Design concept evaluation technique via functional link matrix and fuzzy VIKOR based on left and right scores

Olayinka Olabanji and Khumbulani Mpofu

Faculty of Engineering And The Built Environment, Industrial Engineering, Tshwane University Of Technology, Pretoria, South Africa

ABSTRACT
This article presents a new technique for determining the weights of design features by searching for functional links between their sub-features. The method further applies fuzzy VIKOR based on left and right scores to determine the optimal design concept from a decision matrix obtained from three experts view. The application of this technique to the design of a Reconfigurable Assembly Fixture (RAF) shows that it is a viable method for determining the weights of design features and identifying the optimal design concept from a set of alternative designs. In order to support the viability of this technique, the results obtained from its application to the design of a RAF was compared with the results of other Multi-Criteria Decision-Making (MCDM) methods when applied to the design of the RAF. The comparison shows that the technique is feasible and can be employed to determine the weights of design features in order to identify optimal design at the conceptual phase.

1. Introduction

It is an established fact that the performance of a product depends on its design, particularly when the design engineer incorporates all functional requirements in the design features of the product (Olabanji & Mpofu, 2019). Hence, the design features of the product increases to satisfy the end users in terms of functional requirements and customization (Gologlu & Mizrak, 2011; Olabanji & Mpofu, 2020a). Further, the availability of many design features inspires design engineers to have different design concepts, because it is most likely difficult to have a design that will satisfy all the design features. In view of this, design engineers need to undergo a design concept evaluation process to select the optimal design from available alternative designs (Olabanji, 2018; Renzi & Leali, 2016). Evaluation of alternative design concepts is an important task in the design process because it provides insight to prediction of design performance aside assisting in the identification of optimal design (Olabanji & Mpofu, 2020b; Song et al., 2013). Hence, there is a need to evaluate the design solutions because at early design
phase the manufacturers are interested in producing a product with optimal performance before fabrication.

Evaluation of alternative design concepts can be modelled as a Multi-Criteria Decision-Making model (MCDM) by means of two approaches. These approaches are Multi-Objective Decision Model (MODM) and Multi-Attribute Decision Model (MADM) (Yeo et al., 2004; Zavadaskas et al., 2015). The MODM approach are employed when the design features are considered as an entity and the design alternatives are evaluated by weighting the availability of the design features in them. The MADM approach select optimal design concept from a set of alternatives when the importance attached to the relative requirements of the design features in the design concepts is of less significance (Olabanji & Mpofu, 2014). In essence, the approach is effective for rating design concepts at a glance without analysing the in-depth implication of the relative importance of the design features and their interrelationships. When it is required to rank alternative design concepts with a consideration of the interrelationships and dependencies of the design features, the MADM approach is usually applied because it provides a clear picture of the contributions of each design features to the selected optimal design. Two major tasks in the MADM approach is the determination of weights for the design features and obtaining ratings for availability of the design features in the alternative designs without bias (Olabanji & Mpofu, 2020c; Tiwari et al., 2016).

A good way to obtain the interrelationships and dependencies among design features is to analyze the design features into several sub features. The essence of identifying the relationships and dependencies between the design features and sub features is to know how their weights can be assigned. These sub features describe the relative performance and importance of the design features (Olabanji & Mpofu, 2019; Renzi et al., 2017). Analyzing the design features into sub features will also assist in establishing a decision matrix for the design concepts because it will aid the determination of availability of the design features present in the design concepts (Olabanji & Mpofu, 2020b; Yeo et al., 2004). In practice, weights of design features are usually obtained by evaluation of design requirements from end user’s needs. The evaluation is usually done by decision makers and design experts in order to ensure that all the features are appropriately evaluated following the design requirements. There still exists a trace of bias judgement in apportioning weights to the design features because the decision makers tend to overrate one design requirement than others (Olabanji, 2018; Olabanji & Mpofu, 2020b). Efforts made to eliminate bias judgement in apportioning of weights is the use of more decision makers and design teams (Tiwari et al., 2016). The decisions from each team is averaged to obtain a result or used separately to make decisions on optimal design with an implication that the final decision is based on the different weights from the decision makers or design teams. This implies that there are different solutions based on different apportioning of weights to design features and determination of availability of the design features present in the design concepts (Olabanji & Mpofu, 2020c).

In essence, it can be stated that, apportioning weights to design features and sub features is still a major challenge that requires attention because it has a role to play in deciding the optimal design from a group of design alternatives. Also, irrespective of any computational tool applied in the decision process, obtaining a decision matrix that provides performance of the design concepts in terms of design features is a task that also requires attention because it plays a key role in the final decision on optimal design.
this end, this article proposes a new method for determining weights of design features and sub features using a functional link matrix. The functional link matrix aggregates and fuzzify the number of relational links between the sub features of a design feature and sub features of another design feature. The article further proposes the determination of decision matrix through analysis of availability of sub features in each design concept. The availability of sub features in the design concepts are aggregated using the weights of the sub features in order to create the decision matrix. Fuzzy VIKOR based on left and right scores is proposed as a computational tool for identifying the optimal design concept from the decision matrix.

2. Previous work

Several MODM and MADM models have been developed to solve the problem of decision making in engineering design (Okudan & Tauhid, 2008; Renzi et al., 2017). Among these models are Weighted Decision Matrix (WDM) (Olabanji & Mpofu, 2014), Analytic Hierarchy Process (AHP) (Hambali et al., 2011), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Olabanji & Mpofu, 2019) and Višekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) (Tiwari et al., 2016), bijective soft set theoretic approach (Tiwari et al., 2017). The diversities in dimensions and units of measurements of design features makes it a challenging task to quantify and characterize them using crisp values without bias apportioning. In order to address this challenge, MCDM models are fuzzified using different types of membership functions. Hence, the introduction of fuzzified MCDM models have been able to address the challenge of bias apportioning of crisp values to design features and design concepts during the decision-making process (Akay et al., 2011; Wang, 2002).

Further attempts to improve decision making at conceptual design phase can also be identified as integration of two or more fuzzified MCDM models to increase the computational integrity of the decision process and ensure that the optimal design concept is selected (Renzi et al., 2015; Zhu et al., 2015). Obtaining the weights of design features have been achieved through the use of decision makers. As presented by (Tiwari et al., 2016), four decision makers are selected to assign importance to design attributes. The crisp values assigned were converted to rough numbers and a relative importance was obtained for all the design attributes from the average of the rough numbers. A similar approach was followed in determining the decision matrix but in this case four customers were selected to create different preference matrices which is also recombined to form a rough group preference decision matrix that was solved by a fuzzy VIKOR model.

Contrary to this approach, determination of weights of design features have been achieved through Fuzzified Pairwise Comparison Matrix (FPCM). This usually occurs whenever the fuzzy AHP approach is applied (Olabanji & Mpofu, 2020b; Renzi et al., 2015) or when it is hybridized with other MCDM models (Olabanji & Mpofu, 2020c). The FPCM are solved by determining the Fuzzy Synthetic Extent values of the design features (Güngör et al., 2011). In order to develop a FPCM, design experts view is employed to establish ratings of the design features by fuzzifying the Saaty scale or developing a scale using defined membership function (Chakraborty et al., 2017). Also, development of decision matrices that will display the ratings of alternative design concepts relative to
the design features have also been achieved by using design experts to fuzzify the availability of design features in the design alternatives. A method applied by (Olabanji, 2018) involves analyzing each design feature into various sub-features and rating each design alternative considering the weights of the sub-features obtained from design experts view. In order to reduce the final values of the design concepts, average of the cumulative scores was adopted as the aggregates of the design alternatives (Olabanji & Mpofu, 2019). However, obtaining averages of the cumulative scores for the design alternatives makes the final value dependent on the number of sub-features available in the design feature.

In essence, a lingering challenge that requires attention in the decision-making process for conceptual design is the reduction of human intervention in the determination of weights for the design features and values of the design concepts in the decision matrix. Several decision-making models on the evaluation of conceptual design have addressed this challenge by harnessing views of decision makers and design experts to provide insight on the weights of design features and ratings of the design concepts. Hence, there is a need to develop an alternative method that will provide the weights of design features and sub features without sole dependence on decision experts or decision makers views. In essence, this article presents the determination of weights of design features and sub features from Identification of functional links between sub-features and also, availability of sub-features in the design alternatives was used to obtain the decision matrix.

