Efficient Extraction of Information from Correlation Matrix for Product Design using an Integrated QFD-DEMATEL Method

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Abstract. Decision of importance rating of technical requirements in House of Quality is very important in the quality function deployment process of product design. The correlation matrix in the roof of House of Quality is seldom used by designers as it is difficult to quantify interactions of technical requirements. Although there are a few studies addressed effects of the correlation matrix of House of Quality, very few of them discussed a systematic evaluation for interactions of technical requirements using information of the roof part in House of Quality. A significant gap exists in the efficient extraction of information from the correlation matrix. This paper introduces a method for analyzing the roof data of House of Quality to extract additional information of correlations between technical requirements based on the decision-making trial and evaluation laboratory, analytic network process, and quality function deployment. A case study of designing a hand rehabilitation device is presented to demonstrate advantages of the proposed method.

1 INTRODUCTION

The global competitive market requires products to meet the high customer satisfaction, low production cost and short product development cycle [16]. Product functions are decided in the design stage. A variety of design concepts can be proposed for the product functions to meet customer requirements (CRs) based on design constraints. Quality Function Deployment (QFD) is an approach for mapping CRs to technical requirements (TRs) and guiding designers to search product solutions. The International Organization for Standardization (ISO) defines QFD in the ISO 16355 standard as a method to assure customer satisfaction by designing products in different levels and perspectives [24]. QFD usually consists of two major processes, extracting voice of customers and transferring TRs to product attributes [17]. The QFD decomposition provides valuable information for product design to convert CRs into a measurable process of implementation of product functions.

House of Quality (HOQ) is an essential mapping tool in QFD for designers to find TRs of design concepts and their importance weights. Using HOQ, relations of CRs and TRs can be identified to analyze their effects [14]. Relationship matrix and correlation matrix are two key parts in HOQ templates. The relationship matrix for TRs and CRs is used to find importance weight of TRs. Moreover, effects of TRs on each other are represented in a correlation matrix which is a triangle-shaped 'roof' of HOQ. As HOQ is applied in a hierarchy structure of QFD, weights of TRs have a big impact on design solutions. Inaccurate data in HOQ can lead to an error propagation into other QFD matrices and undesirable products [18]. A considerable amount of research has been conducted for improving the HOQ template and data analysis. However, most of the existing studies focused on enhancing the relationship matrix in HOQ to find the importance weight of TRs [13]. For example, QFD was integrated with methods of Information Entropy [21], Fuzzy Logic [10, 11], Kano [4], and AHP [23, 26].

A variety of models of the data relationship in HOQ have been suggested. The correlation matrix in the roof of HOQ is seldom used by designers as it is difficult to quantify interactions of TRs [8]. In most of HOQ approaches, designers focus on mapping CRs to related TRs and decide importance weights by relations between CRs and TRs. However, data in the correlation matrix are not considered during this process. As some of TRs may not be mutually exclusive in a design solution, it is necessary to model TR interactions in the design process. Generally, relations in the roof matrix are represented with signs or numbers for the degree of correlations between TRs. However, information based on this representation is not clear enough to provide designers details in considering all of TRs interactions [8]. Some methods, such as the Wasserman normalization for incorporating TRs interactions in determining importance weights, may produce an unacceptable outcome [7]. Another problem in the roof part of HOQ is that the intersection between two TRs shows only their effect degree, we cannot conclude whether they have the same effect on each other. For example, a TR may have a strong effect on another TR, but it doesn't necessarily mean that the reverse is the same.

Most of previous research on the roof part of HOQ focused on solving conflicts between technical details using methods like theory of innovation problem solving (TRIZ) [28] and data envelopment analysis (DEA) [29]. A few studies were applied effects of the correlation matrix with TRs' weights to select TRs. For example, a weighted average method was used to prioritize and rank TRs [20]. But if TRs have an equal strength of correlations, their weights will remain the same. In another research, a method was introduced to search correlations between TRs for importance weights [6]. In this work, by adding all of correlation values located at each intersection of TRs, the average weight was decided by multiplying weights in the relationship matrix to re-prioritize TRs. But this method decides correlation coefficients at the criterion level, not the sub-criterion level. In another study, an improved QFD framework was presented for the service quality management [3]. An integrated QFD-AHP-ANP approach was introduced for analysis of relations and correlations of TRs. In the proposed integrated framework, an analytic hierarchy process (AHP) method was used for analysis of the relationship matrix, and an analytic network process (ANP) was applied for modeling interdependence of TRs in the roof part of HOQ. However, this method was reported time-consuming as it requires many pairwise comparisons in the process. A similar study used the ANP approach for investigating inner dependencies and relations within HOQ to decide overall weights of TRs [2]. A recent study proposed an approach for resolving contradictions of CRs using TRIZ tools and adjusting TRs' weights in HOQ [19]. A side roof was added to a HOQ template for finding contradictions among CRs. Information in the roof part of HOQ was used for TRs re-prioritization. Signs were used to show correlations among TRs, but the impact of differences of correlation values was not investigated. Correlation values were suggested to use instead of conventional signs in the roof part of HOQ. Therefore, it is necessary to quantify whether a TR has more effect than others.

Although there are a few studies addressed effects of the correlation matrix of HOQ on the QFD process, based on our knowledge, none of them provides a systematic method to decide TRs interactions and their influence on each other for design solutions using information of the roof part in HOQ. Moreover, even literature on the prioritization of TRs is vast, a significant gap exists in the efficient extraction of information from the correlation matrix. To improve the above-mentioned

limitations, this paper introduces a method for analyzing the roof data of HOQ to extract additional information of correlations between TRs. The method integrates the decision-making trial and evaluation laboratory (DEMATEL), analytic network process, and QFD to model interrelations of TRs. DEMATEL is used for understanding of the correlation and interdependence of TRs through analysis of TRs in cause and effect relations. The final weight is obtained from an ANP super-matrix. The main contribution of our method is the integration of DEMATEL-based analytic network process with QFD to analyze data in the roof part of HOQ and decide final weights of TRs. Handling correlations in HOQ with DEAMETL to evaluate relations between TRs and establishing direct and indirect causal relationships and influence levels are also novel to the literature. Another contribution of this work is the DEMATEL-based analytic network process to efficiently model interrelations among TRs and remove time-consuming pairwise comparisons.

The following section presents a framework of the proposed method to derive influential weights of TRs. Design of a hand rehabilitation device in the case study verifies the proposed method in Section 3, followed by conclusions and further work in Section 4.

