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Determining Optimal Design Specification in the House of Quality

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ABSTRACT

House of Quality (HOQ) that is the first matrix of Quality Function Deployment (QFD), has been broadly used to establish the technical targets of the engineering characteristics. However, there are some methodological shortcomings in the HOQ, regarding of the relationship ratings between customer requirements and engineering characteristics, and the absent of a formal procedure to determine the design specifications. Thus, this paper proposes a formal HOQ procedure to determine the technical targets of engineering characteristics. The swing method and a certain normalization technique to involve the correlations between engineering characteristics are used to obtain better relationships ratings. An optimization model was developed to maximize customer satisfaction, subject to available organizational resource. An example of a wooden dining chair design is presented to illustrate the procedure.

1. INTRODUCTION

QFD is a structured method to translate the voice of customer into a final product through various stages of development and production [1]. QFD has proven to be useful to support product developer to meet the customers' needs by determining on the most paramount part of engineering characteristics development [2, 3]. After the initiation by Akao [4], QFD is now extensively utilized around the world as the basic tools to identify the customers' requirements [3, 5].

In the beginning of the QFD initiation, engineering characteristics were frequently justified by the engineer expert judgement. The result from this process repeatedly given subjective opinion and diverse among experts' judgement [2, 6]. Recently, benchmarks are utilized to measure the engineering characteristics [1]; however, this method have not quantitatively specified the procedure to determine the relationship between customers' requirements and engineering characteristics. Therefore, an optimization model to translate the relationship between customers' needs and engineering characteristics are required.

The method begins by identifying the customer's requirements (CRs) and translating those requirements into engineering characteristics (ECs), and subsequently into part characteristics, process plans and production requirements. Each translation process is carried out using a matrix to convert the input (WHATs) into output (HOWs) [7, 8]. This paper is focused on the first translation matrix, called HOQ. HOQ is considered fundamental in the QFD process, since it largely affects the later translation process. Thus, this paper is focused on several main parts of HOQ.

There are several methodological flaws in the conventional HOQ. The conventional HOQ has no explicit justification in choosing rating series (e.g. 1-3-4 or 1-5-9) to express the relationship between customer requirements and technical requirements [9]. Moreover, the relationship rating in HOQ – which are measured on interval scale (even on ordinal scale) – are usually treated as of measured on ratio or proportional scale [10]. The relationship ratings are employed in later computation to obtain the EC priorities. The computation involves mathematical operations that should use measurements data on ratio scale. Inappropriate rating scale that is utilized in mathematical operation may lead to wrong prioritization of the ECs [10].

Several researches have been developed mathematical model to solve those methodological problems. [11] and [12] proposed mathematical model that involved the resource constraints and method to set the relationship ratings between ECs and ECs. An integrated QFD with stochastic has been developed by [13]. Further, a new approach for engineering characteristics prioritization has been developed by [14, 15]. Then, a study from [16] extended the integrated approach determine ECs prioritization in QFD. Likewise, [17] develop the prioritization model by combining QFD model and fuzzy ANP to determine the weight for ECs. The sophisticated model using fuzzy theory have been developed by Kang and Nagasawa [18], Lim and Chin [19] , Aydin et al. [20] , Xing et al. [21]and Liu et al.[22] However, those research still leave the weakness about the absent of formal decision model to assist the design team in prioritizing and/or setting technical target of the ECs, with the aim of maximizing customer satisfaction, and subject to organizational resource constraints. The extant research so far still heuristically converts the CRs into design specifications. Furthermore, the effect of dependencies among ECs was not properly accounted when prioritizing the ECs. In summary, this paper addresses those issues by modifying the traditional HOQ technique and developing a comprehensive mathematical model to derive the target of the ECs.

2. THE PROPOSED MODEL

The proposed HOQ technique was developed based on Erdil and Arani [23] and Park and Kim [12], instead of determining the optimal EC set to be considered in the design, the aim of the proposed technique is to establish the optimal specifications. The procedure incorporates a method to elicit the utility weights in multi-attribute decision problems, i.e. swing method to assess the magnitudes of relationships between CRs and ECs. The weight of 0 represents the extremely irrelevant EC (so that can be regarded as no relationship with the concerned CR), while the value of 100 is assigned the most related EC [24–26]. Weights of the other ECs are defined proportional to that obtained by the most related EC. Then, the relationship rating between CR_i and EC_j (i.e. R_{ij}) is obtained b normalizing the weights, so that. $\sum_{j=1}^{n} R_{ij} = 1$ for all i.

The obtained rating shows a continuum of rating values specifying the sliding magnitude of relationship, not only represent the order of strength (weak – medium – strong). Thus, those ratings are considered more meaningful. Afterward, the relationship ratings are normalized using equation 1 to accommodate the dependencies between ECs.

$$R_{i,j}^{norm} = \frac{\sum_{k=1}^{n} R_{i,k}\cdot\gamma_{k,j}}{\sum_{j=1}^{n}\sum_{k=1}^{n} R_{i,j}\cdot\gamma_{j,k}} \quad ; \qquad \gamma_{j,k} = \gamma_{k,j} \tag{1}$$

where:
$R_{i,j}^{norm}$ = normalized rating between CR_i and EC_j
R_{ij} = relationship rating between CR_i and EC_j
$\gamma_{j,k}$ = dependency rating between EC_j and EC_k

The new HOQ technique is presented in Figure 1.

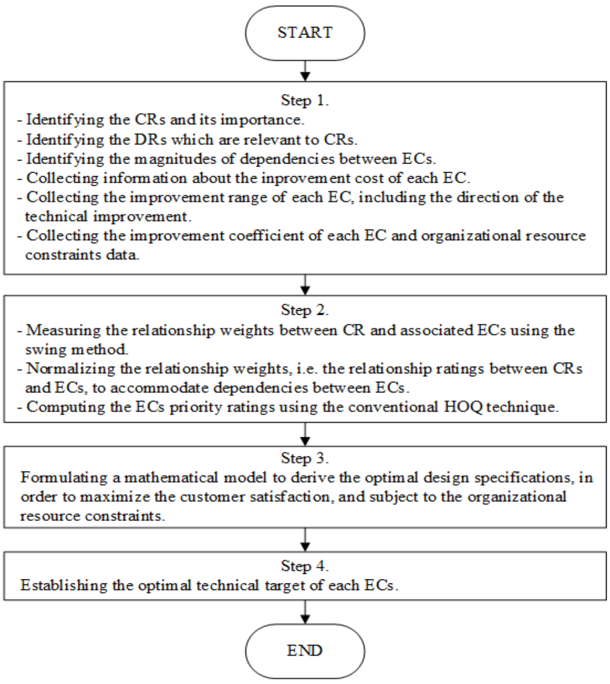


Figure 1. The proposed HOQ technique

The proposed technique begins by identifying the CRs as the main input for HOQ (step 1). There are three methods which are commonly used for gathering the CRs: interviews, focus groups and observing the product in use [27]. For most products, fifty interviews are possibly to many, but ten interviews are possibly not enough to reveal most of the CRs. As a practical guideline, for a product, thirty interviews might reveal 90 per cent of CRs, whereas 2 hours focus group uncover nearly the same number of CRs as two 1-hour interviews [28].

Then a survey is conducted to assess the importance rating of each CR. For CR_i, i =1 to m, the weighted average of importance ratings are computed using Equation 2.

$$d_i^{average} = \frac{\sum_{n=1}^{p} Q'.n'}{Q} \tag{2}$$

where:
$d_i^{average}$ = the importance rating's weighted average for CR_i
Q' = number of respondents at rating n' (a p' point scale rating is used)
Q = total number of respondents

For the purpose of optimization model, $d_i^{average}$ is normalized, so that the sum of $d_i^{average}$ for all CR_i is equal to one (see Equation 3).

$$d_i^{average} = \frac{\sum_{n=1}^{p} Q'.n'}{Q} \tag{3}$$

D_i = the normalized importance of the CR_i

After the CRs are identified, the associated EC_j, j = 1 to n, are generated, as technical metrics of CRs, and the magnitudes of dependencies between ECs are assessed. All of the correlation values between EC_j and EC_k, denoted as γ_{jk}, are placed on the top (the roof part) of HOQ.

Next, the technically achievable range for each EC is described, including its direction of improvement. The technically achievable range restricts the improvement span for EC, thus, the technically achievable range be considered as the improvement range. For EC_j , the improvement range is defined by the lower bound L_j and upper bound U_j . In designing commercial product, the marginally acceptable range may be used as an additional constraint to the improvement span. Marginally acceptable range of certain EC represents the technical range that would just barely make the product commercially viable [27].

Also, information regarding the resource constraints is collected. The organizational resource constraint maybe described as the amount available cost and/or time to make improvement. The improvement coefficients (C_j), which represent the amount of resource needed to make a unit improvement of EC_j, need to be identified in defining a resource constraint. In this paper, the amount of available organizational resource is denoted by B.

In step 2, the swing method is applied to assess the relationship weight between CRs and ECs. Swing method is commonly used to assess the weights in an additive multi attribute utility function. Next, the normalization procedure (see Equation 1) is applied to the relationship ratings, to accommodate the dependencies between ECs. The priority ratings of each EC are computed using the conventional HOQ technique as shown by Equation 4.

$$A_j = \sum_{i=1}^{m} D_i \, . \, R_{i,j}^{norm} \qquad \forall_j \tag{4}$$

where:
A_j = the absolute priority rating of the EC_j

Afterward, an optimization model is constructed (step 3). The complete formulation is presented by Equation 5 to Equation 7.

$$\text{Max } Z = \sum_{j=1}^{n} A_j . X_j \tag{5}$$

Subject to

$$\forall_j; \quad X_j = \left|\frac{T_j - U_j}{U_j - L_j}\right| \text{ for the case the smaller the better, or}$$

$$X_j = \frac{T_j - U_j}{U_j - L_j} \quad \text{for the case the larger the better} \tag{6}$$

$$\sum_{j=1}^{n} C_j . X_j \le B \tag{7}$$

where:
Z = the achieved customer satisfaction level

L_j = the lower limit of the improvement range of EC_j
U_j = the upper limit of the improvement range of EC_j
T_j = the technical target of EC_j
X_j = the percentage of the technical improvement of EC_j
C_j = the improvement coefficient of EC_j
B = the amount of available resource for design improvement

The optimal design specifications are obtained by solving the optimization model to find the optimal technical target (T_j) for all j (step 4).

3. AN ILLUSTRATIVE EXAMPLE

The illustrative the new HOQ technique, an example of designing a wooden dining chair is presented. The first step in implementation of the new HOQ procedure is collecting input data. A survey conducted to identify the CRs of a dining chair. Thirty lead users were intensively interviewed. The interview results revealed that there are five CRs. Then, the second survey was conducted. 263 respondents filled the questionnaires to assess the importance of CRs in a four-point scale. For CR_i, the weighted average of the importance ratings ($d_i^{average}$) was computed using Equation 2. As an example, $d_i^{average}$ was computed as follows. The respondents' assessment results for CR_i showed that there were 4 respondents assigned the value of 1, 20 respondents assigned the value of 2, 80 respondents assigned the value of 3 and 159 assigned the value of 4. Then, $d_i^{average} = \frac{(4\times1)+(20\times2)+(80\times3)+(159\times4)}{263}$, so $d_i^{average}$ is equal to 3.498.