3. Functional link matrix

For ease of analysis, let there be \( m \) number of design features \([d_{F1}, d_{F2}, d_{F3}, \ldots, d_{Fn}]\) that are required to evaluate \( k \) number of design concepts \([D_{C1}, D_{C2}, D_{C3}, \ldots, D_{Ck}]\). If each of the design features is further characterized by \( N \) sets of sub features represented with alphabets \([S_{Fa_1a_2a_3}, S_{Fa_1a_2a_3}, \ldots, S_{Fa_1a_2a_3}]\) such that each set is having \( i \) numbers of sub features \([S_{F_{a_1a_2a_3}}, S_{F_{a_1a_2a_3}}, \ldots, S_{F_{a_1a_2a_3}}]\), then it is worthwhile to know that the number of sub features for each of the design features varies depending on the attributes of the design feature i.e. \((a_i = b_i = c_i, \ldots = n_i) \lor (a_i \neq b_i \neq c_i, \ldots \neq n_i)\). A clear description of the scenario is presented by the matrix in Equation (1). The functional link matrix proposed in this article infers that, the weight of a design feature is a function of the number of occurrences of functional link of all its sub features when compared with the sub features of other design features. Figure 1 shows a description of the comparison by considering Equation (1).

\[
\begin{bmatrix}
  d_{F1} & d_{F2} & d_{F3} & \cdots & d_{Fn} \\
  S_{Fa_1a_2a_3} & S_{Fa_1a_2a_3} & S_{Fa_1a_2a_3} & \cdots & S_{Fa_1a_2a_3} \\
  [S_{df}1, a_1] & [S_{df}2, b_1] & [S_{df}3, c_1] & \cdots & [S_{df}m, n_1] \\
  [S_{df}1, a_2] & [S_{df}2, b_2] & [S_{df}3, c_2] & \cdots & [S_{df}m, n_2] \\
  [S_{df}1, a_3] & [S_{df}2, b_3] & [S_{df}3, c_3] & \cdots & [S_{df}m, n_3] \\
  \vdots & \vdots & \vdots & \ddots & \vdots \\
  [S_{df}1, a_i] & [S_{df}2, b_i] & [S_{df}3, c_i] & \cdots & [S_{df}m, n_i]
\end{bmatrix}
\]

Where; \([S_{df}]_{m, n_i}\) is the \(i^{th}\) sub feature of set \(N\) sub features corresponding to design feature \(m\). In order to capture all the sub features in the comparison process, sub features of the first design feature are compared with the sub features of other design features. This is followed by comparing the sub features of the second design feature with sub
features of other design features but excluding the first design feature to avoid repetition. However, the functional links obtained from initial comparison of the preceding design feature with the current feature under consideration are adopted for the design feature under consideration. The comparison is continued in the same manner while excluding the preceding design features in each case.

Figure 1. Sub features comparison diagram.
Considering Figure 1, if all comparisons with functional links are represented with dotted lines, then the number of functional links for a sub feature in any design feature can be identified and fuzzified using Triangular Fuzzy Numbers (TFNs) which membership function $\mu_m(q)$ as contained in interval $[0 \ 1]$ which is defined in Equation (2). The linguistic scales for the TFN are described in Table 1. It is necessary to know the weights of the sub features in a design feature because it will be considered in aggregating TFNs for the design concepts to develop the decision matrix.

$$
\mu_m(q) = \begin{cases} 
0q < 1, \\
\frac{1}{y - x} q - \frac{1}{y - x} q \in [xy], \\
\frac{1}{z - y} q - \frac{w}{z - y} q \in [yz], \\
0q > z 
\end{cases}
$$

Where $x \leq y \leq z$ and $u, v$ and $w$ represent the lower, modal and upper values of the fuzzy number $M$, respectively. Considering Equation (1), a matrix containing the comparison of design feature one with other design features can be presented in Equation (3).

$$
\begin{bmatrix}
[S_{DF}]_1 \\
[S_{DF}]_2 \\
[S_{DF}]_3 \\
[S_{DF}]_4 \\
\vdots \\
[S_{DF}]_m \\
T_{FL}^d
\end{bmatrix}
\begin{bmatrix}
d_{F1} = d_{F2} & d_{F1} = d_{F3} & d_{F1} = d_{F4} & \cdots & d_{F1} = d_{Fn} \\
F_{SDF}^{1a} & F_{SDF}^{2a} & F_{SDF}^{3a} & \cdots & F_{SDF}^{ma} \\
F_{SDF}^{1b} & F_{SDF}^{2b} & F_{SDF}^{3b} & \cdots & F_{SDF}^{mb} \\
F_{SDF}^{1c} & F_{SDF}^{2c} & F_{SDF}^{3c} & \cdots & F_{SDF}^{mc} \\
F_{SDF}^{1d} & F_{SDF}^{2d} & F_{SDF}^{3d} & \cdots & F_{SDF}^{md} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
F_{SDF}^{1n} & F_{SDF}^{2n} & F_{SDF}^{3n} & \cdots & F_{SDF}^{mn}
\end{bmatrix}
\begin{bmatrix}
\tilde{T}_{FL}^d
\end{bmatrix}
$$

Where $[F_{SDF}]^{ia}$ is the number of identified functional links that is obtained by comparing $i^{th}$ numbers of set ‘$a$’ sub features in design feature one with $i^{th}$ numbers of set ‘$N$’ sub features for design features ‘$m$’. Also, $\tilde{T}_{FL}^d$ is the total TFN for number of functional links for each sub feature of design feature one, while $\tilde{T}_{FL}^d$ is the total TFN for number of functional links for comparing design feature one with any other design features.

Considering Equation (3), the TFN for number of functional links for comparing set ‘$a$’ sub features in design feature one with $i^{th}$ numbers of set ‘$N$’ sub features for other design features $(\tilde{T}_{FL}^d)_{ai}$ can be expressed as:

### Table 1. Linguistic scale for rating availability of the sub features in the design concepts and functional links of design features and sub features.

| Linguistic Scale for availability of sub features in design concepts | Crisp Value | TFN | Number of Functional Links $[N_{FL}]$ | Linguistic Scale for number of functional links available |
|-------------------------------------------------------------------|-------------|-----|-------------------------------------|-------------------------------------------------------|
| Very Low Availability (VLA)                                        | 1           | $\frac{1}{3}$ | 1                                   | Very low functional link                                |
| Low Availability (LA)                                             | 2           | $\frac{1}{2}$ | 2                                   | Low functional link                                    |
| Moderate Availability (MA)                                        | 3           | $\frac{3}{2}$ | 3                                   | Moderate functional link                               |
| High Availability (HA)                                            | 4           | $\frac{2}{3}$ | 4                                   | High functional link                                   |
| Very High Availability (VHA)                                      | 5           | $\frac{5}{3}$ | $\geq$ 5                            | Very High functional link                              |
Similarly, the TFN representing the number of functional links ($\overline{T}^{df}_{FL}$) for comparing design feature one to any other design feature ‘m’ can be expressed as:

$$\overline{T}^{df}_{FL}|_{ai} = \sum_{m=1}^{m=m} \left[ [FL_{Sdf}]_{m}^{1/i} \right] \text{ for } i=1, 2, \ldots \text{number of sub features}$$

It is necessary to normalize the TFNs obtained for the number of functional links because they represent the weights of the sub features and design features. In order to normalize the TFNs, consider a fuzzy number $q_{ij} = (x_{ij}, y_{ij}, z_{ij})$ for $(i = 1, \ldots, n; j = 1, \ldots, m)$ as defined in Equation (2), the normalization process can be represented as; (Aryanezhad et al., 2011; Mokhtarian, 2011; Mokhtarian & Hadi-Vencheh, 2012).

$$\left( q_{ij} \right)_N = \left[ (x_{ij})_N, (y_{ij})_N, (z_{ij})_N \right]$$

$$\left( q_{ij} \right)_N = \left[ \frac{x_{ij} - x_{ij}^{Min}}{\Delta_{Max}^{Min}}, \frac{y_{ij} - x_{ij}^{Min}}{\Delta_{Max}^{Min}}, \frac{z_{ij} - x_{ij}^{Min}}{\Delta_{Max}^{Min}} \right], i = 1, \ldots, n; j \in \Omega_b$$

$$\left( q_{ij} \right)_N = \left[ \frac{z_{ij} - z_{ij}^{Max}}{\Delta_{Max}^{Min}}, \frac{y_{ij} - z_{ij}^{Max}}{\Delta_{Max}^{Min}}, \frac{x_{ij} - z_{ij}^{Max}}{\Delta_{Max}^{Min}} \right], i = 1, \ldots, n; j \in \Omega_c$$

Where $x_{ij}^{Min} = \text{Min} x_{ij}$ and $z_{ij}^{Max} = \text{Max} z_{ij}$; $\Delta_{Max}^{Min} = z_{ij}^{Max} - x_{ij}^{Min}$. Also, $\Omega_b$ and $\Omega_c$ are sets of benefit and cost attributes respectively. Further, it can be implied that the overall TFN representing the number of functional links of design feature one ($[nF_L]_{dF_1}$) when it is compared with all other design features can be obtained by summing all the normalized TFN obtained in Equation (5);

$$[nF_L]_{dF_1} = \sum_{m=2}^{m=m} \left[ \overline{T}^{df}_{FL} \right]_{1,m} = \sum_{m=2}^{m=m} \sum_{i=1}^{n} \left[ [FL_{Sdf}]_{m}^{1/i} \right]$$

It is worthwhile to know that Equations (4) and (9) will also be applied to obtain the number of functional links for other design features and their sub features in the next stages of the comparison process. Further, they (Equations (4) and (9)) represents the weights of the sub features ($\bar{W}_S$) and design features ($W_{dF}$) respectively.

