Title:
An Objective Weighting Method of Function Requirements for Product Design Using Information Entropy

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Introduction:
Product design plays an important role in the product development to meet requirements of the product function, cost and lifecycle [5]. Quality function deployment (QFD) and benchmarking methods are commonly used in the product design process. QFD transforms customers' requirements into product function requirements, and then search product concepts considering the design priority [4]. The benchmarking method compares different product details to take existing products' advantages in the design solution. By comparing different products' performances in the market, the best design solution from benchmarking products can be adapted in the product design, which can reduce cost and improve quality of design solutions. House of Quality (HoQ) is an analytic tool of the QFD method to transform customer requirements (CRs) into function requirements (FRs) and design specifications [2]. Using HoQ, weights of FRs can be decided with different scores of relationships of FRs and CRs. Based on weights of FRs, design alternatives of structures and parameters are evaluated and selected in the conceptual search process using HoQ. However, the existing methods of weighting FRs in QFD are subjective and inaccurate because the traditional weighting process uses subjective ranking methods, such as using 9 marks for the most important, 3 for moderation and 1 for weak, to assign weights to FRs. Weighting FRs relies on customers' comments and experts' experience, which generates the subjective solution [3]. Some products such as rehabilitation devices and medical equipment are used to meet specific requirements of patients. It is very difficult to find enough information in the survey to define CRs and importance rates of CRs accurately, which will affect the solution of weighting FRs [1]. In addition, users may not be able to fully provide their needs to a product, especially for some new products.

For weighting FRs accurately, a benchmarking method can be used for adjusting weights of FRs. If all the benchmarking products provide similar functions, the weight of a FR should be increased. All the benchmarking products with a same function means that this function is attractive and necessary. The weight of a FR should be decreased if this function is rare in the benchmarking products as this function seems less important. To improve the accuracy and objectivity of weighting methods for FRs, an objective weighting method of FRs is therefore proposed in this research based on the information entropy theory in the evaluation of benchmarking products for FRs. The weighting FRs from the information entropy can adjust the initial weight for a final weight of FRs to eliminate subjectivity of the weighting solution. An upper limb rehabilitation device is designed in the case study based on weights of FRs using the proposed method. Products designed by the proposed FR weights and traditional FR weights are compared to verify the proposed method.

Main Idea:

Proposed weighting method

Raw data includes CRs, FRs, and importance rate (IR) of CRs from survey and literature. Initial weights of FRs are decided using HoQ and analytic hierarchy process (AHP) methods. The information entropy and benchmarking method are integrated to improve the accuracy and objectiveness of initial weighting solutions. The initial weights and objective weights of FRs are then combined using the least square method to obtain the final weights of FRs.

Initial weights of FRs by the AHP method

Initial weights of FRs are defined by pairwise comparisons using the AHP method. Based on each CR, a pairwise comparison matrix ***A*** is built to compare importance between all FRs to meet a CR in Eqn. (1). Where matrix ***A*** is $m \times m$ sized, m is the number of FRs. a_{jk} is an entry in the j row and k column of ***A***.

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix} \tag{1}$$

Once matrix ***A*** is built, it is normalized as a pairwise comparison matrix $\boldsymbol{A}_{\text{norm}}$ by making equal to 1 for the sum of entries in each column using Eqn. (2).

$$\bar{a}_{jk} = a_{jk} \Big/ \sum_{l=1}^{m} a_{jk} \tag{2}$$

Based on the i_{th} CR, a weight vector c_{ij} is formed by the average of entries in each row of $\boldsymbol{A}_{\text{norm}}$, which represents importance of FRs to meet the i_{th} CR in Eqn. (3).

$$c_{ij} = \sum_{l=1}^{m} a_{jk} \Big/ m \tag{3}$$

After passing a consistent test, the importance result of FRs for meeting each CR can be calculated one by one using the same process for n times. The absolute weights of FRs can then be calculated by Eqn. (4). Where f_j is the absolute weight of each FR, c_{ij} is the value of relations between CRs and FRs, d_i is importance of the i_{th} CR.

$$f_j = \sum_{i=1}^{n} c_{ij}\, d_i \tag{4}$$

r_j is normalized for a subjective weight of each FR as follows.

$$r_j = f_j \Big/ \sum_{i=1}^{m} f_j \tag{5}$$

Results of initial weights of FRs are then obtained as shown in Eqn. (6).

$$\mathbf{r} = (\mathrm{r}_1, r_2, \cdots, r_m)^{\mathrm{T}} \tag{6}$$

Objective weights of FRs using information entropy

For comparing performance of benchmarking products to meet FRs, matrix ***X*** is built as Eqn. (7). Where t is the number of benchmarking products selected in the market. Parameters and performances for implementing m FRs in t selected benchmarking products can then be determined.

$$\mathbf{X} = (x_{ij})_{m \times t} = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1t} \\ x_{21} & x_{22} & \cdots & x_{2t} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mt} \end{pmatrix} \tag{7}$$