Next, $d_i^{average}$ were normalized using Equation 3 to obtain D_i, for all i. Description of CR_i and the associated $d_i^{average}$ for all i are shown by Table 1, while D_i can be seen Figure 5.

Table 1. Customer requirement list

	Description	$d_i^{average}$
CR_1	Robust	3.498
CR_2	Unhampered seat	2.890
CR_3	Right height from the ground	3.171
CR_4	Comfortable back of seat	3.262
CR_5	Light weighted	2.521

Fifteen related ECs were generated to represent the CRs identified. Then, all γ_{jk}, improvement spans (denoted by L_j and U_j) and the direction of improvements were defined (as presented by Table 2). The improvement ranges were established with respect to technically achievable ranges and human anthropometry.

Meanwhile, the design team also collected the data concerning the resource constraint (i.e. C_j for all j and B). The existing dining chair was designed in the worst specifications, so it produced the worst customer satisfaction level (0%). There was some available resource to improve the dining chair design. In this case example, B was represented by the cost budget and C_j represented the cost needed to make a percentage improvement of EC_j.

Table 2. Engineering characteristics list

	Description	Improvement Range	Description of Improvement
EC_1	Length of front leg	5-7 cm	The larger the better
EC_2	Width of front leg	5-7 cm	The larger the better
EC_3	Height of front leg	39.5-41.5 cm	The smaller the better
EC_4	Length of back leg	5-7 cm	The larger the better
EC_5	Width of back leg	5-7 cm	The larger the better
EC_6	Height of back leg	39.5-41.5 cm	The smaller the better
EC_7	Width of seat	53.6-58.6 cm	The larger the better
EC_8	Length of seat	42.4-45 cm	The larger the better
EC_9	Seat thickness	1.2-4 cm	The larger the better
EC_{10}	Height of arm rest	23-24.5 cm	The smaller the better
EC_{11}	Length of arm rest	30.7-33.7 cm	The smaller the better
EC_{12}	Width of arm rest	9.1-10.8 cm	The larger the better
EC_{13}	Width of back of seat	43-46.6 cm	The larger the better
EC_{14}	Length of back of seat	55.3-59.9 cm	The larger the better
EC_{15}	Angle of back of seat (and horizontal axis)	90-100°	The larger the better

The amount of available cost budget was IDR 10000. C_j for j = 1 to 15 were as follows: 2312.02, 2312.02, -881.7, 2312.02, 2312.02, -881.7, 20047.35, 15858.35, 8067.864, -395.595, -711.24, 1222.436, 3837.169, 3974.722, 0. In this case, C_j mostly concerned with the material cost and the negative values of C_j were defined for EC_j with the smaller the better characteristic.

Then, the second step of the proposed technique was conducted. A technical expert was asked to assess the relationship weight between CRs and ECs using the swing method as follows:

1. Two alternative designs were shown to the technical team, one leads to the worst specifications and the other leads to the best
2. The team was asked to rank the ECs, one by one, by specifying which EC that has the most significant impact on satisfying certain CR if its value swings from the worst to the best.
3. EC with the most significant impact on satisfying CR would obtain the value of 100. The other EC would be compared to the most significant and would be rated proportionally on 0-100 scale. The completely irrelevant EC would gain the weight of 0. The results are shown on Figure 2.
4. The normalization procedure was employed so that the sum of the weights is equal to one, as can be seen in Figure 3.

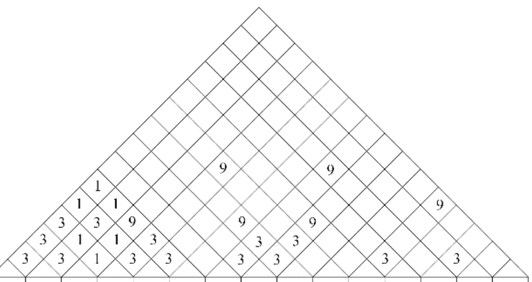
	EC_1	EC_2	EC_3	EC_4	EC_5	EC_6	EC_7	EC_8	EC_9	EC_{10}	EC_{11}	EC_{12}	EC_{13}	EC_{14}	EC_{15}
CR_1	50	50	70	50	50	100									70
CR_2							100	80		30	30				
CR_3			100			80			70						
CR_4													50	80	100
CR_5	20	20	40	20	20	40	100	70	70	20	20	20	70	70	

Figure 2. The impact ratings of ECs to CRs

	EC_1	EC_2	EC_3	EC_4	EC_5	EC_6	EC_7	EC_8	EC_9	EC_{10}	EC_{11}	EC_{12}	EC_{13}	EC_{14}	EC_{15}
CR_1	0.114	0.114	0.159	0.114	0.114	0.227									0.159
CR_2							0.417	0.333		0.125	0.125				
CR_3			0.4			0.32			0.28						
CR_4													0.217	0.348	0.435
CR_5	0.033	0.033	0.067	0.033	0.033	0.067	0.167	0.117	0.117	0.033	0.033	0.033	0.117	0.117	

Figure 3. The normalized impact ratings of ECs to CRs

Then, the other normalization procedure (Equation 1) was employed to the normalized weights. The normalization results were arranged in relationship matrix of the HOQ. Later, the absolute importance for the EC_j (that is A_j) were computed for all j. Then, the complete HOQ matrix could be developed as shown by Figure 4.



	Normalized Importance	EC_1	EC_2	EC_3	EC_4	EC_5	EC_6	EC_7	EC_8	EC_9	EC_{10}	EC_{11}	EC_{12}	EC_{13}	EC_{14}	EC_{15}
CR_1	0.228	0.128	0.128	0.248	0.139	0.139	0.204									0.013
CR_2	0.19							0.162	0.353		0.129	0.357				
CR_3	0.206			0.305			0.339			0.356						
CR_4	0.212													0.468	0.371	0.161
CR_5	0.164	0.035	0.035	0.131	0.035	0.35	0.131	0.126	0.057	0.143	0.025	0.078	0.009	0.13	0.031	
Absolute Importance		0.035	0.035	0.141	0.037	0.037	0.138	0.051	0.076	0.097	0.029	0.081	0.001	0.121	0.084	0.037

Figure 4. The complete HOQ for a dining chair design

The third step is formulating the optimization model. The appropriate mathematical model is presented by Equation 8 to Equation 24.

$$\begin{aligned} \text{Max } Z = {} & 0.035X_1 + 0.035X_2 + 0.141X_3 \\ & +0.037X_4 + 0.037X_5 + 0.138X_6 \\ & +0.051X_7 + 0.076X_8 + 0.097X_9 \\ & +0.029X_{10} + 0.081X_{11} + 0.001X_{12} \\ & +0.121X_{13} + 0.121X_{14} + 0.037X_{15} \end{aligned} \quad (8)$$

Subject to

$$X_1 = (T_1 - 5)/(7 - 5) \quad (9)$$
$$X_2 = (T_2 - 5)/(7 - 5) \quad (10)$$
$$X_3 = |(T_3 - 41.5)/(41.5 - 39.5)| \quad (11)$$
$$X_4 = (T_4 - 5)/(7 - 5) \quad (12)$$
$$X_5 = (T_5 - 5)/(7 - 5) \quad (13)$$
$$X_6 = |(T_6 - 41.5)/(41.5 - 39.5)| \quad (14)$$
$$X_7 = (T_7 - 53.6)/(58.6 - 53.6) \quad (15)$$
$$X_8 = (T_8 - 42.4)/(45 - 42.4) \quad (16)$$
$$X_9 = (T_9 - 1.2)/(4 - 1.2) \quad (17)$$
$$X_{10} = |(T_{10} - 24.5)/(24.5 - 23)| \quad (18)$$
$$X_{11} = |(T_{11} - 33.7)/(33.7 - 30.7)| \quad (19)$$
$$X_{12} = (T_{12} - 9.1)/(10.8 - 9.1) \quad (20)$$
$$X_{13} = (T_{13} - 43)/(46.6 - 43) \quad (21)$$
$$X_{14} = (T_{14} - 55.3)/(59.9 - 55.3) \quad (22)$$
$$X_{15} = (T_{15} - 90)/(100 - 90) \quad (23)$$
$$\begin{aligned} & 2312.02X_1 + 2312.02X_2 + (-881.7X_3) + \\ & 2312.02X_4 + 2312.02X_5 + (-881.7X_6) + \\ & 20047.35X_7 + 15858.35X_8 + 8067.864X_9 \\ & + (-395.595X_{10}) + (-711.24X_{11}) + \\ & 1222.436\ X_{12} + 3837.169\ X_{13} + \\ & 3974.722X_{14} + (0)X_{15} \leq 10000 \end{aligned} \quad (24)$$

Lingo 19.0 was used to solve the optimization model to derive the optimal specifications. T_j and the associated X_j, for all j, are shown in Table 3.

Table 3. Optimal solution

Variable	Value	Variable	Value
T_1	5 cm	X_1	0%
T_2	5.376 cm	X_2	18.784%
T_3	39.5 cm	X_3	100%
T_4	7 cm	X_4	100%
T_5	7 cm	X_5	100%
T_6	39.5 cm	X_6	100%
T_7	53.6 cm	X_7	0%
T_8	42.4 cm	X_8	0%
T_9	1.2 cm	X_9	0%
T_{10}	23 cm	X_{10}	100%
T_{11}	30.7 cm	X_{11}	100%
T_{12}	9.1 cm	X_{12}	0%
T_{13}	46.6 cm	X_{13}	100%
T_{14}	59.9 cm	X_{14}	100%
T_{15}	100°	X_{15}	100%

The optimal specifications lead to the customer satisfaction score of 71.15%. The graphical representation of the dining chair with optimal specifications is shown by the Figure 5.

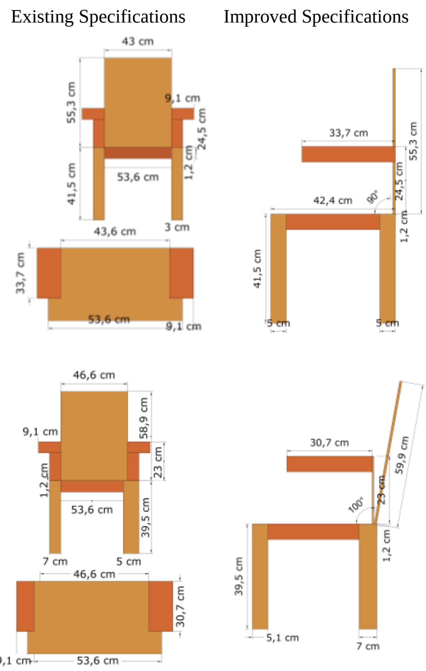


Figure 5. Existing and improved design

4. CONCLUSIONS

This paper has explained a formal HOQ technique to determine the technical target of ECs. The swing method and

Wasserman's normalization procedure was employed to obtain better relationship ratings. A mathematical model was developed to maximize customer satisfaction, subject to available organizational resources. The proposed procedure was applied in designing a wooden dining chair and has improved the customer satisfaction. However, the proposed technique still used ratings which were measured on interval (even on ordinal scale) i.e. CRs' importance ratings and correlation between ECs. For the future research, a better weighting methods need to be employed to assess those values.