4. Fuzzy VIKOR based on left and right scores

Due to non-commensurate attributes of the design features and their sub features, it is necessary to apply a MCDM tool that will provide an optimal solution to the decision problem. It is anticipated that the application of fuzzy VIKOR will provide an optimized solution to ranking of the design concepts because it can eliminate units and dimensions of the design features or sub features (Tiwari et al., 2016; Zhu et al., 2015). The application of left and right scores will improve the degree of accuracy in the computations because the determination of the performance index from the maximum group utility
and minimum individual regret will be based on intervals of fuzzy ratings of the design concepts and weights of the design features. These intervals of fuzzy ratings provide an improved accuracy compared to conventional fuzzy computations where accuracy is based on increased number of alpha level sets, which give rise to high computational volume (Mokhtarian & Hadi-Vencheh, 2012).

The first step in applying the fuzzy VIKOR is to develop a fuzzified decision matrix (Kim & Chung, 2013; Opricovic, 2011). In this article, the fuzzified weighted decision matrix method is applied to create sub decision matrices to consider the contributions of the sub features in the decision process. This will be achieved by employing experts view on rating the availability of the sub features in the design concepts using linguistics scales and TFN in Table 1. The scores are then aggregated using the weights of the sub features. The aggregates of the sub decision matrix for each design feature forms the elements of the required decision matrix alongside the weights of the design features. Hence, it can be implied that the alternative design concepts \([D_{C1,2,3...,k}]\) can be evaluated using identified design features ‘m’ \((d_{Fm})\) having set of sub features N \((S_{FN})\). In essence, an evaluation matrix for the sub-features of any of the design feature can be deduced as;

\[
\begin{bmatrix}
S_F \\
W_{1,m}^{d_f} \\
W_{2,m}^{d_f} \\
W_{3,m}^{d_f} \\
\vdots \\
W_{i,m}^{d_f} \\
\hat{d}_F^j|^{\text{sub}} \\
\hat{d}_C^k|m
\end{bmatrix}
\begin{bmatrix}
DC_1 \\
DE_1 \rightarrow DE_j \\
\hat{d}E_{1,1} \hat{d}E_{1,2} \hat{d}E_{1,3} \hat{d}E_{1,4} \hat{d}E_{1,5} \hat{d}E_{1,6} \hat{d}E_{1,7} \hat{d}E_{1,8} \hat{d}E_{1,9} \hat{d}E_{1,10} \\
DE_1 \rightarrow DE_j \\
\hat{d}E_{2,1} \hat{d}E_{2,2} \hat{d}E_{2,3} \hat{d}E_{2,4} \hat{d}E_{2,5} \hat{d}E_{2,6} \hat{d}E_{2,7} \hat{d}E_{2,8} \hat{d}E_{2,9} \hat{d}E_{2,10} \\
\vdots \\
\vdots \\
\hat{d}E_{k,1} \hat{d}E_{k,2} \hat{d}E_{k,3} \hat{d}E_{k,4} \hat{d}E_{k,5} \hat{d}E_{k,6} \hat{d}E_{k,7} \hat{d}E_{k,8} \hat{d}E_{k,9} \hat{d}E_{k,10}
\end{bmatrix}
\]

Where \(\hat{d}_{E_{j,k,m}}\) is a TFN representing the decision of \(j^{th}\) design expert for \(k^{th}\) design concept, considering \(i^{th}\) sub feature relative to \(m^{th}\) design feature. Where \(W_{i,m}^{d_f}\) is the weight corresponding to the \(i^{th}\) sub feature which can be obtained from Equation (4).

Also, \(\hat{d}_{F|j,k}^{i,|\text{sub}}\) and \(\hat{d}_{C|k,m}^{i}(|\text{agg})\) are the aggregate TFN for \(k^{th}\) design concept considering the decision of \(j^{th}\) design expert and overall TFN for \(k^{th}\) design concept relative to \(m^{th}\) design feature, respectively. \(\hat{d}_{F|j,k}^{i,|\text{sub}}\) and \(\hat{d}_{C|k,m}^{i}(|\text{agg})\) can be obtained from Equations (11) and (12), respectively.

\[
\hat{d}_{F|j,k}^{i,|\text{sub}} = \sum_{i=1}^{j} W_{i,m}^{d_f} \times \hat{d}_{E_{j,k,m}}^{i,|\text{agg}} \\
\forall j = 1, 2, 3,... j
\]

\[
\hat{d}_{C|k,m}^{i}(|\text{agg}) = \sum_{i=1}^{k} \hat{d}_{F|j,k}^{i,|\text{sub}} \\
\forall k = 1, 2, 3,... k
\]
\[
\tilde{d}_C^k_m = \frac{\sum_j d_{F_{ij}}^{k \text{sub}}}{\forall \; k = 1, 2, \ldots, k}
\]

The sub aggregates obtained from evaluating the availability of sub features in the design concepts are harnessed to form the main decision matrix together with the weights of the design features (\(W_{Fd}\)). This can be represented by Equation (13):

\[
\begin{bmatrix}
W_{Fd1}^{\text{sub}}_{\text{agg}} & d_{C1}^{\text{sub}}_{\text{agg}} & d_{C2}^{\text{sub}}_{\text{agg}} & \ldots & d_{C1}^{\text{sub}}_{\text{agg}} \\
W_{Fd2}^{\text{sub}}_{\text{agg}} & d_{C1}^{\text{sub}}_{\text{agg}} & d_{C2}^{\text{sub}}_{\text{agg}} & \ldots & d_{C2}^{\text{sub}}_{\text{agg}} \\
W_{Fd3}^{\text{sub}}_{\text{agg}} & d_{C1}^{\text{sub}}_{\text{agg}} & d_{C2}^{\text{sub}}_{\text{agg}} & \ldots & d_{C3}^{\text{sub}}_{\text{agg}} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
W_{FdM}^{\text{sub}}_{\text{agg}} & d_{C1}^{\text{sub}}_{\text{agg}} & d_{C2}^{\text{sub}}_{\text{agg}} & \ldots & d_{CM}^{\text{sub}}_{\text{agg}} \\
\end{bmatrix}
\]

Where \(\tilde{d}_C^{k\text{sub}}_{m\text{agg}}\) is a TFN representing the sub aggregate score of design concept \(k\) for all the sub features of design feature \(m\). The left and right scores of the elements in the decision matrix and the weights of the design features are important for computations of the separation measures and performance index (Mokhtarian, 2011). Considering Equation (2), the left and right score can be obtained from Equations (14) and (15), respectively. Hence, the TFNs in the decision matrix of Equation (13) can be replaced with their left and right scores components as presented in equation 16 (Li & Fan, 2014).

\[
(L_S)_{ij} = \frac{(y_{ij})_N}{1 + (y_{ij})_N - (x_{ij})_N}
\]

\[
(R_S)_{ij} = \frac{(z_{ij})_N}{1 + (z_{ij})_N - (y_{ij})_N}
\]

The fuzzy worst (\(F_w\)) and best (\(F_b\)) values can be determined in the form of the left \([F_{wL}, F_{wR}]\) and right \([F_{wL}, F_{wR}]\) scores from the left and right scores of the decision matrix. This is obtained by considering the minimum and maximum values of the left scores from all the design features as left worst and left best scores respectively. Also, the minimum and maximum values of the right scores is taken as right worst and right best scores, respectively (Tiwari et al., 2016). In essence, considering Equation (16), the worst \([F_{wL}, F_{wR}]\) and best \([F_{bL}, F_{bR}]\) values can be determined from Equations (17) and (18).
The separation measures comprising of the maximum group utility values ($S_k$) and individual regret values ($R_k$) can also be computed for any design concept 'k' in terms of the left and right scores by combining Equations (16)–(18), as presented in Equations (19) to (22) (Shemshadi et al., 2011).

