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A flexible model for supporting designers and determining design stakeholders' preferences at the early product design stage

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C H R O N I C L E

Article history:
Received:October19, 2018
Received in revised format: October 25, 2018
Accepted:December26, 2018
Available online:
December26, 2018

Keywords:
Forklift Truck
Design concept
Intuitionistic fuzzy TOPSIS
Exponential-related Function
Intuitionistic fuzzy entropy
MCDM

A B S T R A C T

A new flexible and adjustable model which is based on an Intuitionistic Fuzzy TOPSIS model with an exponential-related function and intuitionistic fuzzy entropy method has been presented and apply in this study. For supporting designers in determining design stakeholders' preferences when finding the best compromise between new concepts design during early product development phase. The main advantage of the new model is that it is flexible and adjustable and affords the design stakeholders the option to a change of action in the event they receive new information or reason not to continue with a particular design or product. Finally, it uses both subjective and objective weights methods for the evaluation of the design concepts criteria, which makes the proposed model more realistic and more practical. The model has been applied for the design concept evaluation of seven forklift trucks with the view to improving the reliability of the machine.

1. Introduction

With the increasing competition, globalization and the eclectic approach to the development of today's products, companies are forced to struggle and to maintain their competitiveness.To remain competitive in the market, they sure require a strong marketing power, well-integrated organizations as well as effective and efficient capacities in their research and development (R&D) units, to develop sustainable and innovative products (Fang & Chyu, 2014). Creating innovative product is not an easy task, as there are a whole lot of people involved, and interested in the outcome of the product. People such as the end user (customer), the marketing managers and his team, production engineers, the maintenance workers, recycling specialists, and government representatives, just to mention but a few (Tideman, 2008). These different stakeholders have their own opinion and agenda for the intended product and in most cases, these opinions and agenda are often conflicting with each other. The Designer(s) or Design engineer(s) is/are tasked with the extremely tough task to satisfy the conflicting opinions and agenda of all the different stakeholders. This is most especially critical as it is often very difficult for the designer(s) to determine what those opinions are in the first place (Nuseibeh & Easterbrook, 2000; Tideman, 2008).

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doi: 10.5267/j.ijdns.2018.12.004

Through the years, various tools and methods have been developed that support designers to deal with these kinds of issues as reflected in the following literature; The non-numerical methods which include concept screening by Ulrich & Eppinger (2000) and concept selection method by Pugh (1996). Numerical methods such as the decision matrixes by King and Sivaloganathan, (1999), quality function deployment methods as given in (Justel et al., 2007; Liu, 2011; Marini et al., 2016), analytic hierarchy process method in (Ayağ& Özdemr, 2007; Lin et al., 2008) and the fuzzy set concepts methods in(Aikhuele& Turan, 2017; Aikhuele, 2017; Akay et al., 2011; Liu, 2011). But so far, 'engineering design has basically remained a process in which designers are forced to make assumptions about what other people want. This is especially true when designing products that are new, complex, and involves many different stakeholders and their opinions' (Tideman, 2008). The goal of this study, therefore, is to present and apply a new flexible, adjustable methodology that can effectively support designers in determining stakeholders' preferences and finding the best compromise between those preferences during the product concept design phase of the new product development.

The synthesis of the new product concepts is primarily an intellectual and value-added process which tends to utilize deterministic data. The environment surrounding the final developed product and the eventual end-use of the design is largely uncontrolled and stochastic in nature (Kazmer & Roser, 1999), where the robustness of the design largely determines the product reliability, quality, and efficiency. The product design concept stage conceivably can be referred to as one of the most critical stages in the product design and development process where the final decision to either select or reject a particular design for a given product is made (Aikhuele, 2017). According to Geng et al. (2010), the design decision made at this stage is most crucial for determining the success of both the developed product as well as the development process. While Nikander et al. (2014) describe concept selection as the most important activities in new product development and that the consequences of a poor concept decisions may be disastrous at worst.