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2. First revision: Accepted (05-06-2024)

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D.N. Dian Retno Sari Dewi P. , ST., MT. <dianretnosd@ukwms.ac.id>

Revisions Required MMEP 20240219

editor.mmep iieta.org <editor.mmep@iieta.org> Tue, Mar 26, 2024 at 3:27 PM
To: "dianretnosd@ukwms.ac.id" <dianretnosd@ukwms.ac.id>

Dear Author,

We appreciate your submission to the ***Mathematical Modelling of Engineering Problems*** (***MMEP***) and have completed the review process for your manuscript titled " **Determining Optimal Design Specification in the House of Quality.**"

After careful consideration, we have determined that revisions are necessary before your work can be further considered for publication. Please attend to the following:

[1] **Manuscript Revision:** Incorporate the reviewers' suggestions into your manuscript. Clearly indicate all modifications and include a response letter detailing how each comment was addressed.

[2] **Formatting:** Ensure your final manuscript (7 pages at least) adheres to the provided template.

[3] **Figures:** Submit all original figures in editable format, or adjust the text within figures to Times New Roman, 10 point font.

[4] **Author Identification:** Add ORCID link for each author.

[5] **Correspondence Verification:** Verify the corresponding author's email through previous publications.

[6] **Reference DOIs:** Include DOIs for all cited references. Use Crossref's free DOI guest search (http://www.crossref.org/guestquery/) to find missing DOIs. Format DOIs as complete URLs in your reference list.

[7] **Plagiarism Check:** Ensure the similarity index of your manuscript does not exceed 20%.

Your revised manuscript in WORD format and your response to the reviewers are due by **April 15, 2024**. Failure to adequately address the revision items may result in a delay of acceptance.

Should you have any questions or require clarification on the revision process, please do not hesitate to contact us.

Thank you for your cooperation.

Kind regards,

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Determining Optimal Design Specification in the House of Quality

Comments 1

1. The introduction lacks sufficient background and motivation. The authors should expand this section to provide more context on the research area and gap in knowledge that this work aims to address. What is the specific problem with existing HOQ approaches that this new technique intends to solve? The objectives of the study need to be clearly stated at the end of the introduction.
2. The authors should explicitly clarify the novelty of their proposed HOQ technique compared to existing methods. It would be beneficial to highlight the unique contributions and improvements this paper brings to the field, possibly in a separate subsection within the introduction or methodology.
3. **Mathematical Model Validation:**
   The paper proposes a comprehensive mathematical model. However, there is a need for a more detailed explanation of the validation process for the model. Do the authors compare the results of their model with actual market products or another benchmark? Adding such a comparison would strengthen the paper's validity.
4. **Case Study and Applicability:**
   While an example of a wooden dining chair design is presented, it would be useful to see additional case studies in different contexts to demonstrate the broader applicability of the model. The authors should consider including at least one more case study from a different product category or industry.
5. **Dependency Ratings Explanation:**
   The paper briefly mentions dependency ratings between engineering characteristics. However, the method for determining these ratings is not clear. The authors should provide a more thorough explanation of how dependencies are assessed and incorporated into the model.
6. **Sensitivity Analysis:**
   It would be valuable to include a sensitivity analysis to understand how variations in the input parameters (e.g., customer requirements, engineering characteristics) affect the model's outputs. This would give readers insight into the robustness of the proposed model.
7. **Resource Constraint Considerations:**
   The model is subject to organizational resource constraints, but there is limited discussion on how these constraints are quantified and incorporated. A more detailed treatment of this aspect would be beneficial, including how different types of constraints (e.g., budget, time) are handled.

Comments 2

1. The introduction needs expansion to provide more background context and motivation for the study. The authors should highlight the research gap this work aims to address.
2. More details are needed in the methodology section - the proposed HOQ procedure needs to be described more clearly. Explain the normalization techniques and optimization model formulation in greater depth.
3. The results and discussion are quite limited. Expand this section to provide more insights,

analysis and interpretation of the findings. How well does the model perform? What insights does it provide? Include some discussion of limitations, assumptions, and potential areas of model improvement based on the results. Relate the findings back to previous literature. Does this model perform better than existing HOQ approaches? Why?

4. The conclusion is abrupt and does not summarize the key contributions and outcomes of the study. Relate the conclusions back directly to the research objectives.
5. The paper would benefit from professional editing to improve clarity, grammar, and flow.

3. Revised version received (10-06-2024)

-Revisions and Amends

-Revised version with highlights

Gmail **D.N. Dian Retno Sari Dewi P. , ST., MT. <dianretnosd@ukwms.ac.id>**

Receipt of Revised Manuscript and Recommendation for Language Editing Services MMEP 20240219

editor.mmep iieta.org <editor.mmep@iieta.org> Tue, Apr 9, 2024 at 3:36 PM
To: "D.N. Dian Retno Sari Dewi P. , ST., MT." <dianretnosd@ukwms.ac.id>

Dear author,

I hope this email finds you in good health and spirits. I am writing to inform you that we have successfully received your revised manuscript. Thank you for your prompt response to the reviewers' comments and for making the necessary revisions.

Your manuscript will now be forwarded to the reviewers for further evaluation. We appreciate your patience during this process, as it ensures the highest quality of published work in our journal.

If you are interested in utilizing our language editing services, please let us know.

Once again, we appreciate your contribution to our journal and look forward to progressing with the review process.

Best regards,

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Sent: Monday, April 8, 2024 5:43 PM
To: editor.mmep iieta.org <editor.mmep@iieta.org>
Subject: Re: Revisions Required MMEP 20240219

Dear Editor MMEP,

We appreciate the review of our paper. We have revised our paper according to reviewers' comments. Attached are our revised paper with MMEP format, response to the reviewers and necessary figures. Thank you.

Best regards,

Dian Dewi

On Tue, Mar 26, 2024 at 3:27 PM editor.mmep iieta.org <editor.mmep@iieta.org> wrote:

> Dear Author,
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> We appreciate your submission to the ***Mathematical Modelling of Engineering Problems*** (***MMEP***) and have completed the review process for your manuscript titled " **Determining Optimal Design Specification in the House of Quality.**"
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> [1] **Manuscript Revision:** Incorporate the reviewers' suggestions into your manuscript. Clearly indicate all modifications and include a response letter detailing how each comment was addressed.
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> [2] **Formatting:** Ensure your final manuscript (7 pages at least) adheres to the provided template.
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> [3] **Figures:** Submit all original figures in editable format, or adjust the text within figures to Times New Roman, 10 point font.
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> Your revised manuscript in WORD format and your response to the reviewers are due by **April 15, 2024**. Failure to adequately address the revision items may result in a delay of acceptance.
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> Should you have any questions or require clarification on the revision process, please do not hesitate to contact us.
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Authors : Dian Retno Sari Dewi, Dini Endah Setyo Rahaju, Maureen Angela, Irene Karijadi, Luh Juni Asrini

Title : Determining Optimal Design Specification in the House of Quality

Responses to the Reviewer

The authors gratefully acknowledge the comments and suggestions of the referees. In the revision, we have made major changes on our article to consider all the questions raised by the referees. This revision includes modifications to the original contents and the clarifications of the questions. This document outlines the amendments made to the manuscript in view of the valuable insights provided by the reviewer who required revisions. The below provides the comment of the reviewer, followed by a description of the amendment undertaken.

Revisions based on Reviewer 1 comments

No	Comments	Actions by the authors
1	The introduction lacks sufficient background and motivation. The authors should expand this section to provide more context on the research area and gap in knowledge that this work aims to address. What is the specific problem with existing HOQ approaches that this new technique intends to solve? The objectives of the study need to be clearly stated at the end of the introduction.	Revised. The authors appreciate the advice by the reviewer. We have addressed this now with significantly changes in the introduction section. We add two more paragraph in the last section of introduction to underline what is the gap in the previous literature and what we have developed in the proposed model. We hope that the introduction is more concise and is clear regarding the development of the proposed model and to answer the research questions. Thank you for your suggestions. Here are the paragraphs: After carrying out a thorough literature review, here are the unresolved matters persist that requires further examination to address the weakness of the previous literature. First, the extant research so far still heuristically converts the CRs into design specifications, so it is difficult for decision makers to quantify exact numbers representing the relationship of CRs and ECs due to imprecise nature of human judgment. Second, the nature of decision makers differs significantly due to their background of knowledge and the goal of their departments which frequently contradict each other so it

		is hard to achieve agreement. Third, the effect of dependencies among ECs was not properly accounted when prioritizing the ECs.
2	The authors should explicitly clarify the novelty of their proposed HOQ technique compared to existing methods. It would be beneficial to highlight the unique contributions and improvements this paper brings to the field, possibly in a separate subsection within the introduction or methodology.	Revised. The authors appreciate the advice by the reviewer. We have addressed this now with significantly changes in the introduction section. We add one paragraph in the last section of introduction to underline our unique contributions. Here is the last paragraph: To respond to those weakness, this paper addresses those issues by modifying the traditional HOQ technique and developing a comprehensive mathematical model to derive the target of the ECs. The main contributions are: (1) This study utilize weighted average of the importance ratings to convert the CRs to ECs and to make a consensus among decision makers. (2) This study proposes a relationship ratio to incorporating the effect of dependencies among ECs that was not address properly in the previous research. (3) This study presents a method with a detailed process and numerical illustration that has supposedly advantageous for professionals in the industrial sector to convert customer expectations into design specifications.
3	**Mathematical Model Validation:** The paper proposes a comprehensive mathematical model. However, there is a need for a more detailed explanation of the validation process for the model. Do the authors compare the results of their model with actual market products or another benchmark? Adding such a comparison would strengthen the paper's validity.	The authors appreciate the advice by the reviewer. We provide additional detailed explanations about the numerical calculations of the equations that previously were not given a detailed numerical example, for example: • The weight of customer needs is obtained by dividing the average weight of each customer requirement by their total sum so that weight for

		CR1, CR2, CR3, CR4 and CR5 are 0.228, 0.188, 0.206, 0.212. 0.164 respectively (added after Table 1). • The example of normalization for R33 added after Table 4. • The absolute importance for the ECj (that is Aj) were computed for all j (Equation 4). For example: A1 = (0.228*0.128)+(0.164*0.035)=0.035 > added after Table 4 In this scenario, the research utilizes numerical examples of a wooden chair **based on initial design data derived from actual market products available at the time of the study.** However, validation through respondent comparison between the initial chair design and the improved version cannot be conducted due to financial constraints.
4	**Case Study and Applicability:** While an example of a wooden dining chair design is presented, it would be useful to see additional case studies in different contexts to demonstrate the broader applicability of the model. The authors should consider including at least one more case study from a different product category or industry.	The authors appreciate the advice by the reviewer, however we cannot collect more data for additional case studies in the limited time given to revise (15 days). For the wooden dining chair, we collected 263 respondents to fill the questionnaire and need approximately three months to collect them all. With the clear proposed HOQ technique along with numerical example, we confident that any additional case study can be implemented well.
5	**Dependency Ratings Explanation:** The paper briefly mentions dependency ratings between engineering characteristics. However, the method for determining these ratings is not clear. The authors should provide a more thorough explanation of how dependencies are assessed and incorporated into the model.	Revised. We have addressed this now with significantly changes in section 3 numerical example. We realize that we have not provided a numerical example for calculating the dependency rating so that the example of normalization technique for dependencies ratings between engineering characteristics has been written in section 3 numerical example after Table 4.
6	**Sensitivity Analysis:** It would be valuable to include a sensitivity analysis to understand how	Revised. We have addressed this now with significantly **adding section in section 4 (analysis and discussion)** specifically on

	variations in the input parameters (e.g., customer requirements, engineering characteristics) affect the model's outputs. This would give readers insight into the robustness of the proposed model.	analysis and delivers a sensitivity analysis, complete with Table 6 which conducted sensitivity analysis on budget change to customer satisfaction improvement.
7	**Resource Constraint Considerations:** The model is subject to organizational resource constraints, but there is limited discussion on how these constraints are quantified and incorporated. A more detailed treatment of this aspect would be beneficial, including how different types of constraints (e.g., budget, time) are handled.	Revised. We have addressed this now with significantly **adding section in section 4 (analysis and discussion) specifically on explaining the organizational resource constraints on budget.** We carried out of sensitivity analysis on budget change to customer satisfaction improvement.