\[
S_k^L = \sum_{m=1}^{m=m} [L_{s_{\text{left}}}^m]^* \times \left[ \frac{\text{Min}_m \left[ L_{d_{C}^k}^m \right] - \left[ L_{d_{C}^k}^m \right]}{\text{Max}_m \left[ L_{d_{C}^k}^m \right] - \text{Min}_m \left[ L_{d_{C}^k}^m \right]} \right] + \left[ \frac{\text{Max}_m \left[ L_{d_{C}^k}^m \right] - \left[ L_{d_{C}^k}^m \right]}{\text{Max}_m \left[ L_{d_{C}^k}^m \right] - \text{Min}_m \left[ L_{d_{C}^k}^m \right]} \right] \]
\]

\[
S_k^R = \sum_{m=1}^{m=m} [R_{s_{\text{left}}}^m]^* \times \left[ \frac{\text{Min}_m \left[ R_{d_{C}^k}^m \right] - \left[ R_{d_{C}^k}^m \right]}{\text{Max}_m \left[ R_{d_{C}^k}^m \right] - \text{Min}_m \left[ R_{d_{C}^k}^m \right]} \right] + \left[ \frac{\text{Max}_m \left[ R_{d_{C}^k}^m \right] - \left[ R_{d_{C}^k}^m \right]}{\text{Max}_m \left[ R_{d_{C}^k}^m \right] - \text{Min}_m \left[ R_{d_{C}^k}^m \right]} \right] \]
\]

\[
R_k^L = \text{Max}_m \left[ L_{s_{\text{left}}}^m \right]^* \times \left[ \frac{\text{Min}_m \left[ L_{d_{C}^k}^m \right] - \left[ L_{d_{C}^k}^m \right]}{\text{Max}_m \left[ L_{d_{C}^k}^m \right] - \text{Min}_m \left[ L_{d_{C}^k}^m \right]} \right] + \left[ \frac{\text{Max}_m \left[ L_{d_{C}^k}^m \right] - \left[ L_{d_{C}^k}^m \right]}{\text{Max}_m \left[ L_{d_{C}^k}^m \right] - \text{Min}_m \left[ L_{d_{C}^k}^m \right]} \right] \]
\]

\[
R_k^R = \text{Max}_m \left[ R_{s_{\text{left}}}^m \right]^* \times \left[ \frac{\text{Min}_m \left[ R_{d_{C}^k}^m \right] - \left[ R_{d_{C}^k}^m \right]}{\text{Max}_m \left[ R_{d_{C}^k}^m \right] - \text{Min}_m \left[ R_{d_{C}^k}^m \right]} \right] + \left[ \frac{\text{Max}_m \left[ R_{d_{C}^k}^m \right] - \left[ R_{d_{C}^k}^m \right]}{\text{Max}_m \left[ R_{d_{C}^k}^m \right] - \text{Min}_m \left[ R_{d_{C}^k}^m \right]} \right] \]
\]

Where $[S_k^L, S_k^R]$ and $[R_k^L, R_k^R]$ represent the left and right components of the maximum group utility values and individual regret values, respectively. Further, the performance index function of the design concepts ($Q_k$) can also be obtained in intervals of the left and right scores ($Q_k^{LS}, Q_k^{RS}$) as presented in Equations (23) and (24), respectively.

\[
Q_k^{LS} = v \left[ \frac{S_k^L - S_{LS}^*}{S_{LS}^* - S_{LS}} \right] + (1 - v) \left[ \frac{R_k^L - R_{LS}^*}{R_{LS}^* - R_{LS}} \right] \]
\]

\[
Q_k^{RS} = v \left[ \frac{S_k^R - S_{RS}^*}{S_{RS}^* - S_{RS}} \right] + (1 - v) \left[ \frac{R_k^R - R_{RS}^*}{R_{RS}^* - R_{RS}} \right] \]
Where; $S^L_{Ls} = \min_k S^L_k$, $S^-_{Ls} = \max_k S^L_k$, $S^S_{Rs} = \min_k S^R_k$, $S^-_{Rs} = \max_k S^R_k$, $R^L_{Ls} = \min_k R^L_k$, $R^-_{Ls} = \max_k R^L_k$, $R^S_{Rs} = \min_k R^S_k$, $R^-_{Rs} = \max_k R^S_k$. $\nu$ represents the weight of the strategy for maximum group utility which is usually taken as 0.5, and $1 - \nu$ is the weight of the individual regret for an opponent strategy. The $(Q_k)$ can be obtained from the average of the interval values of the performance index as presented in Equation (25) (Mokhtarian & Hadi-Vencheh, 2012; Wang & Lee, 2009).

$$Q_k = \frac{Q^L_{k} + Q^S_{k}}{2}$$

5. Case study: evaluation of conceptual designs of Reconfigurable Assembly Fixture (RAF)

In order to appraise the performance of the developed MADM model, it will be tested to evaluate four conceptual designs of a RAF (Olabanji, 2015; Olabanji et al., 2016). It is worthwhile to know that due to the computational procedure and classification of associated design features and sub features related to different product, a single case study will be explicitly presented in this article. This procedure can be re-applied for other engineering products in as much as their design features and sub-features are identified. In order to simplify the application of the concept evaluation technique to other case studies, a framework that provides a simple glance of the procedure is presented in Figure 2. Eight design features are identified to extensively describe the RAF with various sub features (Figure 3). Since there are eight design features, it is expected that each design feature will undergo seven comparison. This is why there are seven dotted lines from the design features as presented in Figure 2. Tables 2 to 9 presents the functional link chart for the design features. The shaded portions of the chart in Table 3 to 9 signifies functional links from previous comparison. The number of links are fuzzified and the TFNs for $\left[\tilde{T}_{FL}^d\right]^N$, $\left[\tilde{T}_{FL}^f\right]^N$, and $\left[n\tilde{F}_{FL}\right]^N$ are obtained from Equations (4), (5) and (9), respectively, the normalization was done using Equations (6)–(9).

Further, the weights of the sub features obtained from Tables 2–9 are used in determining the cumulative TFN for the design concepts by applying Equation (11), considering the availability of the sub features in the design concepts. Sub decision matrices are created in each case following Equation (10) as presented in Tables 10–17.

Considering the $\left[\tilde{d}_{C}^E\right]^{K}$ of the design concepts from all the design features in Tables 10–17, a decision matrix can be created alongside the weights of the design features ($W_{d_{FL}}$). By applying Equations (13) and (14), the left and right scores of these TFNs can be obtained and a decision matrix represented by the left and right scores of the $C_{TFN}$ of the design concepts and weights of the design features can be developed by following Equation (15). The fuzzy worst and best scores are also obtained from Equations (16) and (17) in the form of left and right scores component. Further, following Equations (18) to (21), the left and right scores component of the separation measures comprising of the maximum group utility values ($S_k$) and individual regret values ($R_k$) can also be computed for all the design concept as presented in Table 18.

In the same vein, the left and right scores component of the performance index function for each design concepts $(Q_k)$ can be obtained by applying Equations (22) and
(23). The performance indices which is required for ranking the design concepts is obtained from the left and right scores component applying Equation (24) as presented in Table 19.

6. Discussion of results

Consider the value of \( \tilde{T}_{FL}^{dF} \) for functionality when compared with reconfigurability in Table 2 and the value of \( \tilde{T}_{FL}^{dF} \) for reconfigurability when compared with functionality in Table 3, it may be expected that both TFNs will be equal since the two design features under consideration are compared vice-versa. However, the two TFNs are not equal because their number of sub features differs. The difference in number of sub features changes the allocation of functional links which also affects the allocation of TFNs but the total number of functional links in each case did not change. This scenario also occurred in all the comparisons from Tables 3-9. Also, in Tables 8 and 9 where the number of sub features for maintainability is the same as that of assembly and disassembly, the \( \tilde{T}_{FL}^{dF} \) is different because the allocation of the functional links changes thereby giving the two design features different weight. Hence, it can be stated that, the weight of the design features is a function of allocation of functional links between their sub features irrespective of the number of sub features apportioned to the design features. Further, the functional link technique was able to obtain different values for the sub features under the same design feature as seen in Tables 2-9. These values depend on the number of functional links that the sub feature has when compared with sub features of other design features. Also, considering Tables 10-17, it can be deduced that the high availability of a sub feature in a design concept does not denote that the design concept is the optimal design because there is a need to consider the weight of the sub feature and also the high availability of other sub features and their weights in other design concepts. Hence the technique of using design experts view to quantify the availability of sub features in the design concepts has been able to create an extensive result on the performance of each design concepts towards the development of the decision matrix. Converting the TFNs of the decision matrix to left and right scores in Table 18 provided a clearer picture on the positions of the design concepts relative to the fuzzy worst and best values. This improves the integrity in the computational process for determining the maximum group utility values and individual regret values because the left and right scores for the worst and best values cannot be attributed to a particular design concept because of the ties in values as observed in Table 18. Finally, the performance indices obtained from the left and right scores of the maximum group utility and individual regret values proved that identification of optimal design concept is possible and it is also necessary to consider that all other design concepts cannot have zero performance. In essence, the selection process showed the strengths and weaknesses of the design concepts considering the importance of the design features and sub features in the optimal design.
7. Comparison with other methods