The increasing demand to enhance product design quality assurance by practitioners and researchers has resulted in the ever-increasing call for the building in of all product attributes of performance during the early product design stage. With the increasing competitions in the market, the trend in today's product development engineering can be said to be moving toward the design, development, and manufacturing of more sophisticated products with higher reliability and quality. Better sustainability feature, safer performance and shorter developmental time. However, before implementing any design changes, it is critical to consider the future needs and its implication in the new product. Analyzing the design problems in a broader term will allow for more flexibility in the decision-making process, rather than the traditional step-by-step progression approach that ends up with a single design concept ranking solution. Flexibility in product concept design assessment results, involves the interpretation of the available information, drawing conclusions and considering the possible implications of such conclusions. A good decision-making process must be able to identify and take into account the weakness or potential weaknesses of the DMs (uncertainties) in the preference judgment they provide and, routinely evaluate the direction of the result and outcome with the view to taking steps necessary to improve the final decision. Hence, there can be more than one design solution depending on the DMs interest and the decision-making process. The flexibility here is mainly to allow the product development team the opportunity to reverse their decision or position when there is clear evidence that the chosen design or concept is not visible at the last minute.

To avoid the consequences of a poor concept decisions a new flexible, adjustable methodology which is based on the integration of the Intuitionistic fuzzy TOPSIS model which based on an exponential-related function (IF-TOPSIS$_{EF}$) and intuitionistic fuzzy entropy (IFE) method originally presented in (Aikhuele & Turan, 2017), is proposed for supporting designers in determining stakeholders' preferences and for finding the best compromise between those preferences during the product concept design phase of new products.The main advantage of this model is that it is flexible and adjustable and affords the design stakeholders the option to a change of action in the event they receive new information or reason not to continue with a particular design or product. And finally, it uses both subjective and objective weights methods for the evaluation of the design concepts criteria, which makes the proposed model more realistic and more practical. The rest of the paper is organized as follows; in section 2, the concept of the intuitionistic fuzzy set (IFS), the IFE, and the exponential-related function in the Intuitionistic Fuzzy TOPSIS model arepresented. The algorithm of their integration is presented in section 3. In section 4, a numerical case study is presented to demonstrate the effectiveness of the model, while some concluding remarks are given in section 5.

2. Preliminaries

In this section, the concept of theintuitionistic fuzzy set as described by Atanassov, (1986), the exponential-related function andthe IFE are presented, while their integration is presented in the proceeding section.

2.1. Intuitionistic Fuzzy Set

Definition 1

If the IFS A in $X = \{x\}$ is defined fully in the form$A = \{\langle x, \mu_A(x), v_A(x), \pi_A(x)\rangle | x \in X\}$, where$\mu_A: X \rightarrow [0,1]$, $v_A: X \rightarrow [0,1]$ and $\pi_A: X \rightarrow [0,1]$.The different relations and operations for the IFS are shown in Eq. (1) to Eq. (4).

$$A.B = \{\langle x, \mu_A(x).\mu_B(x), v_A(x) + v_B(x) - v_A(x).v_B(x)\rangle | x \in X\} \tag{1}$$

$$A + B = \{\langle x, \mu_A(x) + \mu_B(x) - \mu_A(x).\mu_B(x), v_A(x).v_B(x)\rangle | x \in X\} \tag{2}$$

$$\lambda A = \{\langle x, 1 - (1 - \mu_A(x))^\lambda, (v_A(x))^\lambda\rangle | x \in X\}, \ \lambda > 0. \tag{3}$$

$$A^\lambda = \{\langle x, (\mu_A(x))^\lambda, 1 - (1 - v_A(x))^\lambda\rangle | x \in X\}, \ \lambda > 0 \tag{4}$$

In the following, we make comparisons between two IFS, by introducing the Exponential-related function which is a metric method, derived fromthe traditional exponential score function and accuracy functions.

2.2. Exponential-related function

Definition 2(Aikhuele& Turan, 2017)

Let $A = (\mu, v)$be the intuitionistic fuzzy number. The new exponential-related function *ER* of the intuitionistic fuzzy number can be defined as,

$$ER(A) = e^{\left(\frac{1-\lambda(\mu^2 - v^2)}{3}\right)}, \text{where } E\,R(A) \in [1/e, e] \tag{5}$$

whereλ is the flexibility and adjustability parameter.