Revisions based on Reviewer 2 comments

No	Comments	Actions by the authors
1	The introduction needs expansion to provide more background context and motivation for the study. The authors should highlight the research gap this work aims to address.	Revised. The authors appreciate the advice by the reviewer. We have addressed this now with significantly changes in the introduction section. We add two more paragraph in the last section of introduction to underline what is the gap in the previous literature and what we have developed in the proposed model. We hope that the introduction is more concise and is clear regarding the development of the proposed model and to answer the research questions. Thank you for your suggestions. Here are the paragraphs: After carrying out a thorough literature review, here are the unresolved matters persist that **requires further examination to address the weakness of the previous literature.** First, the extant research so far still heuristically converts the CRs into design specifications, so it is difficult for decision makers to quantify exact numbers representing the relationship of CRs and ECs

		due to imprecise nature of human judgment. Second, the nature of decision makers differs significantly due to their background of knowledge and the goal of their departments which frequently contradict each other so it is hard to achieve agreement. Third, the effect of dependencies among ECs was not properly accounted when prioritizing the ECs. To respond to those weakness, this paper addresses those issues by modifying the traditional HOQ technique and developing a comprehensive mathematical model to derive the target of the ECs. **The main contributions are:** (1) This study utilize weighted average of the importance ratings to convert the CRs to ECs and to make a consensus among decision makers. (2) This study proposes a relationship ratio to incorporating the effect of dependencies among ECs that was not address properly in the previous research. (3) This study presents a method with a detailed process and numerical illustration that has supposedly advantageous for professionals in the industrial sector to convert customer expectations into design specifications.
2	More details are needed in the methodology section - the proposed HOQ procedure needs to be described more clearly. Explain the normalization techniques and optimization model formulation in greater depth.	Revised. We have addressed this now with significantly changes in section 3 numerical example. We realize that we have not provided a numerical example for calculating the dependency rating so that the example of normalization technique for dependencies ratings between engineering characteristics has been written in section 3 numerical example after Table 4. We provide additional detailed explanations about the numerical calculations of the equations that previously were not given a detailed numerical example, for example: • The weight of customer needs is obtained by dividing the average

		weight of each customer requirement by their total sum so that weight for CR1, CR2, CR3, CR4 and CR5 are 0.228, 0.188, 0.206, 0.212. 0.164 respectively (added after Table 1). • The example of normalization for R33 added after Table 4. • The absolute importance for the ECj (that is Aj) were computed for all j (Equation 4). For example: A1 = (0.228*0.128)+(0.164*0.035)=0.035 > added after Table 4
3	The results and discussion are quite limited. Expand this section to provide more insights, analysis and interpretation of the findings. How well does the model perform? What insights does it provide? Include some discussion of limitations, assumptions, and potential areas of model improvement based on the results. Relate the findings back to previous literature. Does this model perform better than existing HOQ approaches? Why?	Revised. We have addressed this now with significantly **adding section in section 4 (analysis and discussion)** specifically on analysis and delivers a sensitivity analysis, complete with Table 6 conducted on sensitivity analysis on budget change to customer satisfaction improvement. The sensitivity analysis also specifically explaining the organizational resource constraints on budget. We carried out of sensitivity analysis on budget change to customer satisfaction improvement.
4	The conclusion is abrupt and does not summarize the key contributions and outcomes of the study. Relate the conclusions back directly to the research objectives.	Revised. We have addressed this now with **significantly changes in section conclusion with clear key contributions to the body of knowledge and practitioners.** Also, this section provides discussion of limitations, and potential areas of model improvement. Here is the text in the conclusion: This paper has proposed a formal HOQ technique to determine the technical target of ECs. The swing method and Wasserman's normalization procedure was employed to obtain better relationship ratings. A mathematical model was developed to maximize customer satisfaction, subject to available organizational resources. The proposed procedure was applied in designing a wooden dining chair and has improved the

		customer satisfaction. A sensitivity analysis has been conducted to obtain the optimal budget to yield customer satisfaction. **Several contributions to the body of knowledge have been obtained to offer a new mathematical model. First,** this study contributes to the using of weighted average of the importance rating to convert the customer requirements to engineering characteristics. **Second,** this study contributes to the engineering characteristics relationship ratio to incorporating the effect of dependencies. Also, **contributions to product development practitioners** by providing mathematical models and their procedures facilitate practitioners in translating consumer desires into technical characteristics to achieve optimal consumer satisfaction within technical specifications and cost constraints, with detailed numerical example. However, the proposed technique still used ratings which were measured on interval (even on ordinal scale) i.e. CRs' importance ratings and correlation between ECs. For future research, better weighting methods need to be employed to assess those values.
5	The paper would benefit from professional editing to improve clarity, grammar, and flow.	The authors appreciate the advice by the reviewer. We have carried out the professional editing.

Mathematical Modelling of Engineering Problems
Vol., No., Month, Year, pp. **-**
Journal homepage: http://iieta.org/journals/mmep

Determining Optimal Design Specification in the House of Quality

Dian Retno Sari Dewi[1*], Dini Endah Setyo Rahaju[2], Maureen Angela[3], Irene Karijadi[4], Luh Juni Asrini[5]

[1,2,3,4,5] Industrial Engineering Department, Widya Mandala Catholic University, Surabaya 60114, Indonesia

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ABSTRACT

The House of Quality (HOQ), which serves as the initial matrix in Quality Function Deployment (QFD), is widely employed to set the technical objectives for engineering characteristics. Nevertheless, there exist methodological deficiencies within the HOQ, concerning the assessment of relationship ratings between customer requirements and engineering characteristics, as well as the lack of a structured process for determining design specifications. Therefore, this study proposes a formal HOQ procedure to determine the technical targets of engineering characteristics. The swing method and a specific normalization technique are utilized to incorporate correlations between engineering characteristics, aiming to improve relationship ratings. Additionally, an optimization model has been devised to maximize customer satisfaction within the constraints of available organizational resources. The procedure is illustrated using a wooden dining chair design as an example.

1. INTRODUCTION

QFD is a structured method to translate the voice of customer into a final product through various stages of development and production [1]. QFD has proven to be useful to support product developers to meet the customers' needs by determining on the most paramount part of engineering characteristics development [2, 3]. After the initiation by Akao [4], QFD is now extensively utilized around the world as the basic tools to identify the customers' requirements [3, 5].

In the beginning of the QFD initiation, engineering characteristics were frequently justified by the engineer expert judgement. The result from this process repeatedly gives subjective opinions and is diverse among experts' judgement [2, 6]. Recently, benchmarks are utilized to measure the engineering characteristics [1]; however, this method has not quantitatively specified the procedure to determine the relationship between customers' requirements and engineering characteristics [7]. Therefore, an optimization model to translate the relationship between customers' needs and engineering characteristics are required.

The method begins by identifying the customer's requirements (CRs) and translating those requirements into engineering characteristics (ECs), and subsequently into part characteristics, process plans and production requirements. Each translation process is carried out using a matrix to convert the input (WHATs) into output (HOWs) [8, 9]. This paper is focused on the first translation matrix, called HOQ. HOQ is considered fundamental in the QFD process, since it largely affects the later translation process. Thus, this paper is focused on several main parts of HOQ.

There are several methodological flaws in the conventional HOQ. The conventional HOQ has no explicit justification in choosing rating series (e.g. 1-3-4 or 1-5-9) to express the relationship between customer requirements and technical requirements [10]. Moreover, the relationship rating in HOQ – which are measured on interval scale (even on ordinal scale) – are usually treated as of measured on ratio or proportional scale [11]. The relationship ratings are employed in later computation to obtain the EC priorities. The computation involves mathematical operations that should use measurements data on ratio scale. Inappropriate rating scale that is utilized in mathematical operation may lead to wrong prioritization of the ECs [11].

Several researches have developed mathematical models to solve those methodological problems. Askin and Dawson [12] and Park and Kim [13] proposed a mathematical model that involved the resource constraints and method to set the relationship ratings between ECs and ECs. An integrated QFD with stochasticity has been developed by [14]. Further, a new approach for engineering characteristics prioritization has been developed by [15, 16]. Then, a study from [17] extended the integrated approach to determine ECs prioritization in QFD. Likewise, [18] develop the prioritization model by combining QFD models and fuzzy ANP to determine the weight for ECs. The sophisticated model using fuzzy theory have been developed by Kang and Nagasawa [19], Lim and Chin [20] , Aydin et al. [21] , Xing et al. [22] and Liu et al.[23]. However, those research still leave the weakness about the absence of formal decision model to assist the design team in prioritizing and/or setting technical targets of the ECs, with the aim of maximizing customer satisfaction, and subject to organizational resource constraints.

After carrying out a thorough literature review, here are the unresolved matters that require further examination to address the weakness of the previous literature. First, the extant research so far still heuristically converts the CRs into design specifications, so it is difficult for decision makers to quantify exact numbers representing the relationship of CRs and ECs due to imprecise nature of human judgment. Second, the nature of decision makers differs significantly due to their background of knowledge and the goal of their departments which frequently contradict each other so it is hard to achieve agreement. Third, the effect of dependencies among ECs was not properly accounted for when prioritizing the ECs.

To respond to those weaknesses, this paper addresses those issues by modifying the traditional HOQ technique and developing a comprehensive mathematical model to derive the target of the ECs. The main contributions are: (1) This study utilizes weighted average of the importance ratings to convert the CRs to ECs and to make a consensus among decision makers. (2) This study proposes a relationship ratio to incorporate the effect of dependencies among ECs that was not addressed properly in the previous research. (3) This study presents a method with a detailed process and numerical illustration that is supposedly advantageous for professionals in the industrial sector to convert customer expectations into design specifications.

2. THE PROPOSED MODEL

The proposed HOQ technique was developed based on Erdil and Arani [24] and Park and Kim [13], instead of determining the optimal EC set to be considered in the design, the aim of the proposed technique is to establish the optimal specifications. The procedure incorporates a method to elicit the utility weights in multi-attribute decision problems, i.e. swing method to assess the magnitudes of relationships between CRs and ECs. The weight of 0 represents the extremely irrelevant EC (so that can be regarded as no relationship with the concerned CR), while the value of 100 is assigned the most related EC [25–27]. Weights of the other ECs are defined proportional to that obtained by the most related EC. Then, the relationship rating between CR_i and EC_j (i.e. R_{ij}) is obtained by normalizing the weights, so that. $\sum_{j=1}^{n} R_{ij} = 1$ for all i.