In order to examine and ascertain the performance of the decision model, it is necessary to compare the results obtained with the results of other methods that have been applied to the design of the RAF as presented in Table 20. These methods are; Weighted Decision Matrix (WDM), Analytic Hierarchy Process (AHP), Fuzzified Weighted Decision Matrix
(FWDM) Hybridized Fuzzy Analytical Hierarchy Process (FAHP) and Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS) and Hybridized FWDM and FTOPSIS.
### Table 2. Functional link matrix for weight of functionality and its sub features.

| Sub Features | FU = 4 | SE = 4 | EN = 4 | MA = 4 | LC = 4 | MN = 4 | AD = 4 |
|--------------|--------|--------|--------|--------|--------|--------|--------|
| CW           | CW = 4 | T, CU, CO | CW = 4 | T, CU, CO | CW = 4 | T, CU, CO | CW = 4 | NC, TA, TD, DC |
| SW           | SW = 3 | IT, CU, CO | SW = 3 | IT, CU, CO | SW = 3 | IT, CU, CO | SW = 3 | NC, AL, AA, DC |
| AF           | AF = 4 | MO, UC, SC | AF = 4 | MO, UC, SC | AF = 4 | MO, UC, SC | AF = 4 | NC, AC AA |
| DW           | DW = 4 | MO, UC, SC | DW = 4 | MO, UC, SC | DW = 4 | MO, UC, SC | DW = 4 | DC |
| ML           | ML = 3 | MO, UC, CO | ML = 3 | MO, UC, CO | ML = 3 | MO, UC, CO | ML = 3 | AC, DC |
| SL           | SL = 5 | MO, UC, SC | SL = 5 | MO, UC, SC | SL = 5 | MO, UC, SC | SL = 5 | 2 |
| PA           | PA = 2 | IT, DT | PA = 2 | IT, DT | PA = 2 | IT, DT | PA = 2 | AC, DC |

### Table 3. Functional link matrix for weight of reconfigurability and its sub features.

| Sub Features | RE = 4 | FU = 4 | SE = 4 | EN = 4 | MA = 4 | LC = 4 | MN = 4 | AD = 4 |
|--------------|--------|--------|--------|--------|--------|--------|--------|--------|
| MO           | MO = 4 | AF, DW, ML, SL | MO = 4 | AF, DW, ML, SL | MO = 4 | AF, DW, ML, SL | MO = 4 | NC, AC, TA, TD, DC |
| IT           | IT = 5 | CW, SW, DW, SL, PA | IT = 5 | CW, SW, DW, SL, PA | IT = 6 | CW, SW, DW, SL, PA | IT = 5 | AC, DC |
| CU           | CU = 5 | CW, SW, AF, ML, SL | CU = 5 | CW, SW, AF, ML, SL | CU = 5 | CW, SW, AF, ML, SL | CU = 5 | NC, TA, TD, DC |
| CO           | CO = 5 | CW, SW, AF, DW, ML | CO = 5 | CW, SW, AF, DW, ML | CO = 5 | CW, SW, AF, DW, ML | CO = 5 | AC, AA |
| SC           | SC = 4 | CW, SW, AF, DW, SL | SC = 4 | CW, SW, AF, DW, SL | SC = 4 | CW, SW, AF, DW, SL | SC = 5 | NC, AC, TA, TD, DC |
| DT           | DT = 2 | SL, PA | DT = 2 | SL, PA | DT = 2 | SL, PA | DT = 2 | AC, AA |

### Matrix Representations

For Table 2:
$$T_{F_{2}}^{N} = \begin{bmatrix} 3 & 5 & 9 & 11 \\ 6 & 9 & 12 & 14 \\ 9 & 12 & 15 & 18 \\ 11 & 14 & 18 & 21 \end{bmatrix}$$

For Table 3:
$$n_{F_{1}}^{I} = \begin{bmatrix} 3 & 9 & 22 & 39 \\ 6 & 21 & 39 & 58 \\ 9 & 39 & 58 & 87 \\ 12 & 58 & 87 & 116 \end{bmatrix}$$
Table 4. Functional link matrix for weight of serviceability and its sub features.

| Sub Features | SE ⇄ FU | SE ⇄ RE | SE ⇄ EN | SE ⇄ MA | SE ⇄ LC | SE ⇄ MN | SE ⇄ AD | $F_{FL}$ |
|--------------|--------|--------|--------|--------|--------|--------|--------|--------|
| CS | CS = 0 | CS = 1 | CS = 0 | CS = 3 | CS = 5 | CS = 0 | | |
| | IT, CU, DT | AP | DP | DA, RC, SD | RM, MC, LP, MS, RF |
| SP | SP = 7 | SP = 2 | SP = 5 | SP = 3 | SP = 4 | | | |
| | CW, SW, AF, DW, ML, SL, PA | EC, EU | AP, OM, IP, PI | DA, OC, SD | MC, LP, MS, TA, TD, DC |
| LT | LT = 4 | LT = 2 | LT = 1 | LT = 2 | LT = 3 | LT = 3 | | |
| | SW, AF, DW, PA | SH, OM, MT | SR, RC, OC | MC, MF, RF | AC, TA, TD |
| SS | SS = 5 | SS = 2 | SS = 3 | SS = 2 | SS = 5 | | | |
| | MO, CU, CO, SC, DT | EU, SH | OM, MT, IP | RC, OC | MC, LP, AA, TA, DC |
| TS | TS = 5 | TS = 3 | TS = 2 | TS = 3 | TS = 2 | | | |
| | IT, CU, CO, SC, DT | SH, EC, EU | DA, RC, OC | MC, LP, MS | TA, TD |
| FP | FP = 0 | FP = 1 | FP = 2 | FP = 0 | FP = 4 | | | |
| | DT | SH, OM, MT | RC, OC | RM, DM, MF, RF | AC, DC |
| NP | NP = 0 | NP = 1 | NP = 4 | NP = 4 | NP = 2 | | | |
| | MO, IT, CO, SC | PD | OM, MT, IP | DA, SR, OC, SD | MC, LP, TA, TD |
| UL | UL = 5 | UL = 2 | UL = 0 | UL = 1 | UL = 2 | | | |
| | MO, IT, CU, CO, SC | SH, EC | OC | MF, RF | |

Considering the comparison of results with other multicriteria decision model, it is evident that the proposed concept selection technique is viable because of the conformity in the results obtained. Hence, it can be hypothetically stated that the determination of weights of design features and sub features from functional links of sub-features will provide values that can be related to the importance of the design feature in the optimal design. Rather than employing design experts view to assign weight to a design feature or a sub feature, the proposed method can be applied to use the design experts view to indicate the relationships between the sub features which in a way reduce the bias of over scoring a design feature or sub feature. With this method it can be assured that the design feature with the highest value has the highest functional links from its sub-features by virtue of comparing them with sub features of other design features.

In essence, the concept selection technique proposed in this article is useful to design engineers and managers or directors of industries because it provides a holistic approach to consideration of all the design features before deciding on which product to design and fabricate. This technique will also enable design engineers or decision makers in product
Table 5. Functional link matrix for weight of environment and its sub features.

| Features | SH | EC | EU | PD | HE |
|----------|----|----|----|----|----|
| SH = 7  | SH = 2 | SH = 2 | SH = 1 | SH = 3 | SH = 2 |
| CW, SW, AF, DW, ML, SL, PA | IT, DT | LT, SS, TS, FP, UL | MT | OM | OM |
| EC = 2  | EC = 6 | EC = 3 | EC = 1 | EC = 1 | EC = 1 |
| AF, PA | MO, IT, CU, CO, SC, DT | MO, IT, CU, CO, SC, DT | MO, CU, CO, SC, DT | MO, IT, CO, SC | MO |
| EU = 5  | EU = 3 | EU = 2 | EU = 0 | EU = 3 | EU = 3 |
| SW, AF, DW, ML, SL | MO, CU, SC, DT | SP, SS, TS | SP, SS, TS | PD | AP 
| PD = 0  | PD = 1 | PD = 2 | PD = 2 | PD = 3 | PD = 2 |
| HE = 1  | HE = 2 | HE = 0 | HE = 0 | HE = 2 | HE = 1 |
| AF, IT, DT | AP | AP | AP | AP | AP |
| 7/2 | 15/7 | 22/17 | 22/17 | 22/17 | 22/17 |

Table 6. Functional link matrix for weight of manufacturing and its sub features.

