A new multi-criteria product design concept evaluation with consideration of product architecture, process and supply chain design

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Abstract

This paper proposes a new multi-criteria decision making model to evaluate product design alternatives. It enables us to evaluate architecture of a new product by considering different criteria relating to product, process, and supply chain design. The model also uses life cycle assessment to evaluate alternatives. To deal with the vagueness of some data used in life cycle assessment, fuzzy set theory is employed. A real case is used to illustrate the efficiency of the model. In final, the conclusions and future research directions are proposed.

Keywords

Multi-criteria decision making; product, and supply chain design; Life cycle assessment; Uncertainty; Modularity

1. Introduction

Today, with large mass markets changing into smaller niche markets with higher product variety, competitors are under pressure to introduce new products with higher quality, shorter time intervals, and lower price. To satisfy this aims, many decisions should be considered in the early stages of developing a product. Making decisions, separately, can lead to local solutions instead of global solutions (Gunasekaran, 1998). Developing an integrated method that concurrently considers decisions in product design, manufacturing process, and supply chain design can lead to global solutions.

Some approaches have been developed to deal with product development. Concurrent engineering (CE) is an efficient approach that considers the effect of design decisions on manufacturing /assembling processes. Researchers reported a 30–60% reduction in time-to-market, 15–50% reduction in life cycle costs and a 55–95% reduction in requested engineering changes (Ganapathy, 1998; Terwiesch, 2002) with the implementation of CE. With the advent of new approaches in industry such as mass customization in the recent decades, Fine argued that CE alone can no longer give a competitive advantage and should enlarge its scope by adding supply chain considerations (Fine, 1998). Therefore, he introduced a new approach called three-dimensional concurrent engineering (3D-CE) which considers supply chain, process and product design decisions in the early stages of developing a product. How to generate and to select the optimal product design, manufacturing/assembling processes and supply chain design in a simultaneous and integrated manner is one of main challenges in 3D-CE.

The early stages of product development is the most important element of a new product development (NPD) process, because of its effect on other areas in the NPD such as manufacturing and supply chain design. Researchers have demonstrated more than 70 percent of Manufacturing /Assembling costs are affected by decisions taken at the early stages of design (Dieter, 2000). Life cycle assessment is an important area in NPD because of decision points in life cycle phases (design, production, use, recycling) may impact on the product architecture, process, and supply chain.

To get right decisions requires different and certain data. But, in the early design stages of developing a new product, uncertainty and vagueness of data is a main challenge that can impact on new product process development. So, how to deal with different type of data appeared in different stages NPD process is an interesting and applicable topic for researchers. Developing an integrated and efficient manner that can guarantee usefulness of data including in some or all stages of life cycle of a product is a main challenge in new product development process.

The main aim of this paper is to develop an integrated and efficient method to select the optimal product design, manufacturing/ assembling processes and supply chain by considering some phases of the product life-cycle (design, production, use). How to deal with different types of data related to different areas in NPD, is another aim of this paper.

This paper is organized as follows. In Section 2, we review, the literature related to simultaneous evaluation of product, process and supply chain design. Section 3 presents the proposed method to select and rank configurations including product design, manufacturing/assembling processes and supply chain. In this section, a new method to obtain degree of modularity of components involved in a new product is also developed. Section 4 illustrates the applicability and efficacy of the proposed model with a real case. Finally, Section 5 identifies conclusions and directions for further investigations.

2. Literature Review

Different researches have focused on evaluation and selection of design alternatives (Ayağ et al. 2009; Davoodi et al. 2011; Song et al. 1012; Shidpour et al.2013; 2016). Most researches in product design have considered the close link between product and process by developing concurrent engineering. With the development of 3D-CE approach, Petersen et al. (2005) proposed a theoretical model to achieve higher product development team effectiveness by integrating suppliers into the new product development process in the 3D-CE environment. Fixson (2005) proposed a mechanism based on product architecture to coordinate decisions across products, manufacturing processes, and supply chains. Tchidi and He (2010) introduced an extended quality functional deployment process, in a 3D-CE environment that transforms customer requirements into product design, process design and supply chain design. Marsillac and Roh (Marsillac, 2014) investigated the direct and indirect impact of product design on process and supply chain activities by studying multiple cases. These studies have more focused on qualitative insights than on quantitative approaches when analyzing various 3D-CE tradeoffs.