The obtained rating shows a continuum of rating values specifying the sliding magnitude of the relationship, not only representing the order of strength (weak – medium – strong). Thus, those ratings are considered more meaningful. Afterward, the relationship ratings are normalized using equation 1 to accommodate the dependencies between ECs.

$$R_{i,j}^{norm} = \frac{\sum_{k=1}^{n} R_{i,k} \cdot \gamma_{k,j}}{\sum_{j=1}^{n}\sum_{k=1}^{n} R_{i,j} \cdot \gamma_{j,k}} \quad ; \qquad \gamma_{j,k} = \gamma_{k,j} \qquad (1)$$

where:

$R_{i,j}^{norm}$ = normalized rating between CR_i and EC_j
R_{ij} = relationship rating between CR_i and EC_j
$\gamma_{j,k}$ = dependency rating between EC_j and EC_k
The new HOQ technique is presented in Figure 1.

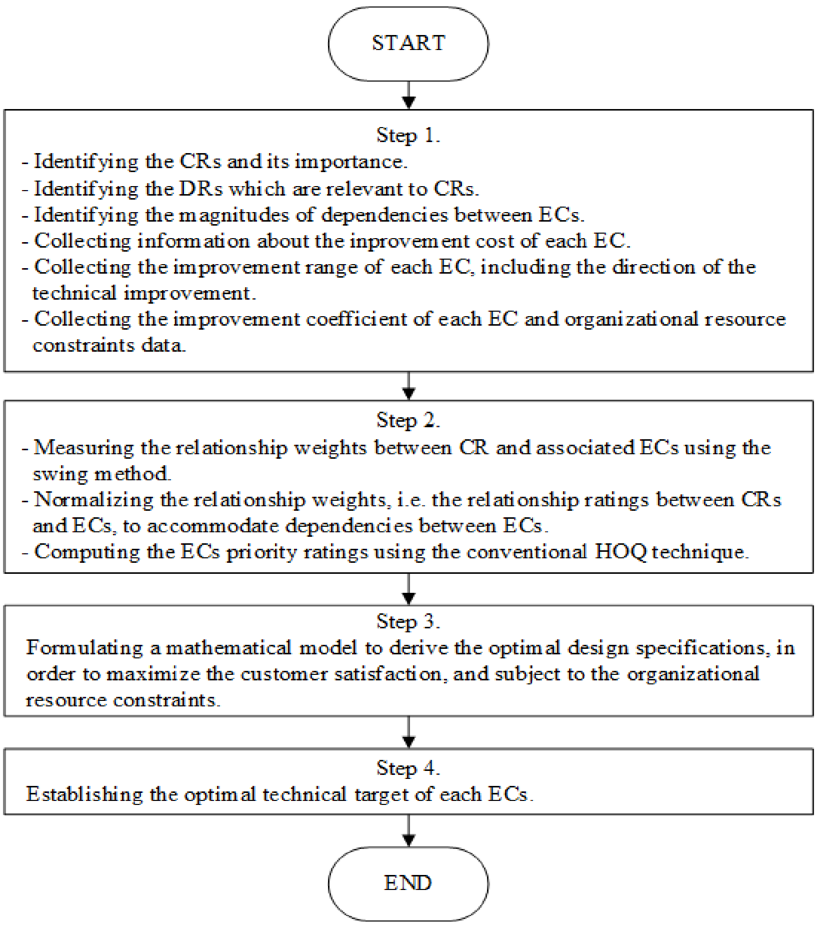


Figure 1. The proposed HOQ technique

The proposed technique begins by identifying the CRs as the main input for HOQ (step 1). There are three methods which are commonly used for gathering the CRs: interviews, focus groups and observing the product in use [28]. For most products, fifty interviews are possibly too many, but ten interviews are possibly not enough to reveal most of the CRs. As a practical guideline, for a product, thirty interviews might reveal 90 per cent of CRs, whereas 2 hours focus group uncover nearly the same number of CRs as two 1-hour interviews [29].

Then a survey is conducted to assess the importance rating of each CR. For CR_i, i =1 to m, the weighted average of importance ratings are computed using Equation 2.

$$d_i^{average} = \frac{\sum_{n=1}^{p} Q'.n'}{Q} \quad (2)$$

where:

$d_i^{average}$ = the importance rating's weighted average for CR_i
Q' = number of respondents at rating n' (a p' point scale rating is used)
Q = total number of respondents

For the purpose of optimization model, $d_i^{average}$ is normalized, so that the sum of $d_i^{average}$ for all CR_i is equal to one (see Equation 3).

$$d_i^{average} = \frac{\sum_{n=1}^{p} Q'.n'}{Q} \quad (3)$$

D_i = the normalized importance of the CR_i

After the CRs are identified, the associated EC_j, j = 1 to n, are generated, as technical metrics of CRs, and the magnitudes of dependencies between ECs are assessed. All of the correlation values between EC_j and EC_k, denoted as γ_{jk}, are placed on the top (the roof part) of HOQ.

Next, the technically achievable range for each EC is described, including its direction of improvement. The technically achievable range restricts the improvement span for EC, thus, the technically achievable range can be considered as the improvement range. For EC_j , the improvement range is defined by the lower bound L_j and upper bound U_j . In designing commercial products, the marginally acceptable range may be used as an additional constraint to the improvement span. Marginally acceptable range of certain EC represents the technical range that would just barely make the product commercially viable [28].

Also, information regarding the resource constraints is collected. The organizational resource constraint maybe described as the amount available cost and/or time to make improvement. The improvement coefficients (C_j), which represent the amount of resource needed to make a unit improvement of EC_j, need to be identified in defining a resource constraint. In this paper, the amount of available organizational resource is denoted by B.

In step 2, the swing method is applied to assess the relationship weight between CRs and ECs. Swing method is commonly used to assess the weights in an additive multi attribute utility function. Next, the normalization procedure (see Equation 1) is applied to the relationship ratings, to accommodate the dependencies between ECs. The priority ratings of each EC are computed using the conventional HOQ technique as shown by Equation 4.

$$A_j = \sum_{i=1}^{m} D_i \, . R_{i,j}^{norm} \qquad \forall_j \quad (4)$$

where:

A_j = the absolute priority rating of the EC_j

Afterward, an optimization model is constructed (step 3). The complete formulation is presented by Equation 5 to Equation 7.

$$\text{Max } Z = \sum_{j=1}^{n} A_j . X_j \quad (5)$$

Subject to

$\forall_j$; $\quad X_j = \left|\frac{T_j - U_j}{U_j - L_j}\right|$ for the case the smaller the better, or

$X_j = \frac{T_j - U_j}{U_j - L_j}$ for the case the larger the better (6)

$$\sum_{j=1}^{n} C_j \, . X_j \leq B \quad (7)$$

where:

Z = the achieved customer satisfaction level
L_j = the lower limit of the improvement range of EC_j
U_j = the upper limit of the improvement range of EC_j
T_j = the technical target of EC_j
X_j = the percentage of the technical improvement of EC_j
C_j = the improvement coefficient of EC_j
B = the amount of available resource for design improvement

The optimal design specifications are obtained by solving the optimization model to find the optimal technical target (T_j) for all j (step 4).

3. AN ILLUSTRATIVE EXAMPLE

The illustrative the new HOQ technique, an example of designing a wooden dining chair is presented. The first step in implementation of the new HOQ procedure is collecting input data. A survey conducted to identify the CRs of a dining chair. Thirty lead users were intensively interviewed. The interview results revealed that there are five CRs. Then, the second survey was conducted. 263 respondents filled the questionnaires to assess the importance of CRs in a four-point scale. For CR_i, the weighted average of the importance ratings ($d_i^{average}$) was computed using Equation 2. As an example, $d_i^{average}$ was computed as follows. The respondents' assessment results for CR_i showed that there were 4 respondents assigned the value of 1, 20 respondents assigned the value of 2, 80 respondents assigned the value of 3 and 159 assigned the value of 4. Then, $d_i^{average} = \frac{(4\times1)+(20\times2)+(80\times3)+(159\times4)}{263}$, so $d_i^{average}$ is equal to 3.498.

Next, $d_i^{average}$ were normalized using Equation 3 to obtain D_i, for all i. Description of CR_i and the associated $d_i^{average}$ for all i are shown by Table 1.

Table 1. Customer requirement list

	Description	$d_i^{average}$
CR_1	Robust	3.498
CR_2	Unhampered seat	2.890
CR_3	Right height from the ground	3.171
CR_4	Comfortable back of seat	3.262
CR_5	Light weighted	2.521

The weight of customer needs is obtained by dividing the average weight of each customer requirement by their total sum so that weight for CR_1, CR_2, CR_3, CR_4 and CR_5 are 0.228, 0.188, 0.206, 0.212. 0.164 respectively. Fifteen related ECs were generated to represent the CRs identified. Then, all γ_{jk}, improvement spans (denoted by L_j and U_j) and the direction of improvements were defined (as presented by Table 2). The improvement ranges were established with respect to technically achievable ranges and human anthropometry.

Meanwhile, the design team also collected the data concerning the resource constraint (i.e. C_j for all j and B). The existing dining chair was designed in the worst specifications, so it produced the worst customer satisfaction level (0%). There were some available resources to improve the dining chair design. In this case example, B was represented by the cost budget and C_j represented the cost needed to make a percentage improvement of EC_j.

Table 2. Engineering characteristics list

	Description	Improvement Range	Description of Improvement
EC_1	Length of front leg	5-7 cm	The larger the better
EC_2	Width of front leg	5-7 cm	The larger the better
EC_3	Height of front leg	39.5-41.5 cm	The smaller the better
EC_4	Length of back leg	5-7 cm	The larger the better
EC_5	Width of back leg	5-7 cm	The larger the better
EC_6	Height of back leg	39.5-41.5 cm	The smaller the better
	Description	**Improvement Range**	**Description of Improvement**
EC_7	Width of seat	53.6-58.6 cm	The larger the better
EC_8	Length of seat	42.4-45 cm	The larger the better
EC_9	Seat thickness	1.2-4 cm	The larger the better
EC_{10}	Height of arm rest	23-24.5 cm	The smaller the better
EC_{11}	Length of arm rest	30.7-33.7 cm	The smaller the better
EC_{12}	Width of arm rest	9.1-10.8 cm	The larger the better
EC_{13}	Width of back of seat	43-46.6 cm	The larger the better
EC_{14}	Length of back of seat	55.3-59.9 cm	The larger the better
EC_{15}	Angle of back of seat (and horizontal axis)	90-100°	The larger the better

The available cost budget was IDR 10000. C_j for j = 1 to 15 were as follows: 2312.02, 2312.02, -881.7, 2312.02, 2312.02, -881.7, 20047.35, 15858.35, 8067.864, -395.595, -711.24, 1222.436, 3837.169, 3974.722, 0. In this case, C_j mostly concerned with the material cost and the negative values of C_j were defined for EC_j with the smaller the better characteristic.

Then, the second step of the proposed technique was conducted. A technical expert was asked to assess the relationship weight between CRs and ECs using the swing method as follows:

1. Two alternative designs were shown to the technical team, one leads to the worst specifications and the other leads to the best
2. The team was asked to rank the ECs, one by one, by specifying which EC that has the most significant impact on satisfying a certain CR if its value swings from the worst to the best.
3. EC with the most significant impact on satisfying CR would obtain the value of 100. The other EC would be compared to the most significant and would be rated proportionally on 0-100 scale. The completely irrelevant EC would gain the weight of 0. The results are shown on Table 3.
4. The normalization procedure was employed so that the sum of the weights is equal to one, as can be seen in Table 4.

