The results in each sub-criterion offer new details and information in raw material supplier selection. On the one hand, in the smartphone supply chain, the quality in defect rate and consistency directly affects the performance of the raw material supplier. In the new result from the four raw materials, when quality increases 11% in plastic, 12% in nickel, 27% in phosphor bronze, and 18% in stainless-steel, the first supplier is replaced by the second supplier. On the other hand, although each sub-criterion (Delays, Asset and debts, and Supplier contract) achieves the maximum weight in synthetic value, the results remain the same that the first supplier is not replaced. In this case, those three sub-criteria are defined as fundamental elements that all raw material suppliers are crucial toward maintaining in high performance.

For future research, this research work can be extended to similar components that are produced at a millimeter scale size and assembled from several material parts by obtaining new main and sub-criteria relevant to the manufacturers. In addition, the paper can be extended when the total volume orders from clients are supplied by a single raw material supplier that cannot satisfy demands from a manufacturer, and so more than one supplier for each material can be selected in the supplier selection. Ultimately, by adjusting the parameter in sub-criteria or other elements, this paper can be expanded to provide alternative information in different scenarios to select the suitable suppliers in supplier selection.

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