2   PROPOSED METHOD

2.1   Quality Function Deployment (QFD)

QFD is a structured approach to transform qualitative customers' requirements into quantitative product characteristics and map product functions into design concepts. From a technical viewpoint, HOQ as a tool of QFD applies forms of the matrix and table to translate voice of customers into design solutions [12]. A general form of HOQ is shown in Figure 1.
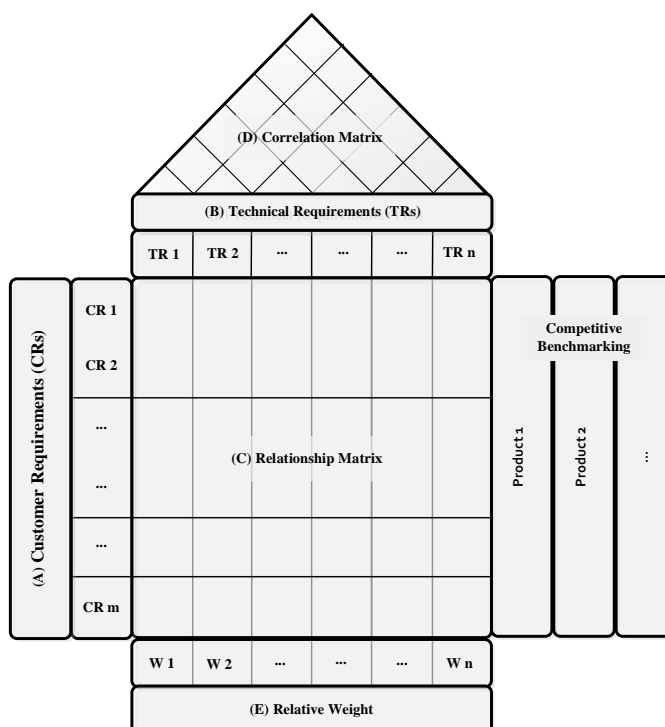
Figure 1: A general form of HOQ.

HOQ provides a tool to establish relationships between CRs (Whats) and TRs (Hows) by a combination of following matrices: (A) Whats matrix, (B) Hows matrix, (C) Central relationship

matrix between WHATs and HOWs, (D) Interrelationship matrix among HOWs, and (E) Matrix of weights of HOWs. In the relationship matrix, a scaling system (such as 1-3-9) is usually employed to represent the degree of strength (weak–medium–strong) between each pair of CRs and TRs [27]. The importance weight of each TR can be obtained from the relationship matrix and CRs weight as follows.

$$W_j = \sum_{i=1}^{m} d_i . R_{ij} \tag{2.1}$$

where d_i signifies the weight of CR_i and $\sum d_i = 1$; R_{ij} is the relation value between TR_j and CR_i and m is the number of CRs. W_j can be normalized for each TR as follows.

$$W_j^n = \frac{W_j}{\sum_{j=1}^{r} W_j} \tag{1.2}$$

where r is the number of TRs. Based on calculated W_j^n, the relative technical importance can be used for prioritization of TRs. Although Equation (2.2) can be used to decide the importance weight of TRs based on the relationship matrix of HOQ, the solution is inaccurate as dependencies among TRs are not considered. In general, in most of HOQ templates, it is assumed that TRs are mutually independent. But this assumption is not practical in real design problems. As a result, the technical correlation matrix (the triangular shaped matrix shown in Figure 1) between each pair of TRs should be taken into account in the calculation of normalized weights of TRs. In the following section, a method is proposed to solve this problem based on combined ANP and DEMATEL.

2.2 Decision Making Trial and Evaluation Laboratory (DEMATEL)

DEMATEL provides a comprehensive process to obtain a structural model of casual relationships among criteria in complex decision-making problems [22]. Comparing with other techniques like AHP, it has advantages such as modeling interdependence between factors via the causal diagram, which is ignored in traditional methods [15]. This research applies the DEMATEL technique to evaluate interdependent relationships between TRs in HOQ and divide them into cause and effect groups.

Figure 2 shows two forms of the correlation matrix in HOQ. In a common HOQ as shown in Figure 1, it is assumed that TRs have the equal effect in intersections of the correlation matrix, which results in a triangular shape of the roof. However, this simplified assumption affects the TRs selection in design. For real-world design problems, a square-shaped form of the roof is suggested for considering unequal mutual interactions. The suggested form is a non-symmetric square matrix that includes design information from both directions of correlations. Data can be collected from users and experts to indicate degrees of the direct effect of TRs on each other in the correlation matrix with a scale range such as from 0 for no effect to 4 for very high effect. An initial matrix A can be formed either by converting the triangular shape correlation matrix into a symmetric square matrix or using a non-symmetric square matrix as follows.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix} \tag{2.3}$$

N is a normalized initial influence-relation matrix which is shaped by normalizing average matrix A.
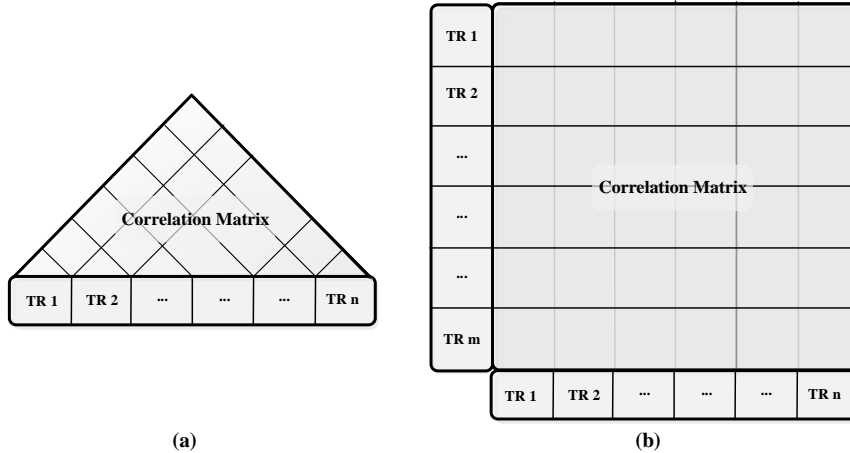
$$N = s \times A, \qquad s > 0 \tag{2.2}$$

or

$$[N_{ij}]_{n\times n} = s[a_{ij}]_{n\times n}, \quad s > 0, \quad i,j\epsilon\{1,2,\dots,n\} \tag{2.3}$$

Where the value s can be obtained as follows.

$$s = \frac{1}{max(\sum_{j=1}^{n} a_{ij}, \sum_{i=1}^{n} a_{ij})} \tag{2.4}$$

$$\lim_{m\to\infty} N^m = [0]_{n\times n}, 0 \le x_{ij} \le 1 \tag{2.5}$$

Figure 2: Two forms of the correlation matrix in HOQ.