Based on matrix ***X***, the information entropy of FRs is calculated using Eqns. (8) and (9). The value of information entropy E_i can be calculated using Eqn. (8) to define the difference of parameters and performances between t selected benchmarking products.

$$E_i = -K \sum_{j=1}^{t} P_{ij} \ln P_{ij}, \;\; K = 1/\ln t \tag{8}$$

Where, a probability function P_{ij} is determined by parameters in Eqn. (9) as follows.

$$P_{ij} = x_{ij} \Big/ \sum_{j=1}^{t} x_{ij} \tag{9}$$

For comparing data with different dimensions, results of objective weights of FRs in Eqn. (8) are transferred into interval from 0 to 1 for normalization using Eqn. (10).

$$k_i = \frac{E_i - \min_{-1\le i\le n}\{E_i\}}{\max_{1\le i\le n}\{E_i\} - \min_{1\le i\le n}\{E_i\}} \quad (i = 1, 2, \ldots, m) \tag{10}$$

Results of objective weights of FRs are then obtained as shown in Eqn. (11).

$$\mathbf{k} = (k_1, k_2, \cdots, k_m)^{\mathrm{T}} \tag{11}$$

Final weights by adjusting the initial weights

Using AHP and HoQ methods, comments of experts are considered to define initial weights of FRs in Eqn. (6). Considering objective factors, objective weights of FRs are defined using Eqn. (11). Initial weights of FRs are adjusted by objective weights to define final weights of FRs using the least square method based on Eqns. (12) and (13).

$$\min F(u) = \sum_{i=1}^{t}\sum_{j=1}^{m}\left\{\left[\left(r_j - w_j\right)s_{ij}\right]^2 + \left[\left(k_j - w_j\right)s_{ij}\right]^2\right\} \tag{12}$$

$$\mathbf{S} = (s_{ij})_{t\times m} = \mathbf{X}^{\mathrm{T}}, \sum_{j=1}^{m} w_j = 1, \ w_j \ge 0 \ \ (\mathrm{j} = 1, 2, \cdots \mathrm{m}) \tag{13}$$

Final weights of FRs are shown in Eqn. (14) for product design.

$$\mathbf{w} = (w_1, w_2, \cdots, w_m)^{\mathrm{T}} \tag{14}$$

Based on the final weights of FRs, the design priority can be decided accurately from benchmarking products for the best function component.

Case study:

A case study is conducted to verify the proposed objective weighting method of FRs. An upper limb rehabilitation device is designed for recovery of patients' injured joints. Relations between FRs and CRs for design of an upper limb rehabilitation device are shown in Tab. 1. The existing weighting methods can only consider opinion of experts, which cannot provide accurate weights of FRs for rehabilitation device. The proposed weighting method is used to improve the accuracy and objectiveness of weighting FRs.

CRs	IR	FR.1	FR.2	FR.3	FR.4	FR.5	FR.6	FR.7	FR.8	FR.9	FR.10
1. Accurate movement	5	0.31	0.09	0	0.10	0	0.10	0	0.04	0.05	0.31
2. Movement feedback	3	0.35	0.07	0.26	0	0	0	0	0.10	0.05	0.17
3. Automatic	5	0.23	0.10	0.13	0.05	0	0.20	0.05	0.12	0.08	0.04
4. Support the arm	4	0.06	0	0	0.14	0	0.49	0.10	0	0.05	0.16
5. Easy operation	3	0.15	0.02	0	0.27	0	0.15	0	0.38	0	0.03
6. Interesting	2	0	0	0.51	0	0	0.15	0.10	0.11	0	0.13
7. Light weight	4	0	0	0	0.06	0.06	0.12	0.33	0.38	0	0.05
8. Reasonable price	5	0.07	0.03	0.05	0.16	0.02	0.03	0.23	0.33	0.01	0.08
9. Adaptability	3	0.02	0.01	0.05	0.39	0	0.08	0.25	0.05	0.02	0.14
10. Portability	5	0	0	0	0.06	0	0	0.61	0.15	0.05	0.06
11. Safety	3	0.05	0.02	0	0.12	0	0.02	0.15	0.14	0.33	0.17
12. Material	4	0	0	0	0.03	0.53	0	0.24	0.16	0.01	0.03
Absolute weights by AHP		5.01	1.47	2.85	5.11	2.44	5.15	8.83	7.59	2.39	5.20

Tab. 1: CRs, FRs, IRs and weights.

Initial weights of FRs are defined using the AHP method. For correlations of FRs and CRs, the 10 FRs are compared each other using Eqns. (1-3) to obtain the initial weights of FRs in Tab. 1. The 10 FRs in Tab. 1 to meet CRs include sensor selection FR.1, motor selection FR.2, interactive function FR.3, adjustable height and length FR.4, suitable material FR.5, flexible movement structure FR.6, portable design FR.7, lightweight design FR.8, displacement limit FR.9, and degree of freedom design FR.10. These FRs are shown in the first row of Tab. 1. Each row shows the related FR weight to meet a CR. IR of a CR is shown in the second column. Absolute weights from the AHP method are defined by sum of multiplying IR of CRs and weights of FRs using Eqn. (4) as shown in the last row.