2.3. The intuitionistic fuzzy entropy (IFE)

Definition 3(Aikhuele& Turan, 2017c; Liu & Ren, 2014)

Let consider an intuitionistic fuzzy set A in the universe of discourse $X = \{x_1, x_2, x_3, \ldots, x_n\}$.The intuitionistic fuzzy set A is transformed into a fuzzy set to structure an entropy measure of the intuitionistic fuzzy set by means of $\mu_{\bar{A}}(x_i) = (\mu_A(x_i) + 1 - v_A(x_i))/2$. Based on the definition of fuzzy information entropy,Liu & Ren, (2014)proposes the intuitionistic fuzzy entropy as follows;

$$E(A) = \frac{1}{n}\sum_{i=1}^{n} \text{Cot}\left(\frac{\pi}{4} + \frac{\left|\mu^2{}_A(x_i) - v^2{}_A(x_i)\right|}{4}\pi\right) \tag{6}$$

Such that, when the criteria weights are completely unknown, the IFE can be used to determine the weights. Where the criteria weight is given as;

$$W_j = \frac{1 - H_j}{n - \sum_{j=0}^{n} H_j} \tag{7}$$

where $W_j \in [0,1]$, $\sum_{j=1}^{n} W_j = 1$, $H_j = \frac{1}{m}E(A_j)$ and $0 \le H_j \le 1$ for $(j = 1, 2, 3, \ldots, n)$.

3. The Proposed Integrated Model

In this section, the algorithm for the integratedIF-TOPSIS-EF model, the IFE method, and the FAHP model are presented using a stepwise procedure. The flowchart for the proposed integrated model is shown in Figure 1 below.

Step 1: A group of Decision Makers (DMs) with weight vector $\lambda = (\lambda_1, \lambda_2, \lambda_3, .., \lambda_l)^T$ are engaged, and their preferences/judgments which are given using linguistic variables as shown in Table 1 below, are aggregate using Intuitionistic Fuzzy Weighted Geometric (IFWG) operator (Xu & Yager, 2006) after they have been converted to intuitionistic fuzzy number (IFNs). The aggregated DMs individual assessment matrices $D^k(k = 1,2,3, \ldots, l)$is described in this study a the comprehensive group assessment matrix $(R_{mxn}(x_{ij}))$;