The total influence matrix T is an n × n matrix as follows.

$$\begin{aligned}
T &= N + N^2 + \cdots + N^m \\
&= N(I + N + N^2 + \cdots + N^{m-1}) \\
&= N(I + N + N^2 + \cdots + N^{m-1})(I - N)(I - N)^{-1} \\
&= N(I - N)^{-1}, \quad When \lim_{m\to\infty} N^m = [0]_{m\times m}
\end{aligned} \tag{2.6}$$

where I is an $n \times n$ matrix. The sum of columns and rows in total influence matrix T can be characterized as R and C vectors as follows.

$$R = [r_i]_{n\times 1} = \left(\sum_{j=1}^{n} t_{ij}\right)_{n\times 1} \tag{2.7}$$

$$C = [c_j]'_{1\times n} = \left(\sum_{i=1}^{n} t_{ij}\right)'_{1\times n} \tag{2.8}$$

where r_i is a member of vector R, c_j is a member of vector C, and t_{ij} represents each member of total influence matrix T. In the following section, ANP and its process are presented to solve interdependence among TRs generated by the DEMATEL to form a super matrix.

2.3 Analytic Network Process (ANP)

ANP is a decision-making technique to systematically model all kinds of dependence among criteria by considering all relations as networks [9]. We use it to analyze the total influence matrix formed by DEMATEL. TRs with same characteristics in a large HOQ can be grouped into small sized clusters based on similar criteria. For example, we can form a cost sub-matrix including manufacturing cost and operation cost. In small HOQs, each TR can be considered as a separate dimension. Figure 3 shows a detail algorithm of the proposed method. The structure of the total-influenced matrix for sub-criterion T_c is shown below.

Proposed Algorithm
Input: Modified correlation matrix $A_r = [a_{ij}]_{n \times n}, r = 1,2, \dots, N$ (Number of respondents)
Output: Improved weights of TRs

1:     $A_{sum} = A_1$
2:     for $r = 2 \ to \ N$
3:         $A_{sum}(r) = A_{sum} + A_r$
4:     end for
5:     $A = A_{sum}/N$ //Calculating the initial average matrix
6:     for $j = 1 \ to \ n$
7:         $P(j) = sum(a_{ij})$
8:     end for
9:     for $i = 1 \ to \ n$
10:         $Q(i) = sum(a_{ij})$
11:     end for
12:     $N = A/\max(P, Q)$ //Calculating normalized initial average matrix
13:     $T_c = N(I - N)^{-1}$ //Calculating the total influence matrix
14:     for $j = 1 \ to \ n$
15:         $D(j) = sum(t_{ij})$
16:     end for
17:     for $i = 1 \ to \ n$
18:         $R(i) = sum(t_{ij})$
19:     end for
20:     for each $T_c^{ij} \in T_c$
21:         $e_i = \sum_{j=1}^{m} t_{ij}$
22:         $T_c^{norm} = \frac{T_c}{e_i}$ //Calculating normalized total influence-relation matrix
23:     end
24:     $Q = (T_c^{norm})'$ //Obtaining unweighted super matrix
25:     for each $T_c^{ij} \in T_c$
26:         $d_i = \frac{\sum_{i=1}^{m} \sum_{j=1}^{m} t_{ij}}{m \times m}$
27:     end
28:     Construct total influence-relation matrix T_D of criteria
29:     Calculate normalized total influence-relation matrix T_D^{norm}
30:     $W = T_D^{norm} \times Q$ //Calculating weighted super matrix
31:     $While \ \varepsilon < defined \ accuracy$ //Calculating weighted super matrix
32:     $Q = (T_c^{norm})'$ //Obtaining unweighted super matrix
33:     $Influential \ weights = \lim_{\alpha \to \infty}(W)^{\alpha}$ //Obtaining unweighted super matrix
34:     end

Figure 3: Proposed algorithm for calculating influential weights of TRs.

$$T_c = \begin{array}{cc} & \begin{array}{ccccc} D_1 & \dots & D_j & \dots & D_n \end{array} \\ \begin{array}{c} \\ c_{11} \\ \vdots \\ D_1 \quad c_{1m_1} \\ \vdots \\ \vdots \quad c_{i1} \\ \vdots \\ D_i \quad c_{im_i} \\ \vdots \\ \vdots \quad c_{n1} \\ \vdots \\ D_n \quad c_{nm_n} \end{array} & \begin{array}{c} \begin{array}{ccccc} c_{11} \dots c_{1m_1} & \dots & c_{i1} \dots c_{im_i} & \dots & c_{n1} \dots c_{nm_n} \end{array} \\ \begin{bmatrix} T_c^{11} & \dots & T_c^{1j} & \dots & T_c^{1n} \\ \vdots & & \vdots & & \vdots \\ T_c^{i1} & \dots & T_c^{ij} & \dots & T_c^{in} \\ \vdots & & \vdots & & \vdots \\ T_c^{n1} & \dots & T_c^{nj} & \dots & T_c^{nn} \end{bmatrix} \end{array} \end{array} \qquad (2.9)$$

where D_n symbolizes the nth criterion; C_{nm} represents the mth sub-criterion in the nth criterion. In order to use this matrix to decide the inner dependency, it should be first normalized and then transposed. Each sub-criterion can be normalized as follows.

$$d_{ci}^{11} = \sum_{j=1}^{m_1} t_{ij}^{11}, \qquad i = 1,2,\dots m_1 \qquad (2.10)$$

$$T_c^{norm\,11} = \begin{bmatrix} \dfrac{t_{c_{11}}^{11}}{d_{c_1}^{11}} & \dots & \dfrac{t_{c_{1j}}^{11}}{d_{c_1}^{11}} & \dots & \dfrac{t_{c_{1m_1}}^{11}}{d_{c_1}^{11}} \\ \\ \vdots & & \vdots & & \vdots \\ \\ \dfrac{t_{c_{i1}}^{11}}{d_{c_i}^{11}} & \dots & \dfrac{t_{c_{ij}}^{11}}{d_{c_i}^{11}} & \dots & \dfrac{t_{c_{im_1}}^{11}}{d_{c_i}^{11}} \\ \\ \vdots & & \vdots & & \vdots \\ \\ \dfrac{t_{c_{m_11}}^{11}}{d_{c_{m_1}}^{11}} & \dots & \dfrac{t_{c_{m_1j}}^{11}}{d_{c_{m_1}}^{11}} & \dots & \dfrac{t_{c_{m_1m_1}}^{11}}{d_{c_{m_1}}^{11}} \end{bmatrix} \qquad (2.11)$$

After normalizing matrix T_c, a new matrix is obtained as Equation (2.14).