Using Eqn. (5) and (6), initial weights of FRs can be normalized and defined in Eqn. (15).

$$\mathbf{r} = (0.109, 0.032, 0.062, 0.111, 0.053, 0.112, 0.192, 0.165, 0.052, 0.113)^{T} \tag{15}$$

Four popular rehabilitation devices in the market are selected for benchmarking. Parameters and performance for meeting the 10 FRs in the four selected devices are determined. Results are normalized and used to create matrix ***X*** as Eqn. (16) using Eqn. (7). When values are close to each other in a row in Eqn. (16), design solutions are similar to meet the FR in the four benchmarks.

$$\mathbf{X}_{\text{norm}} = (x_{ij})_{m\times t} = \begin{pmatrix} 0.313 & 0.250 & 0.125 & 0.313 \\ 0.313 & 0.313 & 0.125 & 0.250 \\ 0.111 & 0.222 & 0.445 & 0.222 \\ 0.266 & 0.236 & 0.232 & 0.266 \\ 0.182 & 0.091 & 0.273 & 0.455 \\ 0.266 & 0.333 & 0.200 & 0.200 \\ 0.285 & 0.143 & 0.429 & 0.143 \\ 0.387 & 0.237 & 0.054 & 0.323 \\ 0.265 & 0.220 & 0.265 & 0.250 \\ 0.278 & 0.278 & 0.167 & 0.278 \end{pmatrix} \tag{16}$$

Using Eqns. (8-11), objective weights of FRs using information entropy can be decided as follows.

$$\mathbf{k} = (0.117, 0.117, 0.048, 0.175, 0.011, 0.151, 0.053, 0.000, 0.175, 0.156)^{T} \tag{17}$$

Using Eqns. (12) and (13), final weights of FRs are defined in Eqn. (18).

$$\mathbf{w} = (0.113, 0.073, 0.053, 0.135, 0.033, 0.125, 0.121, 0.081, 0.123, 0.143)^{T} \tag{18}$$

Design priorities from the traditional and proposed methods are listed in Tab. 2.

FRs	FR1	FR2	FR3	FR4	FR5	FR6	FR7	FR8	FR9	FR10
Weight by traditional method (r)	6	10	7	5	8	4	1	2	9	3
Weight by proposed method (w)	6	8	9	2	10	3	5	7	4	1
Difference	0	+2	-2	+3	-2	+1	-4	-5	+5	+2

Tab. 2: Design priorities based on traditional and proposed methods.

Based on the final weights of FRs, the design priority of a rehabilitation device can be decided accurately. The priority is then used to design sequence to meet the FR in product design.

Design result and evaluation of the proposed method

For comparison, two rehabilitation devices are designed based on weights of proposed and traditional methods respectively as shown in Figs. 1 and 2. The device in Fig. 1 has a better performance in rehabilitation for many FRs including adjustment height, adjustment length, degree of freedom and flexible movement structure, which can meet requirements for most users in rehabilitation to improve the competitiveness of the product in the market. The device by the proposed weighting method has a large adjustment ranges which can be used for both adults and children. However, the device in Fig. 2 can only be used for adults. The device in Fig. 1 has 5 motors for the passive exercise of serious patients. As limitations in degrees of the freedom and flexible movement structure, the device in Fig. 2 cannot be used for serious injured patients.

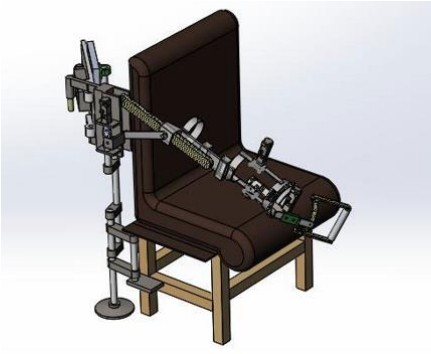

Fig. 1: Design solution by proposed method.

Fig. 2: Design solution by traditional method.

Comparing devices in Figs. 1 and 2, the only advantage of the design by the traditional weighting method is that the device can meet the portable requirement. However, the function of portability may not be very useful for most of patients if they complete the rehabilitation in hospitals and therapy centers. The device designed based on the traditional weighting method cannot meet requirements of most of patients as function performances in benchmarking products are ignored in weighting FRs. Therefore, the proposed weighting method can improve the design solution using improved weights of FRs in product design.

Conclusions:

This paper presented an objective weighting method for FRs using the information entropy, least square and benchmarking methods. The similarity of functions in benchmarking products is considered to adjust weights of FRs, which can improve the accuracy and objectiveness of weighting FRs. Design of rehabilitation devices in the case study verified advantages of the proposed method compared to solutions from the traditional weighting method.

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