Feng et al. (2011) proposed a model that simultaneously determines the tolerances in the product design and suppliers of components. Fine et al (2005) proposed a goal programming model to address (3D-CE) and to analyze the trade-off among objectives. Afrouzy et al. (2016) proposed a multi echelon multi product multi period supply chain model which incorporates product development and new product production and their effects on supply chain configuration. Baud-Lavigne et al. (2016) presented a Mixed Integer Linear Program (MILP) that simultaneously considers the construction of the bill of materials and the design of the supply chain network.

The design evaluation usually involves both tangible and intangible criteria, along with quantitative and qualitative performance measurements. So, focusing on only one of the qualitative or quantitative approaches may cause distortion in the design evaluation. This motivates a hybrid approach based on combining quantitative and qualitative approaches.

Product architecture design needs to be evaluated from a life cycle perspective. Literature reviews show that most papers in product design evaluation generally consider the phases of “design” and “production” (Koufteros et al. 2002; Kim et al. 2002; Kota et al. 2002; Afrouzy et al. 2016). Although considering other phases of lifecycle in a model increase the difficulty of correct evaluation of product design alternatives because of the uncertainty and vagueness in the early design stages of NPD process, but increase the applicability of the proposed models.

The main aim of this paper is to develop an integrated and efficient method to select the optimal product design, manufacturing/assembling processes, and supply chain by considering uncertainty and vagueness of data in some phases of the product life-cycle. To achieve this objective, we develop a model based on qualitative and quantitative objectives “Cost”, “Quality”, “Lead Time”, “Serviceability,” and “Delivery reliability of suppliers”. We develop a new method to obtain product modularity that is used to obtain objective “Quality” for new products.

3. The proposed model

This method includes some stages that are explained step by step as follows:

3.1. Determine configurations of product design, process and supply chain. Since each product architecture consists of several components it can create different supply chain or network. Accordingly, all potential configurations of product design, manufacturing/assembling process, and supply chain is determined.

3.2. Determining objectives and constraints of company for evaluation of configurations.

3.3. **Stage 1**: Qualitative and quantitative evaluations.

In this stage, values of all objectives with consideration of constraints for each configuration are determined. Indices and variables used in the model are defined: $i=1, 2, \ldots, n$ (Index of configurations including product design, process, and suppliers); $j,l=1,2, \ldots, m_i$ (Index of components); $s=0, 1, \ldots, S$ (Index of suppliers); $f=1, 2, \ldots, z$(Index of functions);

D: Anticipated demand for new product; P_{ijs}: Cost of component j purchased from supplier s for configuration i; C_{jli} : Assembling cost of component j to component l in the process i;T^1_{js}: Lead time of component j purchased from supplier s;T^2_{jli} : Assembling time of component j to component l in the process i; R_i: Yield of assembly process, for configuration i; q_{ijs} :Quality of component j purchased from supplier s, in configuration i; a_{jli} :Sequence of assembling component j to component l in configuration i; O_s: Cost of ordering from supplier s; w_f :Proportion of function f in total quality; v_{ifj} :Rate of sharing of component j in performance of function f in configuration i; b_{ij}: The number of components j, involved in configuration i; g: The number of working hours. The objectives are described as follows:

Objective 1: costs of purchasing, assembling, and ordering.

$$Z_i^1 = \sum_{j \in i} \sum_{s \in i} p_{ijs} + \sum_{j \in i} \sum_{\substack{k \in i \\ j \neq k}} b_{ij} a_{jli} c_{jli} + \sum_{s \in i} o_s \quad \forall i \tag{1}$$

Objective 2: time-to-market; including delivery lead time of suppliers and assembling time for manufacturing a product.

$$Z_i^2 = \sum_{j \in i} \frac{1}{(m_i \times D \times b_{ij})} \sum_{s \in i} T_{js}^1 X_{js} + \sum_{j \in i} \sum_{\substack{k \in i \\ j \neq k}} \left(\frac{T_{jli}^2}{R_i \times g \times 60} \right) \quad \forall i \tag{2}$$

Term ($R_i \times g \times 60$) shows the available useful working hours for assembling products.