Table 3. The impact ratings of ECs to CRs

	EC_1	EC_2	EC_3	EC_4	EC_5	EC_6	EC_7	EC_8	EC_9	EC_{10}	EC_{11}	EC_{12}	EC_{13}	EC_{14}	EC_{15}
CR_1	50	50	70	50	50	100									70
CR_2							100	80		30	30				
CR_3			100			80			70						
CR_4													50	80	100
CR_5	20	20	40	20	20	40	100	70	70	20	20	20	70	70	

Table 4. The normalized impact ratings of ECs to CRs

	EC_1	EC_2	EC_3	EC_4	EC_5	EC_6	EC_7	EC_8	EC_9	EC_{10}	EC_{11}	EC_{12}	EC_{13}	EC_{14}	EC_{15}
CR_1	0.114	0.114	0.159	0.114	0.114	0.227									0.159
CR_2							0.417	0.333		0.125	0.125				
CR_3			0.400			0.32			0.280						
CR_4													0.217	0.348	0.435
CR_5	0.033	0.033	0.067	0.033	0.067	0.067	0.167	0.117	0.117	0.033	0.033	0.033	0.117	0.117	

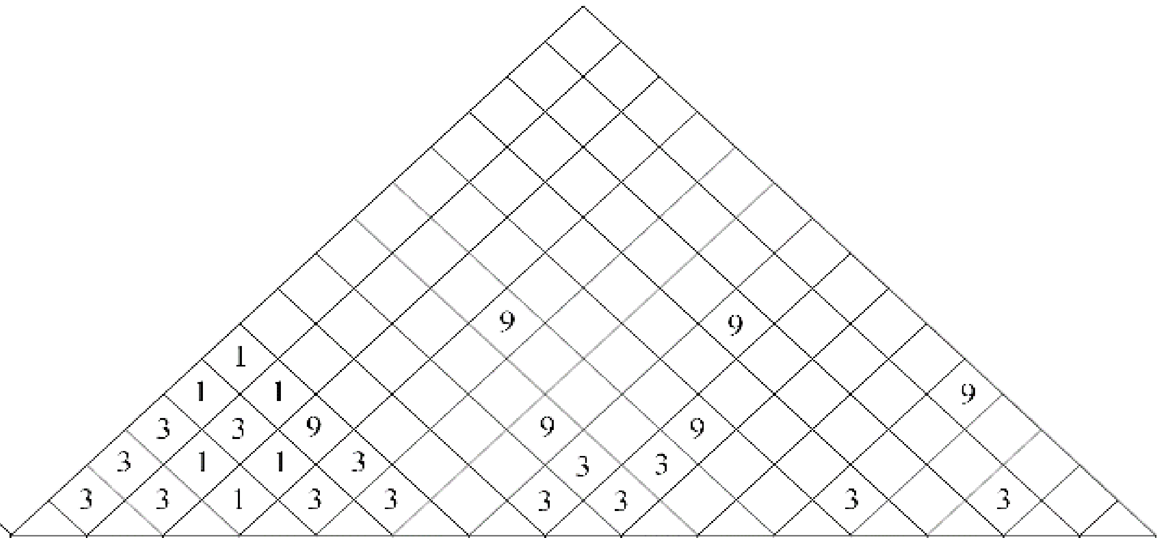
Then, the other normalization procedure (Equation 1) was employed to the normalized weights. The normalization results were arranged in the relationship matrix of the HOQ. The example of normalization for R_{33} is as follows.

$$R_{33}^{norm} = \frac{R_{33}.\gamma_{33} + R_{36}.\gamma_{63} + R_{39}.\gamma_{93}}{R_{33}.\gamma_{33} + R_{36}.\gamma_{63} + R_{39}.\gamma_{93} + R_{33}.\gamma_{63} + R_{36}.\gamma_{66} + R_{39}.\gamma_{96} + R_{33}.\gamma_{93} + R_{36}.\gamma_{69} + R_{39}.\gamma_{99}}$$

$$R_{33}^{norm} = \frac{(0.4 * 1) + (0.32 * 9) + (0.28 * 9)}{(0.4 * 1) + (0.32 * 9) + (0.28 * 9) + (0.4 * 9) + (0.32 * 1) + (0.28 * 9) + (0.4 * 9) + (0.32 * 9) + (0.28 * 1)}$$

Later, the absolute importance for the EC_j (that is A_j) were computed for all j (Equation 4). For example: $A_1 = (0.228 * 0.128) + (0.164 * 0.035) = 0.035$.

Then, the complete HOQ matrix could be developed as shown by Figure 2.



Normalized Importance		EC1	EC2	EC3	EC4	EC5	EC6	EC7	EC8	EC9	EC10	EC11	EC12	EC13	EC14	EC15
CR_1	0.228	0.128	0.128	0.248	0.139	0.139	0.204									0.013
CR_2	0.19							0.162	0.353		0.129	0.357				
CR_3	0.206			0.305			0.339			0.356						
CR_4	0.212													0.468	0.371	0.161
CR_5	0.164	0.035	0.035	0.131	0.035	0.35	0.131	0.126	0.057	0.143	0.025	0.078	0.009	0.13	0.031	
Absolute Importance		0.035	0.035	0.141	0.037	0.037	0.138	0.051	0.076	0.097	0.029	0.081	0.001	0.121	0.084	0.037

Figure 2. The complete HOQ for a dining chair design

The third step is formulating the optimization model. The appropriate mathematical model is presented by Equation 8 to Equation 24.

$$\text{Max } Z = 0.035X_1 + 0.035X_2 + 0.141X_3 + 0.037X_4 + 0.037X_5 + 0.138X_6 + 0.051X_7 + 0.076X_8 + 0.097X_9 + 0.029X_{10} + 0.081X_{11} + 0.001X_{12} + 0.121X_{13} + 0.121X_{14} + 0.037X_{15} \quad (8)$$

Subject to

$$X_1 = (T_1 - 5)/(7 - 5) \quad (9)$$

$$X_2 = (T_2 - 5)/(7 - 5) \quad (10)$$

$$X_3 = |(T_3 - 41.5)/(41.5 - 39.5)| \quad (11)$$

$$X_4 = (T_4 - 5)/(7 - 5) \quad (12)$$

$$X_5 = (T_5 - 5)/(7 - 5) \quad (13)$$

$$X_6 = |(T_6 - 41.5)/(41.5 - 39.5)| \quad (14)$$

$$X_7 = (T_7 - 53.6)/(58.6 - 53.6) \quad (15)$$

$$X_8 = (T_8 - 42.4)/(45 - 42.4) \quad (16)$$

$$X_9 = (T_9 - 1.2)/(4 - 1.2) \quad (17)$$

$$X_{10} = |(T_{10} - 24.5)/(24.5 - 23)| \quad (18)$$

$$X_{11} = |(T_{11} - 33.7)/(33.7 - 30.7)| \quad (19)$$

$$X_{12} = (T_{12} - 9.1)/(10.8 - 9.1) \quad (20)$$

$$X_{13} = (T_{13} - 43)/(46.6 - 43) \quad (21)$$

$$X_{14} = (T_{14} - 55.3)/(59.9 - 55.3) \quad (22)$$

$$X_{15} = (T_{15} - 90)/(100 - 90) \quad (23)$$

$$2312.02X_1 + 2312.02X_2 + (-881.7X_3) + 2312.02X_4 + 2312.02X_5 + (-881.7X_6) + 20047.35X_7 + 15858.35X_8 + 8067.864X_9 + (-395.595X_{10}) + (-711.24X_{11}) + \quad (24)$$

$1222.436 X_{12} + 3837.169 X_{13} + 3974.722 X_{14} + (0) X_{15} \leq 10000$

Lingo 19.0 was used to solve the optimization model to derive the optimal specifications. T_j and the associated X_j, for all j, are shown in Table 5.

Table 5. Optimal solution

Variable	Value	Variable	Value
T_1	5 cm	X_1	0%
T_2	5.376 cm	X_2	18.784%
T_3	39.5 cm	X_3	100%
T_4	7 cm	X_4	100%
T_5	7 cm	X_5	100%
T_6	39.5 cm	X_6	100%
T_7	53.6 cm	X_7	0%
T_8	42.4 cm	X_8	0%
T_9	1.2 cm	X_9	0%
T_{10}	23 cm	X_{10}	100%
T_{11}	30.7 cm	X_{11}	100%
T_{12}	9.1 cm	X_{12}	0%
T_{13}	46.6 cm	X_{13}	100%
T_{14}	59.9 cm	X_{14}	100%
T_{15}	100°	X_{15}	100%

The optimal specifications lead to the customer satisfaction score of 71.15%. The graphical representation of the dining chair with optimal specifications is shown by Figure 3.

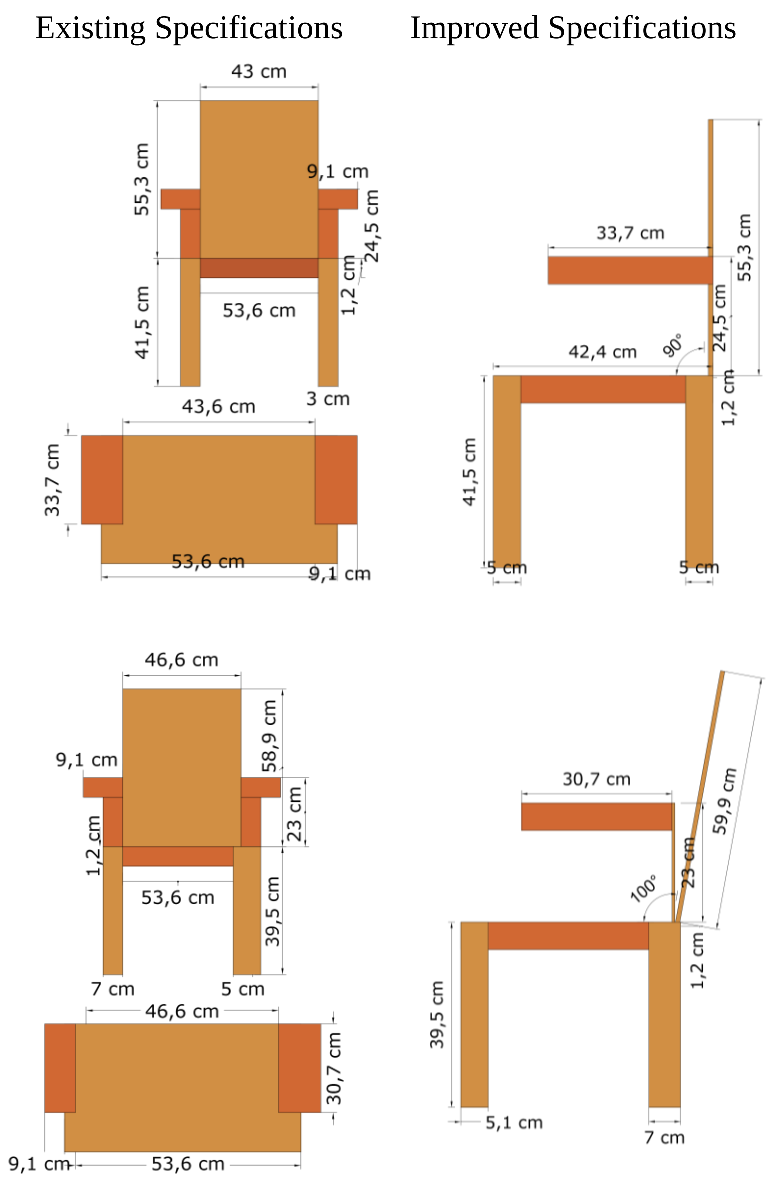


Figure 3. Existing and improved design

4. ANALYSIS AND DISCUSSION

In the formation of HOQ matrix, several pieces of information are required, namely customer needs, customer importance weights, technical characteristics, CRs and ECs relationships, ECs relationships and absolute importance. The relationship ratings between ECs have been normalized. With this normalization, it is expected that new priorities can be formed as it accommodates the relationships between engineering characteristics. For example, comfortable back of seat (CR_4), which is related to engineering characteristic backrest position (EC_{15}), before normalization, EC_{15} was the dominant characteristic influencing CR_4 with a rating value of 0.435. However, after normalization, EC_{15} becomes non-dominant, with a value of 0.16. This is because EC_{15} does not have a relationship with other engineering characteristics (in this case, EC_{13} and EC_{14}).