$$T_c^{norm} = \begin{array}{cc} & \begin{array}{ccccc} D_1 & \dots & D_j & \dots & D_n \end{array} \\ \begin{array}{c} \\ c_{11} \\ \vdots \\ D_1 \quad c_{1m_1} \\ \vdots \\ \vdots \quad c_{i1} \\ \vdots \\ D_i \quad c_{im_i} \\ \vdots \\ \vdots \quad c_{n1} \\ \vdots \\ D_n \quad c_{nm_n} \end{array} & \begin{array}{c} \begin{array}{ccccc} c_{11} \dots c_{1m_1} & \dots & c_{i1} \dots c_{im_i} & \dots & c_{n1} \dots c_{nm_n} \end{array} \\ \begin{bmatrix} T_c^{norm\,11} & \dots & T_c^{norm\,1j} & \dots & T_c^{norm\,1n} \\ \vdots & & \vdots & & \vdots \\ T_c^{norm\,i1} & \dots & T_c^{norm\,ij} & \dots & T_c^{norm\,in} \\ \vdots & & \vdots & & \vdots \\ T_c^{norm\,n1} & \dots & T_c^{norm\,nj} & \dots & T_c^{norm\,nn} \end{bmatrix} \end{array} \end{array} \qquad (2.12)$$

Unweighted super matrix Q is a transpose of normalized total influence-relation matrix T_c^{norm} .

$$Q = (T_c^{norm})'$$
(2.13)

The weighted super matrix is calculated by multiplying the normalized total influence-relation matrix of dimensions T_D^{norm} and unweighted super matrix as follows.

$$W = T_D^{norm} \times Q$$
(2.14)

The weighted super matrix is then limited to a large power α until it converges in a stable super-matrix. Influential weights are then used in HOQ to obtain the final weight of TRs.

$$Influential\ weights = \lim_{\alpha \to \infty} (W)^\alpha$$
(2.15)

3 CASE STUDY

3.1 Design of a Hand Rehabilitation Device

Design of rehabilitation devices is a complex decision-making process as different assumptions and constraints have to be considered. In this case study, CRs and their weights were collected from literature [5]. Figure 4 shows a HOQ of the design problem. Its left column shows CRs with their weights. In order to meet these requirements and quantify quality characteristics of design concepts, 13 TRs were identified based on benchmarking products [1, 25]. The relationship matrix in the HOQ provides relations of CRs and TRs. Only this matrix is used to decide importance weights of TRs in the traditional HOQ template. However, there may be some TRs with close correlations to affect each other for the design solution. For example, the deriving method has a big impact on the device noise and motion velocity of the structure. It is not enough to decide TRs' weights based on TRs interactions with CRs only. It is therefore necessary to find interrelations of TRs using the correlation matrix in the roof of HOQ.