Objective 3: overall quality perceived by customers based on the functional performance of the product.

$$Z_i^3 = \sum_{f=1}^{m} w_f \sum_{j \in i} v_{ifj} \sum_{s \in i} \frac{\beta q_{ijs}}{M_{ij}} \quad \forall i \tag{3}$$

The rate of participation each component in functions for each configuration (v_{ifj}) and the proportion of each function in the "Quality" objective (w_f) are determined by decision makers (DMs). In this objective, quality is depended on two factors: quality of components purchased from suppliers (q_{ijs}) and modularity degree of component *j*, in configuration *i*, shown by M_{ij} , where β is applied to bring the modularity values into the range of [0, 1]. Modularity is defined as a scheme that allocates physical components to each function and determines the interfaces among interacting physical components (Ulrich, 1995).

The method proposed to obtain modularity degree of components (M_{ij}) is started by developing the function-component allocation (FCA) matrix showing the relation between components and functions. According FCA matrix, two indices are determined. The first index (X) shows the number of functions that each component is involved in. The second index (Y) assesses the total number of components contributing to the set of functions obtained in index X. These indices are used to construct a two dimensional graph that we call it "modularity graph". Horizontal and vertical axes in this graph display indices X and Y, respectively. The method to get a degree of modularity proposed in this paper is based on the relative distance of each point in this graph from the perfect modular point (PMP) and Perfect Integral Point (PIP). PMP shows a one-one relation between components and functions which indices get values X=1 and Y=1. PIP represents a complicated relation between components and functions and indices get X=m (number of functions) and Y=n (number of components). The relative modularity degree of each component is obtained by using formula (4):

$$M_j = \frac{d(j, PIP)}{d(j, PIP) + d(j, PMP)} \tag{4}$$

Where $d(j, PIP)$ and $d(j, PMP)$ are the weighted hamming distances (Hamming, 1950) of each point (*j*) in modularity graph from PMP and PIP, respectively which are calculated as follows:

$$d(j, PMP) = d\left\{(x_j, y_j), (1,1)\right\} = \sqrt{(x_j - 1)^2 + (y_j - 1)^2} \tag{5}$$

$$d(j, PIP) = d\left\{(x_j, y_j), (m,n)\right\} = \sqrt{(x_j - m)^2 + (y_j - n)^2} \tag{6}$$

Objective 4. Serviceability: One aspect of product design that affects customer satisfaction is the easiness of performing a service. According to Martin and Ishii (1996) the process to perform the required regular services has 4 stages "Identify", "Access", "Availability" and "Replacement". In this paper, serviceability for each product architecture (or configuration) is evaluated by DMs based on these stages using linguistic terms shown in Table 1.

Table 1. Linguistic terms for the evaluation of qualitative criteria

Linguistic values	Triangular fuzzy numbers
Very Poor (VP)	(0,0,1)
Poor (P)	(0,1,3)
Medium Poor(MP)	(1,3,5)
Medium (M)	(3,5,7)

Medium Good (MG)	(5,7,9)
Good (G)	(7,9,10)
Very Good (VG)	(9,10,10)

Objective 5. Delivery Reliability of suppliers: It shows performance of suppliers in delivering the components to the buyers at the right place, at the agreed time, and in the required quantity (Huang et al. 2007). Our method uses three factors "correctness", "timekeeping", and "completeness" proposed by Huang et al. (2007) to obtain delivery reliability of suppliers which are assessed using linguistic terms in Table 1.

3.4. Collect data related to each configuration and evaluate objectives for each configuration and develop a list of configuration that satisfies constraints.

3.5. **Stage 2**: Rank.