To determine customer satisfaction level, it has been expressed with mathematical equations 5. X_j represents the percentage of technical improvement of EC_j with values ranging from 0 to 1, and A_{ij} is the absolute priority rating of the EC_j. The maximum value obtained for customer satisfaction is 1 (100%). The range constraint of EC_j is established with equation 6, where T_i represents the technical target of EC_j with lower and upper limit of the improvement range. Another main constraint is the product development cost represented by equation 7. If there is no improvement in EC_j, then the value of C_i for that EC_j. will be 0.

We can see from table 5 the optimal solution, it is apparent that for X_1, X_7, X_8, X_9, and X_{12}, the values are 0, indicating that their performance is within the minimum range of characteristics or equal to the initial characteristics. Conversely, X_3, X_4, X_5, X_6, X_{10}, X_{11}, X_{13}, X_{14}, and X15 are within the performance range of maximum characteristics.

The sensitivity analysis was conducted to determine the change in budget towards customer satisfaction. Table 6 illustrates the contribution of budget changes for every increase of 1000 IDR towards the improvement of customer satisfaction. In this numerical example, the given budget is 10000 IDR, resulting in a customer satisfaction level of 71.15% at this budget.

Table 6. Sensitivity analysis on budget change to customer satisfaction improvement

Budget (IDR)	Customer satisfaction (%)	Delta
1000	54.77	
2000	56.88	2.11
3000	58.99	2.11
4000	61.11	2.12
5000	63.19	2.08
6000	64.79	1.60
7000	66.39	1.60
8000	67.99	1.60
9000	69.59	1.60
10000	71.15	1.56
11000	72.67	1.52
12000	74.19	1.52
13000	75.70	1.51
14000	77.20	1.50
15000	78.47	1.27
16000	79.67	1.20
17000	80.88	1.21
18000	82.08	1.20
19000	83.28	1.20
20000	84.48	1.20
21000	85.68	1.20
22000	86.89	1.21
23000	87.55	0.66
24000	88.03	0.48
25000	88.51	0.48
26000	88.99	0.48
27000	89.47	0.48
28000	89.95	0.48
29000	90.43	0.48
30000	90.91	0.48

Table 6 indicates that an increase in the budget by 1000 IDR results in a customer satisfaction improvement of approximately 2%. However, when the budget exceeds 23000 IDR, the increase in customer satisfaction becomes insignificant, reaching only 0.48%.

5. CONCLUSIONS

This paper has proposed a formal HOQ technique to determine the technical target of ECs. The swing method and Wasserman's normalization procedure was employed to obtain better relationship ratings. A mathematical model was developed to maximize customer satisfaction, subject to available organizational resources. The proposed procedure was applied in designing a wooden dining chair and has improved the customer satisfaction. A sensitivity analysis has been conducted to obtain the optimal budget to yield customer satisfaction.

Several contributions to the body of knowledge have been obtained to offer a new mathematical model. First, this study contributes to the using of weighted average of the importance rating to convert the customer requirements to engineering characteristics. Second, this study contributes to the engineering characteristics relationship ratio to incorporating the effect of dependencies. Also, contributions to product development practitioners by providing mathematical models and their procedures facilitate practitioners in translating consumer desires into technical characteristics to achieve optimal consumer satisfaction within technical specifications and cost constraints, with detailed numerical example.

However, the proposed technique still used ratings which were measured on interval (even on ordinal scale) i.e. CRs' importance ratings and correlation between ECs. For future research, better weighting methods need to be employed to assess those values.

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Acceptance Letter

Mathematical Modelling of Engineering Problems

April 25, 2024

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Dear Dian Retno Sari Dewi, Dini Endah Setyo Rahaju, Maureen Angela, Irene Karijadi, Luh Juni Asrini,

MS: Determining Optimal Design Specification in the House of Quality

I am pleased to inform you that as per the recommendation of the editorial board, your above-mentioned manuscript has been accepted for publication in Mathematical Modelling of Engineering Problems (ISSN 2369-0739).

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Determining Optimal Design Specification in the House of Quality

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ABSTRACT

The house of quality (HOQ), which serves as the initial matrix in quality function deployment (QFD), is widely employed to set the technical objectives for engineering characteristics. Nevertheless, there exist methodological deficiencies within the HOQ, concerning the assessment of relationship ratings between customer requirements and engineering characteristics, as well as the lack of a structured process for determining design specifications. Therefore, this study proposes a formal HOQ procedure to determine the technical targets of engineering characteristics. The swing method and a specific normalization technique are utilized to incorporate correlations between engineering characteristics, aiming to improve relationship ratings. Additionally, an optimization model has been devised to maximize customer satisfaction within the constraints of available organizational resources. The procedure is illustrated using a wooden dining chair design as an example.

1. INTRODUCTION

QFD is a structured method to translate the voice of customer into a final product through various stages of development and production [1]. QFD has proven to be useful to support product developers to meet the customers' needs by determining on the most paramount part of engineering characteristics development [2, 3]. After the initiation by Akao [4], QFD is now extensively utilized around the world as the basic tools to identify the customers' requirements [3, 5].

In the beginning of the QFD initiation, engineering characteristics were frequently justified by the engineer expert judgement. The result from this process repeatedly gives subjective opinions and is diverse among experts' judgement [2, 6]. Recently, benchmarks are utilized to measure the engineering characteristics [1]; however, this method has not quantitatively specified the procedure to determine the relationship between customers' requirements and engineering characteristics [7]. Therefore, an optimization model to translate the relationship between customers' needs and engineering characteristics are required.

The method begins by identifying the customer's requirements (CRs) and translating those requirements into engineering characteristics (ECs), and subsequently into part characteristics, process plans and production requirements. Each translation process is carried out using a matrix to convert the input (WHATs) into output (HOWs) [8, 9]. This paper is focused on the first translation matrix, called HOQ. HOQ is considered fundamental in the QFD process, since it largely affects the later translation process. Thus, this paper is focused on several main parts of HOQ.

There are several methodological flaws in the conventional HOQ. The conventional HOQ has no explicit justification in choosing rating series (e.g. 1-3-4 or 1-5-9) to express the relationship between customer requirements and technical requirements [10]. Moreover, the relationship rating in HOQ – which are measured on interval scale (even on ordinal scale) – are usually treated as of measured on ratio or proportional scale [11]. The relationship ratings are employed in later computation to obtain the EC priorities. The computation involves mathematical operations that should use measurements data on ratio scale. Inappropriate rating scale that is utilized in mathematical operation may lead to wrong prioritization of the ECs [11].

Several researches have developed mathematical models to solve those methodological problems. Askin and Dawson [12] and Park and Kim [13] proposed a mathematical model that involved the resource constraints and method to set the relationship ratings between ECs and ECs. An integrated QFD with stochasticity has been developed by Wang et al. [14]. Further, a new approach for engineering characteristics prioritization has been developed by Shi et al. [15] and Xiao et al. [16]. Then, a study from Ping et al. [17] extended the integrated approach to determine ECs prioritization in QFD. Likewise, Mistarihi et al. [18] developed the prioritization model by combining QFD models and fuzzy ANP to determine the weight for ECs. The sophisticated model using fuzzy theory have been developed by Kang and Nagasawa [19], Lim and Chin [20], Aydin et al. [21], Xing et al. [22] and Liu et al. [23]. However, those researches still leave the weakness about the absence of formal decision model to assist the design team in prioritizing and/or setting technical targets of the ECs, with the aim of maximizing customer satisfaction, and subject to organizational resource constraints.

After carrying out a thorough literature review, here are the unresolved matters that require further examination to address the weakness of the previous literature. First, the extant research so far still heuristically converts the CRs into design specifications, so it is difficult for decision makers to quantify exact numbers representing the relationship of CRs and ECs due to imprecise nature of human judgment. Second, the nature of decision makers differs significantly due to their background of knowledge and the goal of their departments which frequently contradict each other so it is hard to achieve agreement. Third, the effect of dependencies among ECs was not properly accounted for when prioritizing the ECs.

To respond to those weaknesses, this paper addresses those issues by modifying the traditional HOQ technique and developing a comprehensive mathematical model to derive the target of the ECs. The main contributions are:

(1) This study utilizes weighted average of the importance ratings to convert the CRs to ECs and to make a consensus among decision makers.

(2) This study proposes a relationship ratio to incorporate the effect of dependencies among ECs that was not addressed properly in the previous research.

(3) This study presents a method with a detailed process and numerical illustration that is supposedly advantageous for professionals in the industrial sector to convert customer expectations into design specifications.

2. THE PROPOSED MODEL

The proposed HOQ technique was developed based on Erdil and Arani [24] and Park and Kim [13], instead of determining the optimal EC set to be considered in the design, the aim of the proposed technique is to establish the optimal specifications. The procedure incorporates a method to elicit the utility weights in multi-attribute decision problems, i.e. swing method to assess the magnitudes of relationships between CRs and ECs. The weight of 0 represents the extremely irrelevant EC (so that can be regarded as no relationship with the concerned CR), while the value of 100 is assigned the most related EC [25-27]. Weights of the other ECs are defined proportional to that obtained by the most related EC. Then, the relationship rating between CR_i and EC_j (i.e. R_{ij}) is obtained by normalizing the weights, so that $\sum_{j=1}^{n} R_{ij}=1$ for all i.

The obtained rating shows a continuum of rating values specifying the sliding magnitude of the relationship, not only representing the order of strength (weak – medium – strong). Thus, those ratings are considered more meaningful. Afterward, the relationship ratings are normalized using Eq. (1) to accommodate the dependencies between ECs.

$$R_{i,j}^{norm} = \frac{\sum_{k=1}^{n} R_{i,k} \cdot \gamma_{k,j}}{\sum_{j=1}^{n} \sum_{k=1}^{n} R_{i,j} \cdot \gamma_{j,k}}, \gamma_{j,k} = \gamma_{k,j} \quad (1)$$

where,

$R_{i,j}^{norm}$ = normalized rating between CR_i and EC_j

R_{ij} = relationship rating between CR_i and EC_j

$\gamma_{j,k}$ = dependency rating between EC_j and EC_k

The new HOQ technique is presented in Figure 1.