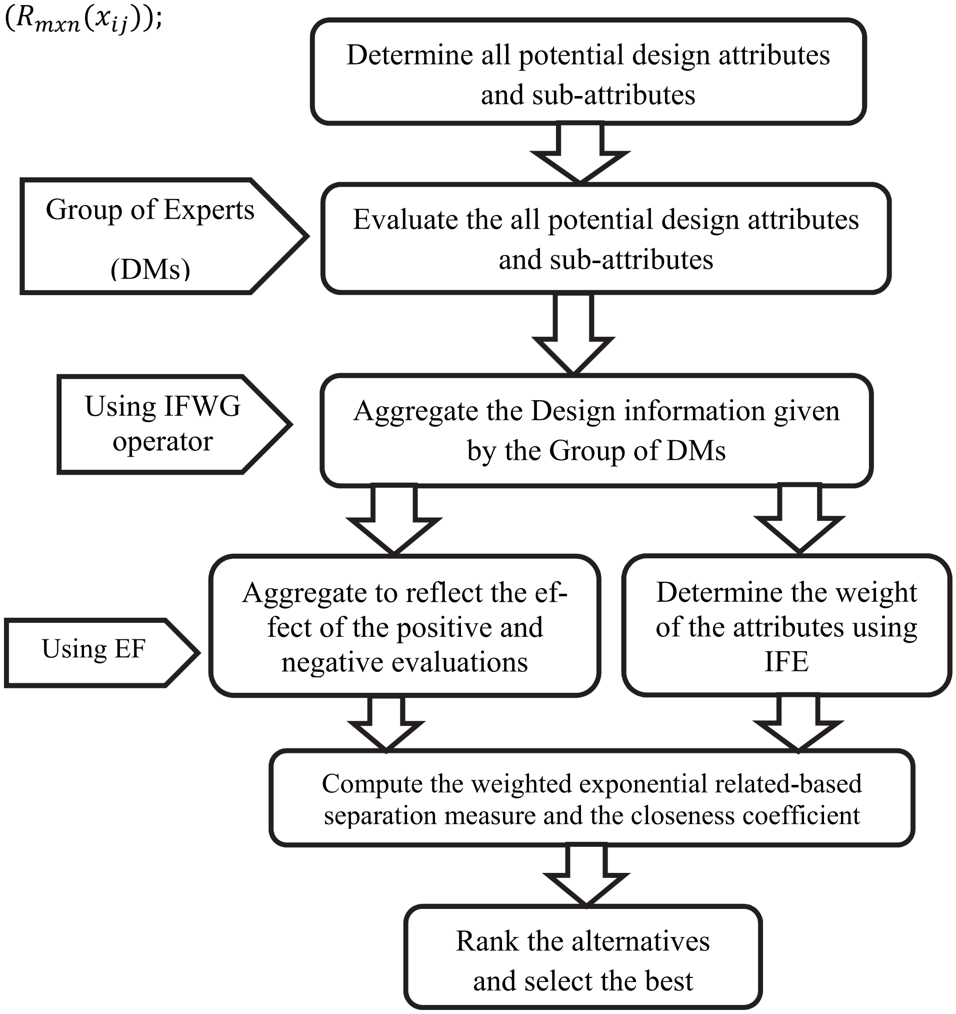

Fig. 1. The schematic flow diagram of the proposed model

$$IFWG\ (d_1 d_2 d_3, \dots, d_n) = \left(\prod_{i=1}^{n} (\mu_{ij})^{w_j}, 1 - \prod_{i=1}^{n} (1 - v_{ij})^{w_j} \right) \tag{18}$$

$$R_{mxn}(a_{ij}) = \begin{bmatrix} (\mu_{11}, v_{11}) & (\mu_{12}, v_{12}) & \dots & (\mu_{1n}, v_{1n}) \\ (\mu_{21}, v_{21}) & (\mu_{22}, v_{22}) & \cdots & (\mu_{2n}, v_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ (\mu_{m1}, v_{m1}) & (\mu_{m2}, v_{m2}) & \cdots & (\mu_{mn}, v_{mn}) \end{bmatrix} \tag{19}$$

Table 1
Fuzzy numbers for approximating the linguistic variable

Linguistic terms	Intuitionistic fuzzy number
Extremely Low (EL)	(0.00, 0.05)
Very Low (VL)	(0.05, 0.10)
Low (L)	(0.10, 0.20)
Medium (M)	(0.30, 0.40)
Good (G)	(0.50, 0.60)
Very Good (VG)	(0.50, 0.60)
High (H)	(0.70, 0.80)
Very High (VH)	(0.80, 0.90)
Extremely High (EH)	(0.90, 1.00)

Step 2: Determine the weight of each of the evaluating criteria $w_j$using the IFE method.

Step 3: Using the exponential related function *ER* (i.e. equation (5)), the comprehensive group assessment matrix$R_{mxn}(x_{ij})$is convert to form the exponential related matrix $ERM_{mxn}\left(ER_{ij}\left(a_{ij}\right)\right)$ which represents the aggregated effect of the positive and negative evaluations in the performance ratings of the alternatives based on the intuitionistic fuzzy set (IFS) data;

$$ERM_{mxn}\left(E_{ij}\left(a_{ij}\right)\right) = \begin{bmatrix} ER_{11}(x_{11}) & ER_{12}(x_{12}) & \dots & ER_{1n}(x_{1n}) \\ ER_{22}(x_{22}) & ER_{22}(x_{22}) & \cdots & ER_{2n}(x_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ ER_{m1}(x_{m1}) & ER_{m2}(x_{m2}) & \cdots & ER_{mn}(x_{mn}) \end{bmatrix} \tag{20}$$

Step 4: Define the IFPIS $A^+ = (\mu_j, v_j)$ and IFNIS $A^- = (\mu_j, v_j)$ for the alternatives *i.e.*

$$A^+ = \{\langle C_j,[1,1]\rangle | C_j \in C\}, \qquad A^- = \{\langle C_j,[0,0]\rangle | C_j \in C\}, \qquad j = 1,2,3, \dots, n.$$

Step 5: Compute the exponential-related function-based separation measures in intuitionistic fuzzy environment $(d^+{}_i(A^+,\ A_i)$ and $(d^-{}_i(A^-,\ A_i)$ for each alternative for the IFPIS and IFNIS.

$$d^+{}_i(A^+, \quad A_i) = \sqrt{\sum_{i=1}^{n} \left[w_j(1 - (\ ERM_{nxm}(a_{ij}))\right]^2} \tag{21}$$

$$d^-{}_i(A^-, A_i) = \sqrt{\sum_{i=1}^{n} \left[w_j(\ ERM_{nxm}(a_{ij}))\right]^2} \tag{22}$$

wherew_j is the weight of the criteria.