3.2 TRs Weights based on Different Roof Shapes

Two scenarios are investigated to compare with the traditional HOQ method. The first one uses the triangular shape roof of HOQ as shown in Figure 4 to form a symmetric initial correlation matrix. The second uses a square asymmetric correlation matrix as shown in Table 1. After normalizing the initial data, total-influenced matrix T_c can be formed using Equation (2.11) for both cases. In matrix Tc, D and R are calculated by adding elements of each row and column in the matrix, respectively. Elements of each row (D) are added for each TR to find its effectiveness on other TRs. Elements of each column (R) are added for each TR to find the total effects (both direct and indirect) received from other factors, or effectiveness of variables. These parameters show effects of TRs on each other. Figure 5 shows prominence-causal relations of TRs obtained by the total influence-relation matrix Tc for both cases, where the horizontal vector (D+R) is amount of TR interactions. In other words, it shows amount of TR interactions and a central role of each TR. The vertical vector (D-R) indicates the effect power of each TR. Therefore, a positive (D-R) shows the causal parameter, otherwise, the parameter receives influence from other TRs. For the first scenario, as the initial matrix is symmetric, all of D-R values are zero, meaning that TRs have the same effect on each other. The horizontal axis however shows important TRs. For the second scenario, it can be concluded that the structure type has a big impact on other TRs, motion velocities and structure size have effects from other TRs.
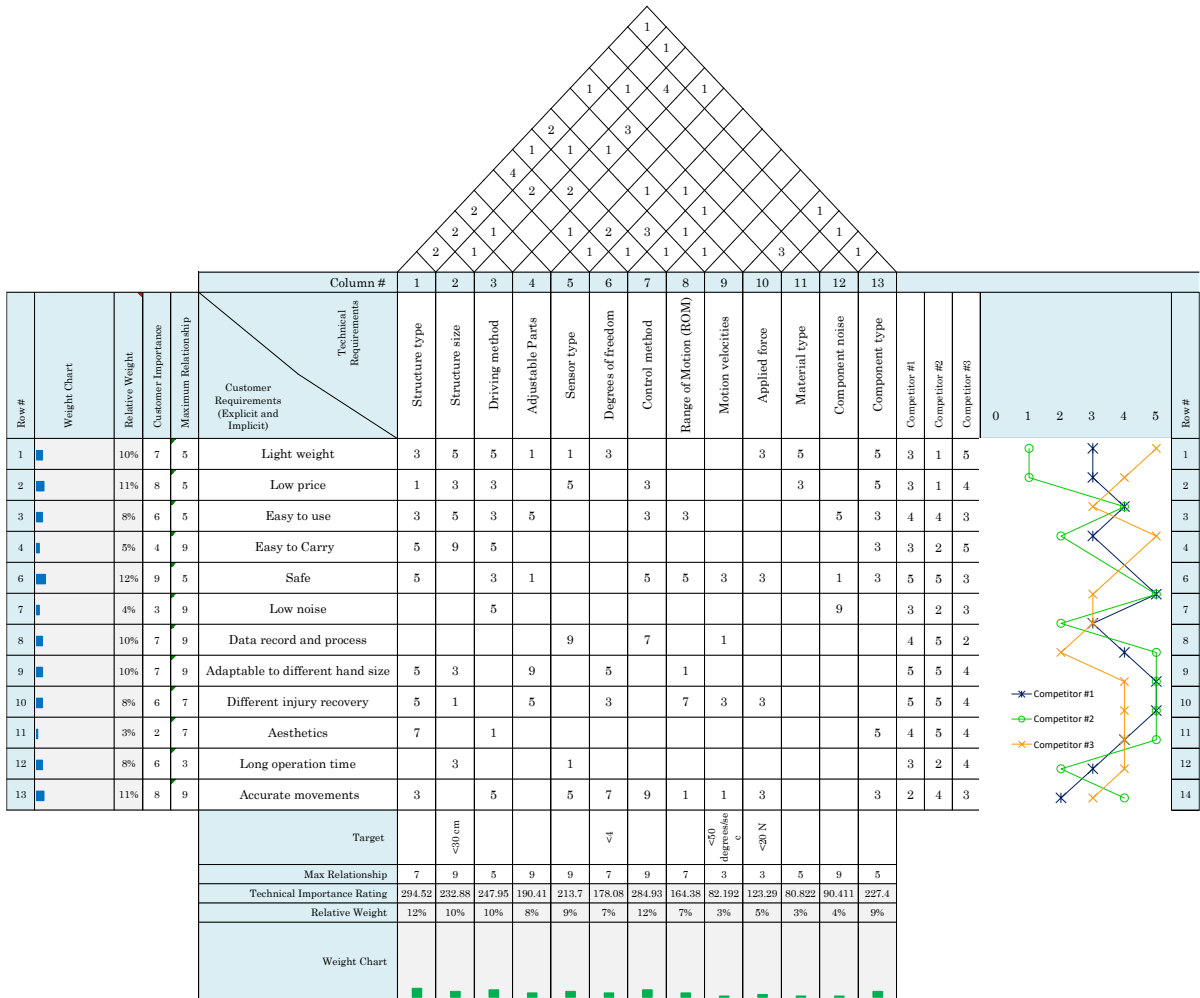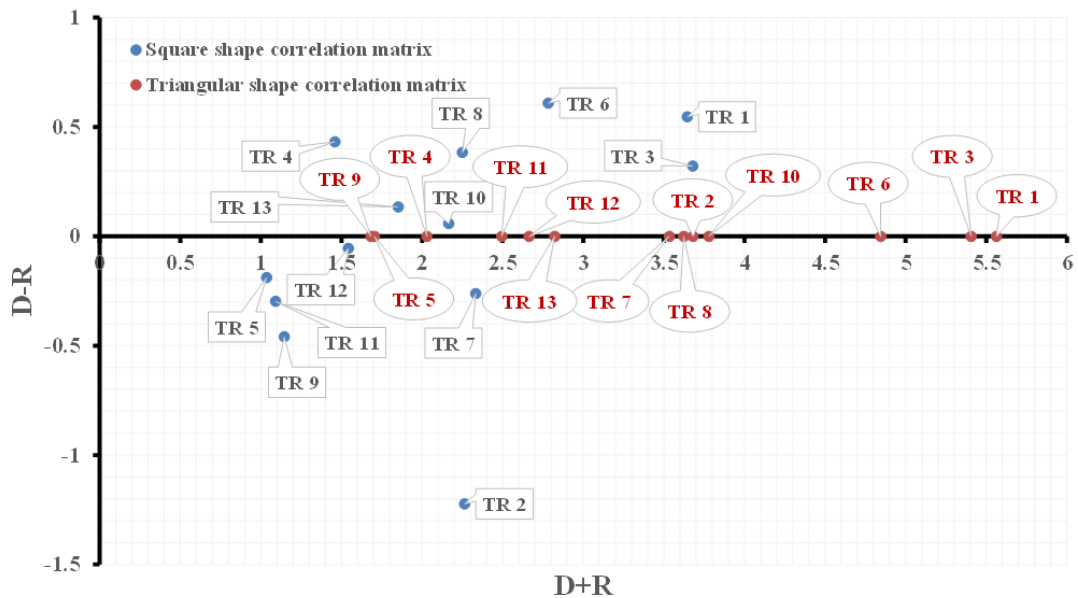
Row #	Relative Weight	Customer Importance	Maximum Relationship	Customer Requirements (Explicit and Implicit)	Structure type	Structure size	Driving method	Adjustable Parts	Sensor type	Degrees of freedom	Control method	Range of Motion (ROM)	Motion velocities	Applied force	Material type	Component noise	Component type	Competitor #1	Competitor #2	Competitor #3	Row #
Column #					1	2	3	4	5	6	7	8	9	10	11	12	13				
1	10%	7	5	Light weight	3	5	5	1	1	3				3	5		5	3	1	5	1
2	11%	8	5	Low price	1	3	3		5		3				3		5	3	1	4	2
3	8%	6	5	Easy to use	3	5	3	5			3	3				5	3	4	4	3	3
4	5%	4	9	Easy to Carry	5	9	5										3	3	2	5	4
6	12%	9	5	Safe	5		3	1		5	5	3	3		1		3	5	5	3	6
7	4%	3	9	Low noise			5									9		3	2	3	7
8	10%	7	9	Data record and process					9		7		1					4	5	2	8
9	10%	7	9	Adaptable to different hand size	5	3		9		5		1						5	5	4	9
10	8%	6	7	Different injury recovery	5	1		5		3		7	3	3				5	5	4	10
11	3%	2	7	Aesthetics	7		1										5	4	5	4	11
12	8%	6	3	Long operation time		3			1									3	2	4	12
13	11%	8	9	Accurate movements	3		5		5	7	9	1	1	3			3	2	4	3	14
Target						<30 cm				▽			<50 degrees/sec	<30 N							
Max Relationship					7	9	5	9	9	7	9	7	3	3	5	9	5				
Technical Importance Rating					294.52	232.88	247.95	190.41	213.7	178.08	284.93	164.38	82.192	123.29	80.822	90.411	227.4				
Relative Weight					12%	10%	10%	8%	9%	7%	12%	7%	3%	5%	3%	4%	9%				

Figure 4: HOQ based on known CRs and TRs of hand rehabilitation devices.

3.3   Discussions and Results

The unweighted super matrix Equation (2.15) was formed by normalizing and processing total-influenced matrix T_c. Tables 2 and 3 show the unweighted super matrix for scenarios one and two. The influential weights are converged after four iterations (Equation (2.17)) for a stable matrix of TR weights. By using the proposed method, we can extract more information from correlations in the roof matrix and re-rank final weights of TRs. Table 4 compares TR weights based on the proposed method using the roof and the traditional approach without using the roof information. The result shows that some TRs' weights have changed compared to those generated by the traditional method. Attentions should be paid to these changes in design. For example, in scenario one, the weight of deriving method is increased to indicate its impact on other TRs like motion velocities, and the reduced weight of sensor type shows its weak interactions with other TRs. Although using the triangular shape correlation matrix can improve weighting methods based on the proposed method, the result obtained by the square shape correlation matrix is closer to reality as interactions of TRs correlations can be fully considered in two directions.