In this stage, decision matrix of TOPSIS is built based on evaluation of objectives obtained from stage 1 for each configuration. Since uncertainty is considered to evaluate objectives "Delivery reliability of suppliers", "Serviceability" and "Time to market", we encounter with different kinds of data including crisp, interval and fuzzy in decision matrix of TOPSIS. To Deal with this issue, we use a novel decision-making method proposed by (Shidpour et al. 2016) to rank configurations. This method develops an interval-based distance measure based on the distance between interval vector of each alternative and interval-based ideal vector. In brief, the steps of this method are expressed as follows:

6.1. Convert all fuzzy numbers in the decision matrix to intervals. For a TFN (*a, b, c*) and confidence level of decision makers (α), the interval value [*L*, *U*] is obtained: using formula (7):

$$\left[L,U\right]=[(b-a)\alpha+a,-(c-b)\alpha+c] \quad \forall\alpha\in[0,1] \tag{7}$$

6.2. Normalize the decision matrix. For this purpose, values of each column are divided to maximum value of each column.

6.3. Estimate the weighted normalized decision matrix ($K=\left[k_{ij}^{-},k_{ij}^{+}\right]$). The weight of objectives is obtained using the fuzzy analytical hierarchy process (AHP) developed by (Van Laarhoven and Pedrycz, 1983).

6.4. Determine the positive-ideal reference and the negative-ideal reference. Based on the weighted normalized decision matrix, positive-ideal reference vector $Z^{+}=(z_1^{+},z_2^{+},...,z_n^{+})$ and negative-ideal reference vector $Z^{-}=(z_1^{-},z_2^{-},...,z_n^{-})$ is dependence to type of criteria, ''Larger-the-better" and "Smaller-the-better" and is obtained as follows (Table 2).

6.5. Construct the distance matrices. The interval distances ($d_{ij}^{P}=[d_{ij}^{P-},d_{ij}^{P+}]$, $i=1,...,m, j=1,...,n$) between intervals in the weighted normalized matrix and values of positive-ideal reference are obtained through formulas (8) and (9):

Table 2. Positive-ideal reference and negative-ideal reference vectors

	Criterion "Smaller-the-better"	Criterion ''Larger-the-better"
Positive-ideal Reference vector $Z^{+}=(z_1^{+},z_2^{+},...,z_n^{+})$	$z_j^{+}=\underset{i}{Min}(k_{ij}^{-})$	$z_j^{+}=\underset{i}{Max}(k_{ij}^{+})$
Negative-ideal reference vector $Z^{-}=(z_1^{-},z_2^{-},...,z_n^{-})$	$z_j^{-}=\underset{i}{Max}(k_{ij}^{+})$	$z_j^{-}=\underset{i}{Min}(k_{ij}^{-})$

$$d_i^{P-}=\sqrt{\sum_{j\in S}\left(k_{ij}^{-}-z_j^{+}\right)^2+\sum_{j\in L}\left(k_{ij}^{+}-z_j^{+}\right)^2} \tag{8}$$

$$d_i^{P+}=\sqrt{\sum_{j\in S}\left(k_{ij}^{+}-z_j^{+}\right)^2+\sum_{j\in L}\left(k_{ij}^{-}-z_j^{+}\right)^2} \tag{9}$$

The lower and upper distance ($d_{ij}^{N} = [d_{ij}^{N-}, d_{ij}^{N+}]$, $i = 1,...,m$, $j = 1,...,n$) between intervals in the weighted normalized matrix and the negative-ideal reference is obtained as follows:

$$d_i^{N-} = \sqrt{\sum_{j \in S}\left(k_{ij}^{+} - z_j^{-}\right)^2 + \sum_{j \in L}\left(k_{ij}^{-} - z_j^{-}\right)^2} \tag{10}$$

$$d_i^{N+} = \sqrt{\sum_{j \in S}\left(k_{ij}^{-} - z_j^{-}\right)^2 + \sum_{j \in L}\left(k_{ij}^{+} - z_j^{-}\right)^2} \tag{11}$$

6.6. Obtain the interval-based relative closeness index: $(RCI_i = \left[RCI_i^L = \frac{d_i^{N-}}{d_i^{N-} + d_i^{P+}}, RCI_i^U = \frac{d_i^{N+}}{d_i^{N+} + d_i^{P-}} \right])$

8. Rank the design concept alternatives based on the order relation $\geq^{\max}$ between two intervals $A = [a_L, a_U] = \langle a_c, a_w \rangle$ and $B = [b_L, b_U] = \langle b_c, b_w \rangle$ proposed by (Bhunia and Samanta, 2014):

$$A \geq^{\max} B \Leftrightarrow \begin{cases} a_c > b_c & if\ a_c \neq b_c \\ a_w \leq b_w & if\ a_c = b_c \end{cases} \tag{12}$$

and $A >^{\max} B \Leftrightarrow A \geq^{\max} B$ and $A \neq B$.
(For more details of the method, refer to Shidpour et al. (2016)).