Step 6: Compute the relative closeness coefficient, (CC_i), which is defined to rank all possible alternatives with respect to the positive ideal solution A^+. The general formula is given as;

$$CC_i = \frac{d^-{}_i(A^-,\ A_i)}{d^-{}_i(A^-,\ A_i) + d^+{}_i(A^+,\ A_i)}, \tag{23}$$

whereCC_i $(i = 1,2,..n)$ is the relative closeness coefficient of A_i with respect to the positive ideal solution A^+ and $0 \leq CC_i \leq 1$.

Step 7: Rank the alternatives in the descending order.

4. Application of the proposed method for concept design for a Forklift truck

In this section, the design concept evaluation of a forklift truck has been presented and investigated using the proposed method. Forklift which is an indispensable piece of machine is mostly used within the manufacturing industry and for warehousing operations. It is used for lifting and moving materials between short distances. Due to the more frequent operations required for the machines, the greater lifting capacity, and the ever-increasing deadweight, the safety, and reliability of the machine has always been called to question. Hence, in improving the reliability of the machine, four new concept designs have been presented as shown in Fig.2**.**

Fig. 2. Concept designs for a Forklift Truck

In this case study, using the stepwise procedurefor the proposed approach, a group of ten (10) DMs with expert (Forklift operators and users) and basic (others) knowledge on design method, Forklift trucks, and product development were invited to give their preference and expert ratings on the four concept design generated after the reliability assessment reports in the earlier Section has been inputted into the new design. Using attributes of product performance; product appearance (C_1), product cost (C_2), quality and reliability (C_3), maintainability (C_4)(Chin et al., 2009), the new designs are evaluated. After a careful analysis of the response/evaluation result from the DMs, Five (5) of the expert's ratings were adopted for the evaluation of the four concept design proper. Based on their level of experience and expertise, the DMs were assigned the following weight vector

$\gamma = \{0.10;\ 0.15; 0.20; 0.15, 0.25\}^T$respectively.

Following the proposed computational algorithm described in the section above, the linguistic evaluations of the design concept with respect to the product performance measures attribute by the experts (DMs) are presented as shown in Table 1 Appendix 2 below. Thereafter, the IFWG operator is used to aggregate the DMs judgments into a comprehensive group preferenceassessment matrixas shown in Table 2after the linguistic have been converted to IFNs.

Table 2
Aggregation of all the Experts assessment

A	*C₁*	*C₂*	*C₃*	*C₄*
A_1	(0.204, 0.215)	(0.376, 0.509)	(0.000, 0.185)	(0.178, 0.173)
A_2	(0.400, 0.600)	(0.765, 0.754)	(0.737, 0.778)	(0.835, 0.849)
A_3	(0.000, 0.240)	(0.704, 0.691)	(0.543, 0.568)	(0.615, 0.494)
A_4	(0.000, 0.606)	(0.000, 0.361)	(0.211, 0.211)	(0.113, 0.333)
A_5	(0.339, 0.315)	(0.638, 0.588)	(0.291, 0.527)	(0.481, 0.467)
A_6	(0.000, 0.210)	(0.638, 0.588)	(0.708, 0.717)	(0.770, 0.762)
A_7	(0.363, 0.491)	(0.398, 0.403)	(0.000, 0.477)	(0.000, 0.425)

With the exponential related function *ER* (5), the comprehensive group assessment matrix is converted to form the exponential-related matrix which represents the aggregated effect of the positive and negative evaluations in the performance ratings of the alternatives based on the intuitionistic fuzzy set (IFS) data. Here, the flexibility and adjustability parameteris introduced. In this case, for convenience, two different flexibility and adjustability range are considered during the design evaluation process, which is when $\lambda = 0.1$and when $\lambda = -0.1$. The introduction of the parameter $\lambda$is expected to allow for flexibility and adjustabilityin the design decision-making and for a more complete view of possible options in the design. Using the Intuitionistic Fuzzy Entropy, the weight of the design attributes were calculated from the comprehensive group preference assessment matrix and result is given by weight vector $\omega_{IFE} = \{0.3453,\ 0.1920,\ 0.2503,\ 0.2124\}^T$respectively. Also, using the FAHP model, the evaluation of the attributes by the experts are given as $\omega_{FAHP} = \{0.2566, 0.3431, 0.1598, 0.2405\}^T$respectively and are combined using the formula $\omega = \omega_{IFE} + \omega_{FAHP})/2$ to form a comprehensive attribute weight for the design evaluation.By following step 4-6 in the IF-TOPSIS$_{EF}$ algorithm, the exponential related function-based separation measures $(d^+{}_i(A^+,\ A_i)$ and $(d^-{}_i(A^-,\ A_i)(i = 1,2, \dots, 4)$ is calculated, follow by the relative closeness coefficient $CC_i\ , (i = 1,2, \dots, 4)$ to the ideal solution using equation (23). Then, the relative closeness coefficients of the risk options are then ranked in the descending order. The final ranking results are shown in Table 3 for the two different flexibility and adjustability range and are represented graphically as shown in Fig. 3.