| Features | AP | OM | MT | IP | PI | PM |
|----------|----|----|----|----|----|----|
| AP = 0  | AP = 5 | AP = 6 | AP = 6 | AP = 7 | AP = 7 | AP = 3 |
| MO, IT, CU, CO, SC | MO, IT, CU, CO, SC, DT | MO, IT, CU, CO, SC, DT | MO, IT, CU, CO, SC, DT | MO, IT, CU, CO, SC, DT | MO, IT, CU, CO, SC, DT | MO, IT, CU, CO, SC, DT |
| AP = 2 | AP = 2 | AP = 2 | AP = 1 | AP = 1 | AP = 1 | AP = 1 |
| CS, SP | DA, SR, OC, SD | OM = 1 | DA, SR, SD | EU | EC, SR, LP, MF, AL, AC |
| AP = 1 | AP = 0 | AP = 0 | AP = 0 | AP = 0 | AP = 0 | AP = 0 |
| PD | OM = 1 | MT = 1 | IP | PI | PM | PM |
| DA | EC | OM | SH, PD | OC | PM |
| AP | AP | AP | AP | AP | AP | AP |
| 15/9/2 | 15/9/6 | 17/11 | 17/11 | 17/11 | 17/11 | 17/11 |
### Table 7. Functional link matrix for weight of maintainability and its sub features.

| Sub Features | MN $\rightarrow$ RE | MN $\rightarrow$ SE | MN $\rightarrow$ MA | MN $\rightarrow$ LC | MN $\rightarrow$ AD |
|--------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| RM           | RM = 0              | RM = 0              | RM = 0              | RM = 0              | RM = 0              |
|              | RM = 1              | RM = 2              | RM = 2              | RM = 2              | RM = 2              |
| DM           | DM = 0              | DM = 1              | DM = 1              | DM = 1              | DM = 1              |
| MC           | MC = 0              | MC = 4              | MC = 4              | MC = 4              | MC = 4              |
| LP           | LP = 0              | LP = 5              | LP = 5              | LP = 5              | LP = 5              |
| MF           | MF = 0              | MF = 3              | MF = 3              | MF = 3              | MF = 3              |
| MS           | MS = 0              | MS = 6              | MS = 6              | MS = 6              | MS = 6              |
| RF           | RF = 0              | RF = 5              | RF = 5              | RF = 5              | RF = 5              |

For the Functional link matrix, $T_{FL} = \frac{97}{4027} / 8173 / 40$.

### Table 8. Functional link matrix for weight of assembly and disassembly and its sub features.

| Sub Features | AD $\rightarrow$ RE | AD $\rightarrow$ SE | AD $\rightarrow$ MA | AD $\rightarrow$ LC | AD $\rightarrow$ MN |
|--------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| NC           | NC = 3              | NC = 4              | NC = 0              | NC = 0              | NC = 3              |
|              | NC = 3              | NC = 4              | NC = 0              | NC = 0              | NC = 3              |
| AL           | AL = 2              | AL = 1              | AL = 0              | AL = 0              | AL = 0              |
| AC           | AC = 4              | AC = 5              | AC = 3              | AC = 2              | AC = 0              |
| AA           | AA = 2              | AA = 2              | AA = 1              | AA = 1              | AA = 0              |
| TA           | TA = 2              | TA = 4              | TA = 5              | TA = 1              | TA = 1              |
| TD           | TD = 2              | TD = 4              | TD = 5              | TD = 1              | TD = 1              |
| DC           | DC = 6              | DC = 6              | DC = 4              | DC = 2              | DC = 1              |

For the Functional link matrix, $T_{FL} = \frac{17}{30} / 7 / 30$ and $n_{FL} = 22 / 918 / 542 / 9$.
Table 9. Functional link matrix for weight of life cycle cost and its sub features.

| Sub Features | LC ⇀ FU | LC ⇀ RE | LC ⇀ SE | LC ⇀ EN | LC ⇀ MA | LC ⇀ MN | LC ⇀ AD |
|--------------|--------|--------|--------|--------|--------|--------|--------|
| DA           | DA = 0 |        | DA = 4 |        | DA = 0 |        | DA = 0 |
|              | IT, CU, CO, SC, DT |        | CS, SP, TS, NP |        |        |        |        |
| SR           | SR = 0 |        | SR = 2 |        | SR = 1 |        | SR = 3 |
|              | IT, DT |        | LT, NP |        | PD     |        | RM, LP |
| RC           | RC = 0 |        | RC = 4 |        | RC = 1 |        | RC = 2 |
|              | MO, IT, CU, SC |        | CS, LT, SS, TS |        | PD     |        | MF, RF |
| OC           | OC = 3 |        | OC = 5 |        | OC = 2 |        | OC = 2 |
|              | DW, ML, SL |        | MO, IT, CU, CO, SC |        | SH, EC |        | TA, DC |
| SD           | SD = 0 |        | SD = 4 |        | SD = 2 |        | SD = 2 |
|              | MO, CU, SC, DT |        | CS, SP, NP |        | SH, PD |        | MF, RF |

Table 10. Availability of sub features of RE considering their weights.

| Sub-Features | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|--------------|-----------|-----------|-----------|-----------|
|              | DE1 | DE2 | DE3 | DE1 | DE2 | DE3 | DE1 | DE2 | DE3 | DE1 | DE2 | DE3 |
| MO/1/9 1/2/8/9 | HA  | VHA | VHA | LA | LA | MA | VHA | HA | HA | HA | MA | HA |
| IT/2/9 11/181 | MA | HA | MA | MA | LA | MA | HA | VHA | VHA | VHA | HA | MA |
| CU/1/6 5/9 17/18 | HA | MA | MA | MA | MA | MA | VHA | VHA | VHA | HA | VHA | HA |
| CO/1/6 5/9 17/18 | HA | HA | VHA | MA | VLA | MA | HA | MA | MA | HA | HA | MA |
| SC/2/9 11/181 | MA | MA | MA | LA | MA | MA | VHA | VHA | VHA | HA | MA | MA |
| DT/07/18 7/9 | HA | MA | HA | LA | MA | MA | VHA | VHA | VHA | HA | MA | MA |

Table 11. Availability of sub features of FU considering their weights.

| Sub-Features | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|--------------|-----------|-----------|-----------|-----------|
|              | DE1 | DE2 | DE3 | DE1 | DE2 | DE3 | DE1 | DE2 | DE3 | DE1 | DE2 | DE3 |
| CW/1/9 7/18 7/9 | HA | MA | MA | MA | HA | MA | HA | VHA | VHA | HA | MA | HA |
| SW/1/6 4/913/18 | HA | HA | MA | MA | MA | LA | VHA | VHA | VHA | HA | MA | MA |
| AF/1/3 11/8 8/9 | MA | MA | MA | MA | MA | LA | VHA | VHA | VHA | HA | MA | MA |
| DW/1/6 1/2 5/6 | MA | HA | MA | MA | MA | MA | VHA | VHA | VHA | HA | MA | MA |
| ML/1/9 4/97/9 | MA | MA | LA | MA | LA | MA | VHA | VHA | VHA | HA | MA | MA |
| SL/1/32/31 | HA | HA | VHA | MA | MA | MA | VHA | VHA | VHA | HA | MA | MA |
| PA/05/18 5/9 | VHA | HA | MA | MA | MA | VHA | VHA | VHA | HA | MA | HA |

design to consider the contributions of the sub features in obtaining the decision matrix due to a consideration of their availability in the design alternatives. Also, the relative importance of design features in the optimal design obtained from the fuzzified functional links is a guarantee that the design features are not just compared from the direction of cost and benefit characteristics.
Table 12. Availability of sub features of AD considering their weights.

| Sub-Features | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|--------------|-----------|-----------|-----------|-----------|
| DE1          | DE2       | DE3       | DE1       | DE2       | DE3       | DE1       | DE2       | DE3       |
| NC[1/5 3/8 5/9] | VHA HA HA | VLA LA VLA | HA MA HA | MA LA MA | MA HA MA | MA LA MA | MA HA MA | MA LA MA |
| AL[01/72/7]   | MA HA MA  | LA MA MA  | HA VHA VHA| MA MA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA |
| AC[3/8 3/5 4/5] | HA MA HA  | HA MA MA  | VHA HA VHA| HA HA HA | HA HA HA | HA HA HA | HA HA HA | HA HA HA |
| AA[0 1/4 4/9] | VHA HA HA  | HA VHA HA  | MA MA HA | VHA VHA HA| MA MA HA | VHA VHA HA| MA MA HA | VHA VHA HA|
| TA[1/33/55/6] | MA MA HA  | HA HA MA  | HA HA HA | HA HA HA | HA HA HA | HA HA HA | HA HA HA | HA HA HA |
| TD[1/33/55/6] | HA MA MA  | MA MA HA  | HA HA VHA| HA HA HA | HA HA HA | HA HA HA | HA HA HA | HA HA MA |
| DC[1/23/41]  | HA HA HA  | HA HA HA | VHA VHA VHA | MA MA HA | VHA VHA VHA | MA MA HA | VHA VHA VHA | MA MA HA |
| $\delta C_m^k$ | 13/455/741/3 | 329/489/7 | 11/317/2131/9 | 23/7869/5 |