Table 3. Function-component allocation matrices for water tank with designs 1 and 2

Design 1		Component				
	Function (w_f)	Reservoir (v_{ifj})	Bed (v_{ifj})	Air vent (v_{ifj})	Inlet pipe (v_{ifj})	Outlet pipe (v_{ifj})
1	Protect water from external factors (0.25)	1(100%)	0	0	0	0
2	Transfer water (0.35)	0	0	0	1(50%)	1(50%)
3	Support water loads (0.08)	0	1(100%)	0	0	0
4	Air evacuation (0.12)	0	0	1(100%)	0	0
5	Transfer loads to surface (0.2)	0	1(100%)	0	0	0
	Index X	1	2	1	1	1
	Index Y	1	2	1	2	2
	Modularity degree	1	0.75	1	0.83	0.83

Design 2		Component						
	Function (w_f)	Reservoir Upper half (v_{ifj})	Reservoir lower half (v_{ifj})	Air vent (v_{ifj})	Overflow pipe (v_{ifj})	Base (v_{ifj})	Inlet pipe (v_{ifj})	Outlet pipe (v_{ifj})
1	Protect water from external factors	1(50%)	1(50%)	0	0	0	0	0
2	Transfer water	0	0	0	0	0	1(50%)	1(50%)
3	Support water loads	1(20%)	1(80%)	0	0	0	0	0
4	Air evacuation	0	0	1(75%)	1(25%)	0	0	0
5	Transfer loads to surface	0	0	0	0	1(85%)	1(15%)	0
	Index X	2	2	1	1	1	2	1
	Index Y	2	2	2	2	2	2	2
	Modularity degree	0.8	0.8	0.86	0.86	0.86	0.8	0.86

4. Numerical example

To demonstrate the applicability of our model, we test it by using two water tanks with different architectures.

According to the proposed method, the following steps are established to identify product design alternatives, assembly processes and suppliers:

Step1. Determine all potential configurations of product design, process and supply chain. According to information, design 1 has 2^6 (no. assembly × no. suppliers) and design 2 has 2^6 potential configurations.

Step2. Evaluate the determined objectives with consideration of different constraints of company for all configurations.

Step2.1. Evaluation of "Cost": After calculating cost for all potential configurations by Eq. 1, the configurations that can satisfy the operational limitation 110$ for cost are selected for the next evaluation. Accordingly, 8 and 31 configurations for designs 1 and 2 satisfied the limitation.

Step2.2. Evaluation of "Time-to-market": Because of uncertainty in delivery time of suppliers, they are expressed by interval numbers. Upper and lower limits for "Time to market" for 39 configurations selected from previous step are obtained using Eq. 2. Among 39 configurations, 18 configurations satisfy time limitation 15 (day).

Step2.3. Evaluation of "Quality": At first, the modularity of each component in each configuration (M_{ij}) is calculated based on the instruction proposed in step3 of section3 shown in Table 3 for two types of water tank. Values of w_f and v_{ifj} are also represented in this Table.

After obtaining modularity, the quality for each configuration of product design, assembly process, and supply network is determined using Eq. 3. Among 18 selected configurations, 8 configurations satisfy quality limitation 0.80.

Step2.4. Evaluation of "Serviceability": Four stages in serviceability are evaluated for each product architecture using linguistic terms in Table 1. By using operational laws for fuzzy numbers, serviceability of design architectures is calculated shown in Table 4.

Table 4. The evaluation of serviceability

Design	DM	Identify	Access	Availability	Replacement
1	1	MG	G	VG	G
	2	MG	G	MG	MG
	3	G	MG	G	VG
2	1	G	VG	G	G
	2	G	MG	M	MG
	3	MG	VG	MG	MG

Step2.5. Evaluation of "Delivery reliability of suppliers": It is determined based on the evaluation of factors " Correctness", " Timekeeping" and "Completeness" by DMs using linguistic terms. The results of evaluation are shown in Table 5.