Table 3
The relative closeness coefficients for the design evaluation for the Forklift Machine

Design-concepts	*X*=$\boldsymbol{\lambda = 0.1}$				*Y*=$\boldsymbol{\lambda = -0.1}$			
	$d^+{}_i$	$d^-{}_i$	CC_i	*Rank*	$d^+{}_i$	$d^-{}_i$	CC_i	*Rank*
A_1	0.2009	0.7064	0.7786	4	0.1990	0.7045	0.7797	4
A_2	0.2019	0.7073	0.7780	5	0.1981	0.7035	0.7803	3
A_3	0.1998	0.7053	0.7792	1	0.2001	0.7056	0.7790	7
A_4	0.2044	0.7098	0.7764	7	0.1956	0.7011	0.7818	1
A_5	0.2001	0.7056	0.7790	3	0.1998	0.7053	0.7792	5
A_6	0.1999	0.7054	0.7791	2	0.2000	0.7055	0.7791	6
A_7	0.2027	0.7081	0.77749	6	0.1973	0.7027	0.7808	2

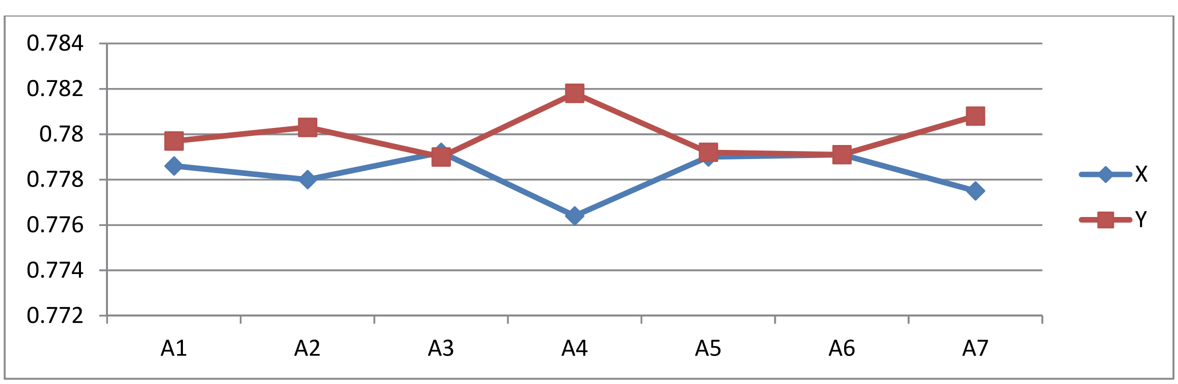

Fig. 3. Graphical representation of the design concept results

Finally, in Table 4, the different ranking order for the alternatives under the different flexibility and adjustability scenario for the product design assessment is presented.

Table 4
The different ranking order for the alternatives under the different flexibility and adjustability scenario