Table 13. Availability of sub features of EN considering their weights.

| Sub-Features | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|--------------|-----------|-----------|-----------|-----------|
| DE1          | DE2       | DE3       | DE1       | DE2       | DE3       | DE1       | DE2       | DE3       |
| SH[1/23/41]  | HA MA HA  | HA HA MA  | HA MA HA | MA HA HA | MA HA HA | MA HA HA | MA HA HA | MA HA HA |
| EC[3/719/2813/14] | HA HA MA | HA HA MA | HA VHA VHA | HA VHA VHA | HA VHA VHA | HA VHA VHA | HA VHA VHA | HA VHA VHA |
| EU[15/283/427/28] | HA HA HA | HA LA MA | HA MA HA | HA MA HA | HA MA HA | HA MA HA | HA MA HA | HA MA HA |
| PD[3/1411/284/7] | HA MA HA | HA MA MA | HA HA VHA| HA HA VHA | HA HA VHA | HA HA VHA | HA HA VHA | HA HA MA |
| HE[01/72/7]  | HA HA MA  | MA MA MA  | MA MA MA | MA MA LA | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| $\delta C_m^k$ | 19/613/297/9 | 25/947/810 | 7/2723/2 | 22/745/743/4 |

Table 14. Availability of sub features of SE considering their weights.

| Sub-Features | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|--------------|-----------|-----------|-----------|-----------|
| DE1          | DE2       | DE3       | DE1       | DE2       | DE3       | DE1       | DE2       | DE3       |
| CS[1/15 1/5 1/3] | MA MA HA  | MA MA LA  | MA MA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA |
| SP[8/15 23/301] | MA HA MA  | LA MA MA  | MA MA MA | MA MA MA | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| LT[4/15 1/2 11/15] | MA HA HA | HA VHA VHA | MA MA MA | MA MA MA | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| SS[2/5 3/5 4/5] | HA HA HA  | VHA HA HA | HA MA HA | HA MA HA | HA MA HA | HA MA HA | HA MA HA | HA MA HA |
| TS[4/15 7/152/3] | MA MA HA | VHA VHA VHA | LA MA MA | MA MA MA | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| FP[01/61/3]  | VHA VHA HA | HA MA HA | MA MA HA | VHA VHA HA | VHA VHA HA | VHA VHA HA | VHA VHA HA | VHA VHA HA |
| NP[4/157/152/3] | MA MA MA | MA MA LA | VHA HA VHA | MA MA MA | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| UL[02/154/15] | HA HA MA  | MA HA HA | HA MA HA | MA MA MA | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| $\delta C_m^k$ | 19/653/727/2 | 13/423/395/7 | 13/423/327/2 | 29/938/527/2 |

Table 15. Availability of sub features of MA considering their weights.

| Sub-Features | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|--------------|-----------|-----------|-----------|-----------|
| DE1          | DE2       | DE3       | DE1       | DE2       | DE3       | DE1       | DE2       | DE3       |
| AP[3/143/79/14] | MA HA HA  | VHA HA VHA | HA HA HA | MA LA MA | MA LA MA | MA LA MA | MA LA MA | MA LA MA |
| OM[2/713/285/7] | HA VHA VHA | VHA VHA VHA | HA VHA VHA | MA MA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA |
| MT[9/281/219/28] | HA HA MA | VHA VHA VHA | MA MA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA |
| IP[13/285/727/28] | HA HA MA | MA MA MA | HA HA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA |
| PI[3/719/281]  | HA MA HA  | VHA VHA VHA | HA HA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA | MA MA HA |
| PM[05/283/7]  | HA HA VHA | VHA VHA VHA | HA HA HA | VHA VHA VHA | HA HA HA | VHA VHA VHA | MA MA HA | VHA VHA VHA |
| $\delta C_m^k$ | 23/736/513 | 18/570/914 | 16/5738/3 | 16/5790/7 |
### Table 16. Availability of sub features of MN considering their weights.

| Sub-Features | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|--------------|-----------|-----------|-----------|-----------|
| RM[2/211/34/7] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| DM[0/2110/21] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| MC[4/213/72/3] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| LP[3/75/71] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| MF[2/74/76/7] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| MS[5/2110/215/7] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| RF[8/212/320/21] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |

\[
\alpha^*_m = 38119/8 \quad 10/371/865/4 \quad 25/874/9121/8 \quad 380/944/3
\]

### Table 17. Availability of sub features of LC considering their weights.

| Sub-Features | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|--------------|-----------|-----------|-----------|-----------|
| DA[1/133/153/13] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| SR[0/265/13] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| RC[0/265/13] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| OC[6/1319/261] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |
| SD[3/264/131/2] | MA MA MA | MA MA MA | MA MA MA | MA MA MA |

\[
\alpha^*_m = 111/329/4 \quad 127/834/5 \quad 4/3454/7 \quad 5/4423/3
\]

### Table 18. Determination of maximum group utility and individual regret values.

| W times | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|---------|-----------|-----------|-----------|-----------|
| L^w | R^w | L^1 | R^1 | L^2 | R^2 | L^3 | R^3 | L^4 | R^4 | F^w | F^w | F^w | F^w |
| RE | 2 | 1 | 1 | 13 | 13 | 3 | 3 | 1 | 1 | 0 | 0 | 0 | 0 |
| FU | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| AD | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| MA | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| MN | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| SE | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| EN | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| LC | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |

Maximum Group Utility Values

\[
S(S_g) = 3 \quad 4 \quad 9 \quad 9
\]

Individual Regret Values

\[
R(R_g) = 7 \quad 7 \quad 7 \quad 7
\]

### Table 19. Performance indices and rank of design alternatives.

| Design Alternatives | Q^*_k | Q^*k | Q_k | Ranking(Q_k Min) |
|---------------------|-------|------|-----|-----------------|
| Concept 1           | 37    | 37   | 37  | 2^{nd}          |
| Concept 2           | 41    | 57   | 64  | 4^{th}          |
| Concept 3           | 0     | 0    | 0   | 1^st            |
| Concept 4           | 85    | 17   | 97  | 3^{rd}          |
Table 20. Comparison of other decision methods for rankings of the RAF.

| Design Concept | Ranking by WDM (Olabanji & Mpofu, 2014) | Ranking by AHP (Olabanji & Mpofu, 2014) | Ranking by FWDM (Olabanji, 2018) | Ranking by Hybridized FAHP-FTOPSIS (Olabanji & Mpofu, 2020c) | Ranking by Hybridized FWDM-FTOPSIS (Olabanji & Mpofu, 2019) | Ranking by proposed Functional Link Matrix and FVIKOR |
|----------------|--------------------------------------|----------------------------------------|-------------------------------|----------------------------------------------------------|----------------------------------------------------------|-------------------------------------------------|
| Concept 1      | 2nd                                  | 3rd                                    | 3rd                           | 3rd                                                      | 3rd                                                      | 2nd                                             |
| Concept 2      | 4th                                  | 4th                                    | 4th                           | 4th                                                      | 4th                                                      | 4th                                             |
| Concept 3      | 1st                                  | 1st                                    | 1st                           | 1st                                                      | 1st                                                      | 1st                                             |
| Concept 4      | 3rd                                  | 2nd                                    | 2nd                           | 2nd                                                      | 2nd                                                      | 3rd                                             |

8. Conclusion

A design concept selection technique is presented in this article. The technique is based on determination of weights of design features and sub features by identifying and fuzzifying functional links of the sub features. A decision matrix is developed from three design experts view and fuzzy VIKOR based on left and right scores is applied to obtain the performance indices of the design alternatives in terms of intervals of fuzzy ratings of the design concepts and weights of the design features. These intervals provided an improved accuracy compared to conventional fuzzy computations which is based on increased number of alpha level sets. In essence the technique will provide an insight on the performance of all the design alternatives based on obtaining information on all the design features and the ability of the sub features in the conceptual designs. Hence, it provides information on the feasibility of a design before product development can commence. The accuracy of the design concept evaluation technique presented in this article can be identified from its ability to distinctively select an optimal concept of a product design from a set of alternatives considering its deviation from the worst and best values from other alternatives. Several types of designed product can be used in as much as they are still at the conceptual design phase and the design features and sub features have been identified from the users or customer requirements. Further, the concept evaluation technique finds more application in engineering design products, or a designed product that will be fabricated. In situations like this the product design is based on identification of design requirements and classification of these requirements into design features and sub-features.