Table 5. The evaluation of serviceability

Supplier	DM	Correctness	Timekeeping	Completeness
1	1	MG	G	VG
	2	MG	G	MG
	3	G	MG	G
2	1	G	VG	G
	2	G	MG	M
	3	MG	VG	MG
3	1	MG	M	G
	2	VG	MG	G
	3	G	G	MG
4	1	G	G	G
	2	M	MG	MG
	3	MG	VG	M
5	1	G	MG	G
	2	MG	MG	M
	3	MG	VG	MG

With respect to network of suppliers in each configuration, total evaluation for this network is done using operational laws for fuzzy numbers.

Values of objectives obtained from before steps for 8 configurations are gathered in the TOPSIS matrix decision (Table 6). In this Table, alternative A*da*(*s1,s2*,...) shows number of design (*d*), assembly sequence (*a*) and suppliers (*s1,s2*,...). For example, "A11(1,4)" identifies this alternative is related to design 1, assembly sequence 1 and suppliers 1 and 4.

As this table shows, we encounter with different types of data including crisp (columns "Cost" and "Quality"), interval (column "Time to market") and fuzzy (columns "Delivery reliability" and "Serviceability"). To rank alternatives, we use the proposed method as follows:

1. Convert all fuzzy numbers in the decision matrix to intervals using Eq. 7 and normalize the decision matrix (Table 7).
2. Estimate the weighted normalized decision matrix. The weight of objectives obtained by using AHP is 0.44, 0.247, 0.17, 0.1, and 0.043. Table 8 shows the weighted normalized decision matrix.
3. The positive-ideal reference and negative-ideal reference are calculated based on Table 8, respectively, (0.315, 0.169, 0.17, 0.1, 0.043) and (0.44, 0.247, 0.167, 0.0788, 0.0332).
4. Construct the distance matrix between the members of the weighted normalized matrix and the positive and negative-ideal references using Eqs.8-11 shown in Table 9.
5. Obtain the interval-based relative closeness index shown in Table 9.
6. Rank configurations based on formula (12): 1>5>6>8>2>4>3>7. The best configuration is A11(1,4). It means design 1, assembly sequence 1 and suppliers 1 and 4 are selected to develop a new water tank.

5. Conclusion

The selection of a design alternative together with the assembly process and suppliers of components in a simultaneous and integrated manner is a very critical step in the NPD process. In this paper, we use a 3D-CE approach to select a configuration (product design, manufacturing processes and supply chain) considering life-cycle phases of a product using a multi-criteria decision making method. We consider impact of product architecture on quality and take account effect of serviceability as one of the main elements impacting on customer satisfaction. We propose methods to select proper configurations among potential candidates and evaluate qualitative objectives with linguistic terms and fuzzy numbers. Because of uncertainty to estimate lead time of components purchased from suppliers, they are expressed as interval numbers. Indeed, we evaluate a decision matrix with different kinds of data.

There are some directions for expanding the proposed research. An interesting approach is to consider some effective parameters in the supply chain design e.g. inventory, safety stock and distribution networks. An important area in NPD is to consider the whole product life-cycle – including phases of "design"," production", "use" and "recycling"- to evaluate product design. In this paper, we do not study the recycling phase of the life-cycle. Recycling would be a possible way to expand this model.

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Table 6. TOPSIS matrix decision

Alternative	Cost	Time to market	Quality	Delivery reliability	Serviceability
A11(1,4)	73.8	[13.2,15.04]	0.815	(17.67,23.5,28)	(6.5,8.33,9.66)
A11(1,3,4)	87	[13.26,15.1]	0.809	(18.11,23.89,28.23)	(6.5,8.33,9.66)
A12(1,3,4)	93	[12.4,14.04]	0.812	(18.11,23.89,28.23)	(6.5,8.33,9.66)
A12(2,3,4)	103	[12.36,13.88]	0.805	(17.89,23.66,28)	(6.5,8.33,9.66)
A21(0,1,2,3)	85.5	[10.33,12.17]	0.812	(18.16,23.91,28.25)	(6.17,7.75,9.42)
A22(0,1,2,3)	88.28	[11.33,12.08]	0.817	(18.16,23.91,28.25)	(6.17,7.75,9.42)
A22(0,1,2,3)	86.4	[12.33,13.88]	0.821	(18.16,23.91,28.25)	(6.17,7.75,9.42)
A22(2,3,5)	94.43	[12.43,14.08]	0.813	(17.89,23.67,28.11)	(6.17,7.75,9.42)