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13
Row #	Structure type	Structure size	Driving method	Adjustable Parts	Sensor type	Degrees of freedom	Control method	Range of Motion (ROM)	Applied velocities	Applied force	Material type	Component noise	Component type
1 Structure type	0	0.15	0.1	0.05	0	0.2	0.05	0.15	0.05	0.05	0	0	0.05
2 Structure size	0	0	0.1	0.05	0.05	0	0	0	0	0	0	0	0
3 Driving method	0.1	0	0	0	0	0	0.15	0.05	0.1	0.15	0.05	0.2	0.1
4 Adjustable Parts	0.15	0.1	0	0	0	0.05	0	0	0	0	0	0	0.05
5 Sensor type	0.1	0.05	0	0	0	0	0.15	0	0	0	0	0	0
6 Degrees of freedom	0.2	0.15	0	0.05	0.1	0	0.05	0.1	0	0.05	0	0	0
7 Control method	0.1	0	0.1	0	0.05	0	0	0.05	0.1	0.1	0	0	0.05
8 Range of Motion (ROM)	0.15	0.1	0.05	0	0	0.15	0.05	0	0.05	0	0	0	0
9 Applied velocities	0	0	0.05	0	0.05	0	0	0	0	0	0	0.05	0
10 Applied force	0.1	0	0.1	0	0	0.05	0.05	0	0	0	0.15	0	0.05
11 Material type	0	0.1	0	0	0	0	0	0	0	0.05	0	0	0.05
12 Component noise	0	0	0.2	0	0	0	0	0	0	0	0.05	0	0
13 Component type	0.1	0.15	0	0.05	0	0	0.05	0	0	0	0.05	0.05	0

Table 1: Normalized square shaped correlation matrix.

Figure 5: DEMATEL prominence-causal relationship of TRs.

Column #	1 Structure type	2 Structure size	3 Driving method	4 Adjustable Parts	5 Sensor type	6 Degrees of freedom	7 Control method	8 Range of Motion (ROM)	9 Applied velocities	10 Applied force	11 Material type	12 Component noise	13 Component type
1 Structure type	0.10088	0.2075	0.12884	0.28199	0.20827	0.22451	0.16526	0.23564	0.07896	0.15297	0.07368	0.06312	0.17593
2 Structure size	0.10649	0.05735	0.0659	0.12772	0.1115	0.11933	0.04814	0.09462	0.03424	0.04756	0.10124	0.03502	0.09561
3 Driving method	0.08405	0.08377	0.07375	0.04906	0.05145	0.0502	0.13151	0.08458	0.16074	0.17605	0.14526	0.33131	0.11156
4 Adjustable Parts	0.08879	0.07836	0.02368	0.05082	0.03753	0.07176	0.02979	0.04236	0.01448	0.02803	0.01958	0.0147	0.08263
5 Sensor type	0.06807	0.07101	0.02578	0.03896	0.04469	0.068	0.11229	0.04017	0.12768	0.02602	0.01572	0.01553	0.02908
6 Degrees of freedom	0.13906	0.14402	0.04766	0.14116	0.12885	0.0793	0.09783	0.17936	0.04699	0.08659	0.03825	0.02379	0.05597
7 Control method	0.08106	0.046	0.09889	0.0464	0.16851	0.07747	0.05122	0.08409	0.14667	0.08438	0.0383	0.0476	0.08983
8 Range of Motion (ROM)	0.13021	0.10188	0.07164	0.07433	0.06791	0.16001	0.09473	0.07477	0.13876	0.0498	0.02951	0.03459	0.04931
9 Applied velocities	0.01591	0.01344	0.04965	0.00927	0.07871	0.01529	0.06025	0.0506	0.02951	0.01566	0.0139	0.09246	0.01486
10 Applied force	0.07566	0.04584	0.13349	0.04404	0.03938	0.06915	0.08509	0.04458	0.03844	0.06391	0.25864	0.06683	0.09882
11 Material type	0.02109	0.05648	0.06375	0.01781	0.01377	0.01768	0.02235	0.01529	0.01975	0.1497	0.05153	0.10257	0.07851
12 Component noise	0.01848	0.01997	0.14868	0.01367	0.01391	0.01124	0.02841	0.01833	0.13433	0.03955	0.10488	0.06771	0.07681
13 Component type	0.07024	0.07438	0.06828	0.10478	0.03552	0.03608	0.07312	0.03563	0.02944	0.07977	0.1095	0.10476	0.04107

Table 2: Unweighted super matrix of the device of scenario one.

| Column #	1 Structure type	2 Structure size	3 Driving method	4 Adjustable Parts	5 Sensor type	6 Degrees of freedom	7 Control method	8 Range of Motion (ROM)	9 Applied velocities	10 Applied force	11 Material type	12 Component noise	13 Component type
1 Structure type	0.10192	0.27207	0.12953	0.2859	0.31041	0.2149	0.17368	0.20878	0.05912	0.1706	0.09049	0.065	0.19899
2 Structure size	0.14196	0.06365	0.04854	0.20918	0.17908	0.15531	0.05239	0.12502	0.02726	0.06495	0.34152	0.03278	0.23931
3 Driving method	0.09819	0.1777	0.06387	0.05238	0.06222	0.05135	0.14929	0.07891	0.2558	0.14276	0.05596	0.42431	0.06089
4 Adjustable Parts	0.05999	0.09079	0.0215	0.03582	0.0303	0.06496	0.02323	0.08967	0.00836	0.02201	0.02817	0.01115	0.08777
5 Sensor type	0.0237	0.07743	0.01181	0.02167	0.02036	0.07825	0.06569	0.02468	0.20456	0.01487	0.01793	0.00619	0.01807
6 Degrees of freedom	0.15325	0.05965	0.04054	0.12731	0.06344	0.06297	0.04624	0.14292	0.01614	0.09069	0.0262	0.02029	0.04395
7 Control method	0.06139	0.03339	0.06153	0.03126	0.14632	0.06607	0.03345	0.08997	0.02796	0.07987	0.02383	0.03035	0.08209
8 Range of Motion (ROM)	0.16426	0.07149	0.1039	0.07454	0.07359	0.17809	0.10307	0.06894	0.03502	0.05877	0.0251	0.05084	0.04899
9 Applied velocities	0.05898	0.03488	0.09217	0.02509	0.03644	0.03358	0.13622	0.09157	0.02903	0.03056	0.01251	0.04483	0.02429
10 Applied force	0.05378	0.03805	0.12171	0.02547	0.02978	0.05235	0.08269	0.02863	0.03739	0.03925	0.16324	0.06322	0.02417
11 Material type	0.01368	0.01491	0.06184	0.00961	0.00798	0.01002	0.02126	0.00863	0.02669	0.17264	0.03043	0.12867	0.07226
12 Component noise	0.02082	0.03247	0.15355	0.01346	0.01302	0.01084	0.03385	0.01798	0.24471	0.02859	0.01684	0.07458	0.07475
13 Component type	0.04805	0.03353	0.0895	0.08833	0.02705	0.02129	0.07895	0.02431	0.02796	0.08444	0.16779	0.04779	0.02446

Table 3: Unweighted super matrix of the device of scenario two.