λ	Ranking order	Best alternative
0.1	$A_3>A_6>A_5>A_1>A_2>A_7>A$	A_3
0.3	$A_3>A_6>A_5>A_1>A_2>A_7>A_4$	A_3
0.4	$A_3>A_6>A_5>A_1>A_2>A_7>A_4$	A_3
0.5	$A_3>A_6>A_5>A_1>A_2>A_7>A_4$	A_3
0.7	$A_3>A_6>A_5>A_1>A_2>A_7>A_4$	A_3
0.9	$A_3>A_6>A_5>A_1>A_2>A_7>A_4$	A_3
0.0	$A_3=A_6=A_5=A_1=A_2=A_7=A_4$	Indifferent
-0.1	$A_4>A_7>A_2>A_1>A_5>A_6>A_3$	A_4
-0.3	$A_4>A_7>A_2>A_1>A_5>A_6>A_3$	A_4
-0.4	$A_4>A_7>A_2>A_1>A_5>A_6>A_3$	A_4
-0.5	$A_4>A_7>A_2>A_1>A_5>A_6>A_3$	A_4
-0.7	$A_4>A_7>A_2>A_1>A_5>A_6>A_3$	A_4
-0.9	$A_4>A_7>A_2>A_1>A_5>A_6>A_3$	A_4

5. Discussion of the Forklift truck design evaluation result

From the ranking result of the different flexibility and adjustability scenario for the Forklift truck in Table 4, the study can conclude that design $A_3$and A_4has the highest priority ranking with respect to the four evaluating criteria and depending on the flexibility and adjustability scenario considered. The flexibility and adjustable parameter provide the DMs more selecting schemes and actionable results for the decision-making process and analysis. Hence, solving the ranking order and decision-making problem, in which the same measure values exist for some alternatives in the same case study. The exponential-related function in the TOPSIS model presented in this study serves as a collective aggregation index for the design alternatives in the evaluation processes even when the input information is of poor-quality or ill-defined.Finally, the proposed model has improved the solution of the Forklift truck design reliability problems by not just assuming the weights of the attributes but using a subjective and objective approach in its computations. Since, in real-life situations, the attributes of most design problems are often complex, so it is difficult to directly give them a weight value.

6. Conclusion

In this paper, a new flexible and adjustable model which is based on the integration of an Intuitionistic fuzzy TOPSIS model which based on an exponential-related function (IF-TOPSIS$_{EF}$) and intuitionistic fuzzy entropy (IFE) method originally presented in (Aikhuele & Turan, 2017), has been proposed. For supporting designers in determining stakeholders' preferences and finding the best compromise between those preferences during the product concept design phase of new products. The main advantage of this model is that it is flexible and adjustable and affords the design stakeholders the option to a change of action in the event they receive new information or reason not to continue with a particular design or product. And finally, it uses both subjective and objective weights methods for the evaluation of the design concepts criteria, which makes the proposed model more realistic and more practical.

To demonstrate the effectiveness of the proposed method, a design concept evaluation of seven forklift truck has been presented and investigated using the proposed method. Forklift which is an indispensable piece of machine is mostly used within the manufacturing industry and for warehousing operations, is used for lifting and moving materials between short distances. Due to the more frequent operations required for the machines, the greater lifting capacity, and the ever-increasing deadweight, the safety, and reliability of the machine has always been called to question. Hence, in improving the reliability of the machine, seven new concept designs have been presentedand investigated.In the future, we will continue working on the application of the proposed method in other domain, specifically for problems with more criteria and alternatives.

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Appendix 1

Table 1
The Linguistic evaluations ofseven Design concepts by the five DMs

Design Concept	Product appearance (C_1)					Product cost (C_2)					Quality and reliability (C_3)					Maintainability (C4)				
	E1	**E2**	**E3**	**E4**	**E5**	**E1**	**E2**	**E3**	**E4**	**E5**	**E1**	**E2**	**E3**	**E4**	**E5**	**E1**	**E2**	**E3**	**E4**	**E5**
A_1	L	VL	L	M	L	H	VH	L	M	L	L	M	L	EL	VL	L	L	L	L	L
A_2	L	L	L	H	VH	H	H	VG	H	VH	VH	H	VH	VH	VG	H	VH	VH	VH	VH
A_3	EL	EL	VL	M	L	VH	EH	H	M	M	L	M	M	VH	VG	H	M	M	M	M
A_4	EL	EL	VL	H	VH	M	M	M	EL	VL	L	L	VL	M	L	L	VL	VL	VL	VL
A_5	L	L	L	M	M	M	M	M	VH	VG	H	VH	VG	L	VL	L	VG	VL	VG	VG
A_6	L	L	L	EL	VL	M	M	M	VH	VG	H	VH	VG	VH	VG	H	VH	VG	VH	H
A_7	L	L	L	VH	VG	M	M	VG	M	L	L	EL	L	VH	VG	H	VG	EL	VL	VG