Table 7. The normalized decision matrix

Alternative	Cost	Time to market	Quality	Delivery reliability	Serviceability
A11(1,4)	[0.716,0.716]	[0.874,0.996]	[0.993,0.993]	[0.788,0.987]	[0.824,1]
A11(1,3,4)	[0.84,0.84]	[0.878,1]	[0.985,0.985]	[0.796,0.999]	[0.824,1]
A12(1,3,4)	[0.90,0.90]	[0.821,0.93]	[0.989,0.989]	[0.804,0.999]	[0.824,1]
A12(2,3,4)	[1,1]	[0.818,0.919]	[0.98,0.98]	[0.796,0.99]	[0.824,1]
A21(0,1,2,3)	[0.83,0.83]	[0.684,0.806]	[0.989,0.989]	[0.806,1]	[0.773,0.954]
A22(0,1,2,3)	[0.86,0.86]	[0.75,0.8]	[0.995,0.995]	[0.806,1]	[0.773,0.954]
A22(0,1,2,3)	[0.84,0.84]	[0.816,0.919]	[1,1]	[0.806,1]	[0.773,0.954]
A22(2,3,5)	[0.92,0.92]	[0.823,0.932]	[0.99,0.99]	[0.796,0.992]	[0.773,0.954]

Table 8. The weighted normalized decision matrix

Alternative	Cost	Time to market	Quality	Delivery reliability	Serviceability
A11(1,4)	[0.315,0.315]	[0.216,0.246]	[0.169,0.169]	[0.0788,0.0987]	[0.0354,0.043]
A11(1,3,4)	[0.37,0.37]	[0.216,0.247]	[0.167,0.167]	[0.0796,0.099]	[0.0354,0.043]
A12(1,3,4)	[0.397,0.397]	[0.203,0.23]	[0.168,0.168]	[0.080,0.099]	[0.0354,0.043]
A12(2,3,4)	[0.44,0.44]	[0.202,0.227]	[0.167,0.167]	[0.0796,0.099]	[0.0354,0.043]
A21(0,1,2,3)	[0.365,0.365]	[0.169,0.199]	[0.168,0.168]	[0.080,0.1]	[0.332,0.041]
A22(0,1,2,3)	[0.377,0.377]	[0.185,0.198]	[0.169,0.169]	[0.080,0.1]	[0.332,0.041]
A22(0,1,2,3)	[0.369,0.369]	[0.202,0.227]	[0.17,0.17]	[0.080,0.1]	[0.332,0.041]
A22(2,3,5)	[0.40,0.40]	[0.203,0. 23]	[0.168,0.168]	[0.0796,0.0992]	[0.332,0.041]

Table 9. The distance matrix and interval-based relative closeness index

No	Alternative	d_i^{N+}	d_i^{N-}	d_i^{P+}	d_i^{P-}	RCI_i^L	RCI_i^U
1	A11(1,4)	0.017	0.0155	0.0191	0.0022	0.449	0.885
2	A11(1,3,4)	0.0061	0.0047	0.0188	0.0055	0.199	0.527
3	A12(1,3,4)	0.0043	0.0021	0.0214	0.0079	0.0907	0.354
4	A12(2,3,4)	0.0025	0.0004	0.0219	0.0167	0.0179	0.131
5	A21(0,1,2,3)	0.0122	0.0079	0.0278	0.0025	0.221	0.83
6	A22(0,1,2,3)	0.0083	0.0064	0.0281	0.0041	0.185	0.669
7	A22(0,1,2,3)	0.0076	0.0054	0.0221	0.0039	0.198	0.657
8	A22(2,3,5)	0.0037	0.0016	0.0217	0.0089	0.0695	0.294

Biographies

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