The modified weights can help designers to choose components and subsystems in a more accurate way in decision-making of the conceptual design. These weights can be used in a sequence of HOQs during the QFD process. For example, for selecting a structure type of the rehabilitation device, designers usually consider factors like the range of motion (ROM), degree of freedom (DOF), component size, etc. These factors can guide designers to select the right structure according to TRs weights. Figure 6 shows three different structure solutions based on different weights using the traditional HOQ, triangle-shaped correlation matrix, and square-shaped correlation matrix, respectively.

In results of using the traditional HOQ, weights of structure type and ROM of finger bones lead to a light finger structure as illustrated in Figure 6 (a). In Scenario 1 (Figure 6 (b)), the weight of ROM is increased for a heavier finger structure with more ROM. As weights of ROM and structure type are highest in Scenario 2, the device structure is improved to meet these requirements (Figure 6 (c)). Compared to structures in Figures 6 (a) and (b), this finger structure can cover more ROM, however, it increases the weight of structure. In all of three cases shown in Figure 6, weights of DOF are very close. Therefore, all finger structure concepts have only one DOF. The finger structure is one of the components in hand rehabilitation devices and there are other components like actuator, motion sensors, etc. to be decided. The selection procedure should be processed similarly using HOQ to map TRs into component levels and the final concept in a QFD process. The final concept of a hand rehabilitation device with electromagnetic actuators according to TRs weights from the square asymmetric correlation matrix is shown in Figure 7.

	TR 1: Structure type	TR 2: Structure size	TR 3: Driving method	TR 4: Adjustable Parts	TR 5: Sensor type	TR 6: Degrees of freedom	TR 7: Control method	TR 8: Range of Motion (ROM)	TR 9: Motion velocities	TR 10: Applied force	TR 11: Material type	TR 12: Component noise	TR 13: Component type
Traditional HOQ	0.12216	0.09659	0.10284	0.07898	0.08864	0.07386	0.11818	0.06818	0.03409	0.05114	0.03352	0.0375	0.09432
Scenario 1 (triangle shape correlation matrix)	0.14642	0.08738	0.11593	0.06194	0.06682	0.08963	0.09439	0.07621	0.03245	0.06224	0.03828	0.04091	0.07601
Scenario 2 (square shape correlation matrix)	0.14757	0.1083	0.11465	0.06406	0.06316	0.07816	0.08517	0.08207	0.04436	0.05576	0.03694	0.04678	0.07302

Table 4: TRs weights based on the proposed method and traditional approach.
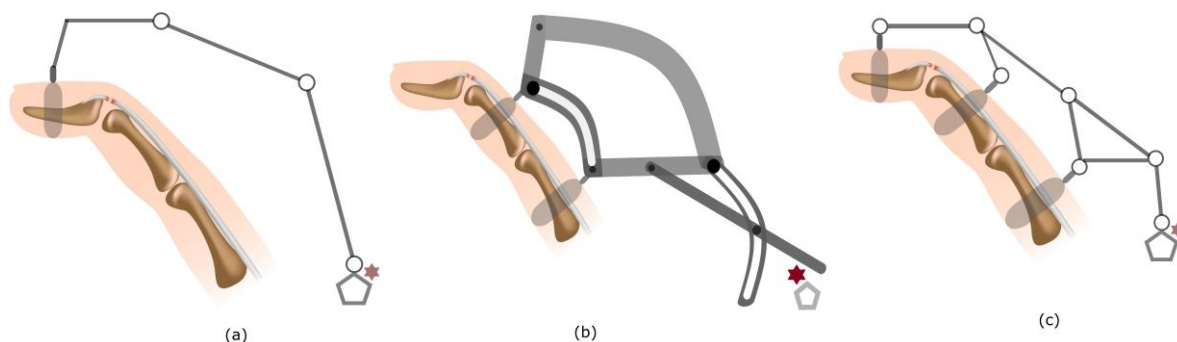
Figure 6: Different structures based on solutions of weights. a) traditional HOQ. b) triangle-shaped correlation matrix. c) square-shaped correlation matrix.

Figure 7: The hand rehabilitation device based on the proposed method using the square asymmetric correlation matrix.

4   CONCLUSIONS

The prioritization of TRs is vital in the QFD process to maximize CRs for a competitive product. This paper introduced an integrated approach of DEMATEL, ANP, and QFD methods for modeling TRs correlations in HOQ to decide TR's weights in product design. It is identified that TRs interactions cannot be fully considered using the triangular shape correlation matrix in the traditional HOQ. A square roof of the HOQ template is recommended. The proposed method can model the influence and interdependence among TRs, which is neglected in the traditional QFD methods. One advantage of the proposed method is that it doesn't need the lengthy data process of pairwise comparisons. The method provides a systematic tool for analyzing interrelations among TRs via prominence-causal relationships. The case study of design for a hand rehabilitation device verified the proposed method. It shows that the importance weights of TRs can be updated by considering correlations among the TRs in the roof part of HOQ. The proposed method can be easily adjusted to solve other design problems where there are correlations among TRs. In this study, CRs were assumed uncorrelated each other and they were mutually independent. The impact of correlations of CRs will be a subject for the future research. It is also recommended to use correlation values instead of conventional signs in HOQ templates.

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REFERENCES

[1] Aggogeri, F.; Mikolajczyk, T.; O'Kane, J.: Robotics for rehabilitation of hand movement in stroke survivors, Advances in Mechanical Engineering, 11(4), 2019, 1–14. https://doi.org/10.1177/1687814019841921.

[2] Aghdam, M.M.; Mahdavi, I.; shirazi, B.; Vahidi, J.: House of quality improvement by new design requirements generation,International Conference on Industrial Engineering and Operations Management (IEOM), 2015, 1-9, https://doi.org/10.1109/IEOM.2015.7093821

[3] Andronikidis, A.: The application of quality function deployment in service quality management, The TQM Journal, 21(4), 2009, 319-333. https://doi.org/10.1108/17542730910965047.

[4] Avikal, S.; Singh, R.; Rashmi, R.: QFD and Fuzzy Kano model based approach for classification of aesthetic attributes of SUV car profile, Journal of Intelligent Manufacturing, 31(2), 2020, 271-284. https://doi.org/10.1007/s10845-018-1444-5.