ORCID

Olayinka Olabanji [http://orcid.org/0000-0001-9347-4595](http://orcid.org/0000-0001-9347-4595)
Khumbulani Mpofu [http://orcid.org/0000-0003-3429-7677](http://orcid.org/0000-0003-3429-7677)

References

Akay, D., Kulak, O., & Henson, B. (2011). Conceptual design evaluation using interval type-2 fuzzy information axiom. *Computers in Industry*, 62(2), 138–146. [https://doi.org/10.1016/j.compind.2010.10.007](https://doi.org/10.1016/j.compind.2010.10.007)
Aryanezhad, M. B., Tarokh, M., Mokhtarian, M., & Zaheri, F. (2011). A fuzzy TOPSIS method based on left and right scores. *International Journal of Industrial Engineering and Production Research, 22*(1), 51–62. https://www.iust.ac.ir/iijeen/article-1-274-en.html

Chakraborty, K., Mondal, S., & Mukherjee, K. (2017). Analysis of product design characteristics for remanufacturing using Fuzzy AHP and Axiomatic Design. *Journal of Engineering Design, 28*(5), 338–368. https://doi.org/10.1080/09544828.2017.1316014

Goloğlu, C., & Mizrak, C. (2011). An integrated fuzzy logic approach to customer-oriented product design. *Journal of Engineering Design, 22*(2), 113–127. https://doi.org/10.1080/09544820903032519

Güngör, Z., Delice, E. K., & Kesen, S. E. (2011). New product design using FDMS and FANP under fuzzy environment. *Applied Soft Computing, 11*(4), 3347–3356. https://doi.org/10.1016/j.asoc.2011.01.005

Hambali, A., Sapuan, S., Rahim, A., Ismail, N., & Nukman, Y. (2011). Concurrent decisions on design concept and material using analytical hierarchy process at the conceptual design stage. *Concurrent Engineering, 19*(2), 111–121. https://doi.org/10.1177/1063293X11408138

Kim, Y., & Chung, E.-S. (2013). Fuzzy VIKOR approach for assessing the vulnerability of the water supply to climate change and variability in South Korea. *Applied Mathematical Modelling, 37*(22), 9419–9430. https://doi.org/10.1016/j.apm.2013.04.040

Li, L., & Fan, G. (2014). Research article fuzzy MADM with triangular numbers for project investment model based on left and right scores. *Research Journal of Applied Sciences, Engineering and Technology, 7*(13), 2793–2797. https://doi.org/10.19026/rjaset.7.601

Mokhtarian, M. (2011). A new fuzzy weighted average (FWA) method based on left and right scores: An application for determining a suitable location for a gas oil station. *Computers & Mathematics with Applications, 61*(10), 3136–3145. https://doi.org/10.1016/j.camwa.2011.03.104

Mokhtarian, M., & Hadi-Vencheh, A. (2012). A new fuzzy TOPSIS method based on left and right scores: An application for determining an industrial zone for dairy products factory. *Applied Soft Computing, 12*(8), 2496–2505. https://doi.org/10.1016/j.asoc.2012.03.042

Okudan, G. E., & Tauhid, S. (2008). Concept selection methods–a literature review from 1980 to 2008. *International Journal of Design Engineering, 1*(3), 243–277. https://doi.org/10.1504/IJDE.2008.023764

Olabanji, O., & Mpofu, K. (2020a). Hybridized fuzzy analytic hierarchy process and fuzzy weighted average for identifying optimal design concept. *Heliyon, 6*(1), 1–13. Elsevier. https://doi.org/10.1016/heliyon.2020.e03182

Olabanji, O., & Mpofu, K. (2020b). Pugh matrix and aggregated by extent analysis using trapezoidal fuzzy number for assessing conceptual designs. *Decision Science Letters, 9*(1), 21–36. https://doi.org/10.5267/j.dsl.2019.9.001

Olabanji, O., Mpofu, K., & Battaia, O. (2016). Design, simulation and experimental investigation of a novel reconfigurable assembly fixture for press brakes. *The International Journal of Advanced Manufacturing Technology, 82*(1–4), 663–679. https://doi.org/10.1007/s00170-015-7341-6

Olabanji, O. M. (2015). *Development of a reconfigurable assembly system for the assembly of press brakes*. A doctoral Thesis in the Department of Industrial Engineering, Tshwane University of Technology. https://books.google.com.ng/books?id=5VNDAAQAACAJ

Olabanji, O. M. (2018). Reconnoitering the suitability of fuzzified weighted decision matrix for design process of a reconfigurable assembly fixture. *International Journal of Design Engineering, 8*(1), 38–56. https://doi.org/10.1504/IJDE.2018.096248

Olabanji, O. M., & Mpofu, K. (2014). Comparison of weighted decision matrix, and analytical hierarchy process for CAD design of reconfigurable assembly fixture. *Procedia CIRP, 23*(1), 264–269. https://doi.org/10.1016/j.procir.2014.10.088

Olabanji, O. M., & Mpofu, K. (2019). Decision analysis for optimal design concept: Hybridized fuzzified weighted decision matrix and fuzzy TOPSIS using design for X tools. *Procedia CIRP, 84*(1), 434–441. https://doi.org/10.1016/j.procir.2019.04.323
Olabanji, O. M., & Mpofu, K. (2020c). Adopting hybridized multicriteria decision model as a decision tool in engineering design. *Journal of Engineering, Design and Technology, 18*(2), 451–479. https://doi.org/10.1108/JEDT-06-2019-0150

Opricovic, S. (2011). Fuzzy VIKOR with an application to water resources planning. *Expert Systems with Applications, 38*(10), 12983–12990. https://doi.org/10.1016/j.eswa.2011.04.097

Renzi, C., & Leali, F. (2016). A multicriteria decision-making application to the conceptual design of mechanical components. *Journal of Multi-Criteria Decision Analysis, 23*(3–4), 87–111. https://doi.org/10.1002/mcda.1569

Renzi, C., Leali, F., & Di Angelo, L. (2017). A review on decision-making methods in engineering design for the automotive industry. *Journal of Engineering Design, 28*(2), 118–143. https://doi.org/10.1080/09544828.2016.1274720

Renzi, C., Leali, F., Pellicciari, M., Andrisano, A. O., & Berselli, G. (2015). Selecting alternatives in the conceptual design phase: An application of Fuzzy-AHP and Pugh’s controlled convergence. *International Journal on Interactive Design and Manufacturing (Ijidem), 9*(1), 1–17. https://doi.org/10.1007/s12008-013-0187-y

Shemshadi, A., Shirazi, H., Toreihi, M., & Tarokh, M. J. (2011). A fuzzy VIKOR method for supplier selection based on entropy measure for objective weighting. *Expert Systems with Applications, 38*(10), 12160–12167. https://doi.org/10.1016/j.eswa.2011.03.027

Song, W., Ming, X., & Wu, Z. (2013). An integrated rough number-based approach to design concept evaluation under subjective environments. *Journal of Engineering Design, 24*(5), 320–341. https://doi.org/10.1080/09544828.2012.732994

Tiwari, V., Jain, P. K., & Tandon, P. (2016). Product design concept evaluation using rough sets and VIKOR method. *Advanced Engineering Informatics, 30*(1), 16–25. https://doi.org/10.1016/j.aei.2015.11.005

Tiwari, V., Jain, P. K., & Tandon, P. (2017). A bijective soft set theoretic approach for concept selection in design process. *Journal of Engineering Design, 28*(2), 100–117. https://doi.org/10.1080/09544828.2016.1274718

Wang, J. (2002). Improved engineering design concept selection using fuzzy sets. *International Journal of Computer Integrated Manufacturing, 15*(1), 18–27. https://doi.org/10.1080/0951920110034996

Wang, T.-C., & Lee, H.-D. (2009). Developing a fuzzy TOPSIS approach based on subjective weights and objective weights. *Expert Systems with Applications, 36*(5), 8980–8985. https://doi.org/10.1016/j.eswa.2008.11.035

Yeo, S., Mak, M., & Balon, S. (2004). Analysis of decision-making methodologies for desirability score of conceptual design. *Journal of Engineering Design, 15*(2), 195–208. https://doi.org/10.1080/09544820310001642191

Zavadskas, E. K., Antuchevičienė, J., & Kapliński, O. (2015). Multi-criteria decision making in civil engineering. Part II–applications. *Engineering Structures and Technologies, 7*(4), 151–167. https://doi.org/10.3846/2029882X.2016.1139664

Zhu, G.-N., Hu, J., Qi, J., Gu, -C.-C., & Peng, Y.-H. (2015). An integrated AHP and VIKOR for design concept evaluation based on rough number. *Advanced Engineering Informatics, 29*(3), 408–418. https://doi.org/10.1016/j.aei.2015.01.010