[5] Boser, Q.A.; Dawson, M.R.; Schofield, J.S.; Dziwenko, G.; Hebert, J.S.: Defining the design requirements for an assistive powered hand exoskeleton, bioRxiv, 2018. https://doi.org/10.1101/492124.

[6] Chavoshi, F.; Shahin, A.: Does correlation matrix influence prioritisation of the results of house of quality? The case of a manufacturing company, International Journal of Productivity and Quality Management, 21(2), 2017, 174-186. https://dx.doi.org/10.1504/IJPQM.2017.083769.

[7] Chen, L.-H.; Chen, C.-N.: Normalisation models for prioritising design requirements for quality function deployment processes, International Journal of Production Research, 52(2), 2014, 299-313. https://doi.org/10.1080/00207543.2013.812813

[8] Iqbal, Z.; Grigg, N.P.; Govindaraju, K.; Campbell-Allen, N.M.: A distance-based methodology for increased extraction of information from the roof matrices in QFD studies, International Journal of Production Research, 54(11), 2016, 3277-3293. https://doi.org/10.1080/00207543.2015.1094585.

[9] Kheybari, S.; Rezaie, F.M.; Farazmand, H.: Analytic network process: An overview of applications, Applied Mathematics and Computation, 367, 2020, 124780. https://doi.org/10.1016/j.amc.2019.124780.

[10] Kutlu Gündoğdu, F.; Kahraman, C.: A novel spherical fuzzy QFD method and its application to the linear delta robot technology development, Engineering Applications of Artificial Intelligence, 87, 2020, 103348. https://doi.org/10.1016/j.engappai.2019.103348.

[11] Li, S.; Tang, D.; Wang, Q.: Rating engineering characteristics in open design using a probabilistic language method based on fuzzy QFD, Computers & Industrial Engineering, 135, 2019, 348-358. https://doi.org/10.1016/j.cie.2019.06.008.

[12] Lin, T.; Ekanayake, A.; Gaweshan, L.S.; Hasan, Z.A.: Ergonomics product development of over bed table for bedridden patients, Computer-Aided Design and Applications, 13(4), 2016, 538-548. http://dx.doi.org/10.1080/16864360.2015.1131550.

[13] Liu, Y.; Han, Y.; Zhou, J.; Chen, Y.; Zhong, S.: Establishing the relationship matrix in QFD based on fuzzy regression models with optimized h values, Soft Computing, 22(17), 2018, 5603-5615. https://doi.org/10.1007/s00500-017-2533-7.

[14] Maritan, D.: Practical Manual of Quality Function Deployment, Springer International Publishing, Switzerland 2014.

[15] Mentes, A.; Akyildiz, H.; Helvacioglu, I.H.: A Grey Based Dematel Technıque for Rısk Assessment of Cargo Shıps,7th International Conference on Model Transformation ICMT, 2014,

[16] Mingshun, Y.; Ting, Y.; Yanjie, L.; Yubo, Z.: Rating the Customer Requirements based on DEMATEL and Entropy, International Journal of Online Engineering, 9, 2013.

[17] Ozlem Erdil, N.; M. Arani, O.: Quality function deployment: more than a design tool, International Journal of Quality and Service Sciences, 11(2), 2019, 142-166. https://doi.org/10.1108/IJQSS-02-2018-0008

[18] Raharjo, H.: On normalizing the relationship matrix in quality function deployment, International Journal of Quality & Reliability Management, 30(6), 2013, 647-661. https://doi.org/10.1108/02656711311325601

[19] Shahin, A.; Bagheri Iraj, E.; Vaez Shahrestani, H.: Developing House of Quality by integrating top roof and side roof matrices and service TRIZ with a case study in banking services, The TQM Journal, 28(4), 2016, 597-612. https://doi.org/10.1108/TQM-10-2012-0075.

[20] Sharma, J.; Rawani, A.: Ranking engineering characteristics in Quality Function Deployment by factoring-in the roof values, International Journal of Productivity and Quality Management, 3(2), 2008, 223-240. https://dx.doi.org/10.1504/IJPQM.2008.016566.

[21] Shi, Y.; Peng, Q.; Zhang, J.: An Objective Weighting Method of Function Requirements for Product Design Using Information Entropy, Computer-Aided Design and Applications, 17(5), 2019, 966-978. https://doi.org/10.14733/cadaps.2020.966-978.

[22] Si, S.-L.; You, X.-Y.; Liu, H.-C.; Zhang, P.: DEMATEL technique: A systematic review of the state-of-the-art literature on methodologies and applications, Mathematical Problems in Engineering, 2018, 2018. https://doi.org/10.1155/2018/3696457.

[23] Song, B.; Peng, Q.; Zhang, J.; Gu, P.: A Fuzzy Number based Hierarchy Analytic Method and Application in Improvement of Rehabilitation Devices, Computer-Aided Design and Applications, 16(2), 2019, 369-381. https://doi.org/10.14733/cadaps.2019.369-381.

[24] Standardization, I.O.f.: Application of statistical and related methods to new technology and product development process — Part 1: General principles and perspectives of Quality Function Deployment (QFD), ISO 16355-1:2015, Switzerland, 2015.

[25] Suarez-Escobar, M.; Gallego-Sanchez, J.A.; Rendon-Velez, E.: Mechanisms for linkage-driven underactuated hand exoskeletons: conceptual design including anatomical and mechanical specifications, International Journal on Interactive Design and Manufacturing (IJIDeM), 11(1), 2017, 55-75. https://doi.org/10.1007/s12008-015-0297-9

[26] Yazdani, M.; Chatterjee, P.; Ebadi Torkayesh, A.: An Integrated AHP-QFD-Based Compromise Ranking Model for Sustainable Supplier Selection, Handbook of Research on Interdisciplinary Approaches to Decision Making for Sustainable Supply Chains, IGI Global, Hershey, PA, USA, 2020, pp. 32-54.

[27] Zare Mehrjerdi, Y.: Quality function deployment and its extensions, International Journal of Quality & Reliability Management, 27(6), 2010, 616-640. https://doi.org/10.1108/02656711011054524

[28] Zhang, F.; Yang, M.; Liu, W.: Using integrated quality function deployment and theory of innovation problem solving approach for ergonomic product design, Computers & Industrial Engineering, 76, 2014, 60-74. https://doi.org/10.1016/j.cie.2014.07.019.

[29] Zheng, H.; Zhang, H.; Zhang, F.: An innovative design of energy-saving products based on QFD/TRIZ/DEA integration,IEEE 17Th International Conference on Industrial Engineering and Engineering Management, 2010, 831-834, https://doi.org/10.1109/ICIEEM.2010.5646494