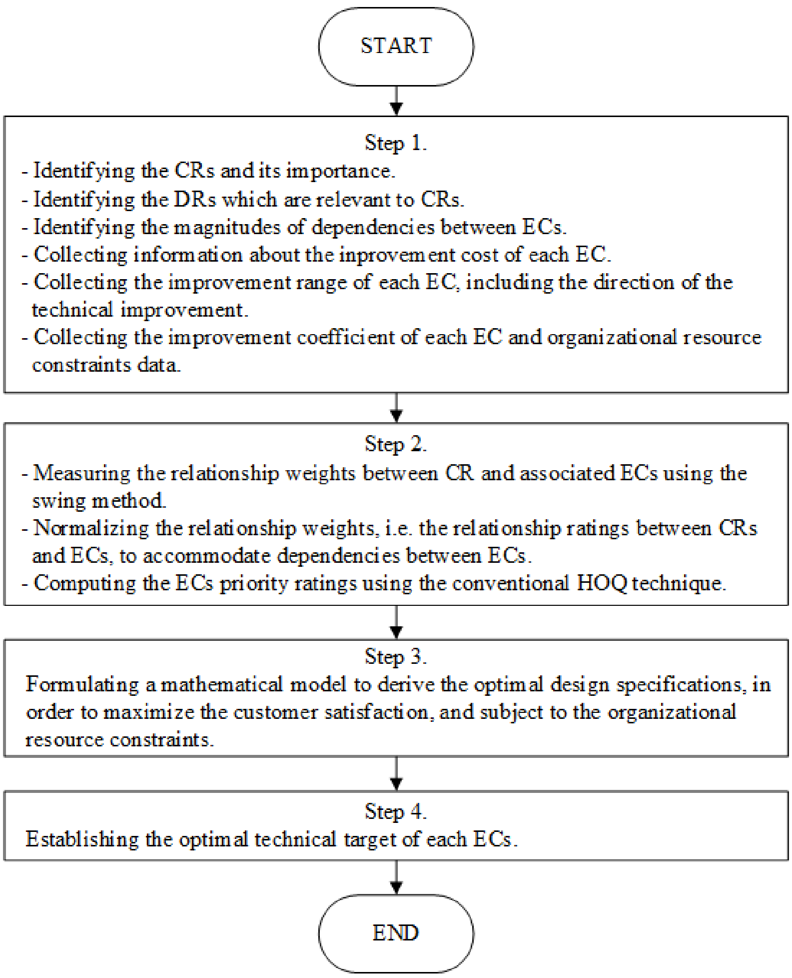


Figure 1. The proposed HOQ technique

The proposed technique begins by identifying the CRs as the main input for HOQ (step 1). There are three methods which are commonly used for gathering the CRs: interviews, focus groups and observing the product in use [28]. For most products, fifty interviews are possibly too many, but ten interviews are possibly not enough to reveal most of the CRs. As a practical guideline, for a product, thirty interviews might reveal 90 per cent of CRs, whereas 2 hours focus group uncover nearly the same number of CRs as two 1-hour interviews [29].

Then a survey is conducted to assess the importance rating of each CR. For CR_i, i=1 to m, the weighted average of importance ratings is computed using Eq. (2).

$$d_i^{average} = \frac{\sum_{n=1}^{p} Q'.n'}{Q} \quad (2)$$

where,

$d_i^{average}$ = the importance rating's weighted average for CR_i

Q' = number of respondents at rating n' (a p' point scale rating is used)

Q = total number of respondents

For the purpose of optimization model, $d_i^{average}$ is normalized, so that the sum of $d_i^{average}$ for all CR_i is equal to one (see Eq. (3)).

$$d_i^{average} = \frac{\sum_{n=1}^{p} Q'.n'}{Q} \quad (3)$$

D_i = the normalized importance of the CR_i

After the CRs are identified, the associated EC_j, j=1 to n, are generated, as technical metrics of CRs, and the magnitudes of dependencies between ECs are assessed. All of the correlation values between EC_j and EC_k, denoted as γ_{jk}, are placed on the top (the roof part) of HOQ.

Next, the technically achievable range for each EC is described, including its direction of improvement. The technically achievable range restricts the improvement span for EC, thus, the technically achievable range can be considered as the improvement range. For EC_j , the improvement range is defined by the lower bound L_j and upper bound U_j . In designing commercial products, the marginally acceptable range may be used as an additional constraint to the improvement span. Marginally acceptable range of certain EC represents the technical range that would just barely make the product commercially viable [28].

Also, information regarding the resource constraints is collected. The organizational resource constraint maybe described as the amount available cost and/or time to make improvement. The improvement coefficients (C_j), which represent the amount of resource needed to make a unit improvement of EC_j , need to be identified in defining a resource constraint. In this paper, the amount of available organizational resource is denoted by B.

In step 2, the swing method is applied to assess the relationship weight between CRs and ECs. Swing method is commonly used to assess the weights in an additive multi attribute utility function. Next, the normalization procedure (see Eq. (1)) is applied to the relationship ratings, to accommodate the dependencies between ECs. The priority ratings of each EC are computed using the conventional HOQ technique as shown by Eq. (4).

$$A_j = \sum_{i=1}^{m} D_i \, . R_{i,j}^{norm} \; \forall_j \quad (4)$$

where,

A_j = the absolute priority rating of the EC_j

Afterward, an optimization model is constructed (step 3). The complete formulation is presented by Eq. (5) to Eq. (7).

$$\text{Max } Z = \sum_{j=1}^{n} A_j . X_j \quad (5)$$

Subject to $\forall_j$; $X_j = \left|\frac{T_j - U_j}{U_j - L_j}\right|$ for the case the smaller the better, or

$$X_j = \frac{T_j - U_j}{U_j - L_j} \text{ for the case the larger the better} \quad (6)$$

$$\sum_{j=1}^{n} C_j \, . X_j \leq B \quad (7)$$

where,

Z = the achieved customer satisfaction level

L_j = the lower limit of the improvement range of EC_j

U_j = the upper limit of the improvement range of EC_j

T_j = the technical target of EC_j

X_j = the percentage of the technical improvement of EC_j

C_j = the improvement coefficient of EC_j

B = the amount of available resource for design improvement

The optimal design specifications are obtained by solving the optimization model to find the optimal technical target (T_j) for all j (step 4).

3. AN ILLUSTRATIVE EXAMPLE

The illustrative the new HOQ technique, an example of designing a wooden dining chair is presented. The first step in implementation of the new HOQ procedure is collecting input data. A survey conducted to identify the CRs of a dining chair. Thirty lead users were intensively interviewed. The interview results revealed that there are five CRs. Then, the second survey was conducted. 263 respondents filled the questionnaires to assess the importance of CRs in a four-point scale. For CR_i, the weighted average of the importance ratings ($d_i^{average}$) was computed using Eq. (2). As an example, $d_i^{average}$ was computed as follows. The respondents' assessment results for CR_i showed that there were 4 respondents assigned the value of 1, 20 respondents assigned the value of 2, 80 respondents assigned the value of 3 and 159 assigned the value of 4. Then, $d_i^{average} = \frac{(4\times1)+(20\times2)+(80\times3)+(159\times4)}{263}$, so $d_i^{average}$ is equal to 3.498.

Next, $d_i^{average}$ were normalized using Eq. (3) to obtain D_i, for all i. Description of CR_i and the associated $d_i^{average}$ for all i are shown by Table 1.

The weight of customer needs is obtained by dividing the average weight of each customer requirement by their total sum so that weight for CR_1, CR_2, CR_3, CR_4 and CR_5 are 0.228, 0.188, 0.206, 0.212. 0.164 respectively. Fifteen related ECs were generated to represent the CRs identified. Then, all γ_{jk}, improvement spans (denoted by L_j and U_j) and the direction of improvements were defined (as presented by Table 2). The improvement ranges were established with respect to technically achievable ranges and human anthropometry.

Meanwhile, the design team also collected the data concerning the resource constraint (i.e., C_j for all j and B). The existing dining chair was designed in the worst specifications, so it produced the worst customer satisfaction level (0%). There were some available resources to improve the dining chair design. In this case example, B was represented by the cost budget and C_j represented the cost needed to make a percentage improvement of EC_j.

Table 1. Customer requirement list

	Description	$d_i^{average}$
CR_1	Robust	3.498
CR_2	Unhampered seat	2.890
CR_3	Right height from the ground	3.171
CR_4	Comfortable back of seat	3.262
CR_5	Light weighted	2.521

Table 2. Engineering characteristics list

	Description	Improvement Range	Description of Improvement
EC_1	Length of front leg	5-7 cm	The larger the better
EC_2	Width of front leg	5-7 cm	The larger the better
EC_3	Height of front leg	39.5-41.5 cm	The smaller the better
EC_4	Length of back leg	5-7 cm	The larger the better
EC_5	Width of back leg	5-7 cm	The larger the better
EC_6	Height of back leg	39.5-41.5 cm	The smaller the better
EC_7	Width of seat	53.6-58.6 cm	The larger the better
EC_8	Length of seat	42.4-45 cm	The larger the better
EC_9	Seat thickness	1.2-4 cm	The larger the better
EC_{10}	Height of arm rest	23-24.5 cm	The smaller the better
EC_{11}	Length of arm rest	30.7-33.7 cm	The smaller the better
EC_{12}	Width of arm rest	9.1-10.8 cm	The larger the better
EC_{13}	Width of back of seat	43-46.6 cm	The larger the better
EC_{14}	Length of back of seat	55.3-59.9 cm	The larger the better
EC_{15}	Angle of back of seat (and horizontal axis)	90-100°	The larger the better

The available cost budget was IDR 10000. C_j for j=1 to 15 were as follows: 2312.02, 2312.02, -881.7, 2312.02, 2312.02, -881.7, 20047.35, 15858.35, 8067.864, -395.595, -711.24, 1222.436, 3837.169, 3974.722, 0. In this case, C_j mostly concerned with the material cost and the negative values of C_j were defined for EC_j with the smaller the better characteristic.

Then, the second step of the proposed technique was conducted. A technical expert was asked to assess the relationship weight between CRs and ECs using the swing method as follows:

(1) Two alternative designs were shown to the technical team, one leads to the worst specifications and the other leads to the best.

(2) The team was asked to rank the ECs, one by one, by specifying which EC that has the most significant impact on satisfying a certain CR if its value swings from the worst to the best.

(3) EC with the most significant impact on satisfying CR would obtain the value of 100. The other EC would be compared to the most significant and would be rated proportionally on 0-100 scale. The completely irrelevant EC would gain the weight of 0. The results are shown on Table 3.

The normalization procedure was employed so that the sum of the weights is equal to one, as can be seen in Table 4.

Table 3. The impact ratings of ECs to CRs

	EC_1	EC_2	EC_3	EC_4	EC_5	EC_6	EC_7	EC_8	EC_9	EC_{10}	EC_{11}	EC_{12}	EC_{13}	EC_{14}	EC_{15}
CR_1	50	50	70	50	50	100									70
CR_2							100	80		30	30				
CR_3			100			80			70						
CR_4													50	80	100
CR_5	20	20	40	20	20	40	100	70	70	20	20	20	70	70	

Table 4. The normalized impact ratings of ECs to CRs

	EC_1	EC_2	EC_3	EC_4	EC_5	EC_6	EC_7	EC_8	EC_9	EC_{10}	EC_{11}	EC_{12}	EC_{13}	EC_{14}	EC_{15}
CR_1	0.114	0.114	0.159	0.114	0.114	0.227									0.159
CR_2							0.417	0.333		0.125	0.125				
CR_3			0.400			0.32			0.280						
CR_4													0.217	0.348	0.435
CR_5	0.033	0.033	0.067	0.033	0.067	0.067	0.167	0.117	0.117	0.033	0.033	0.033	0.117	0.117	

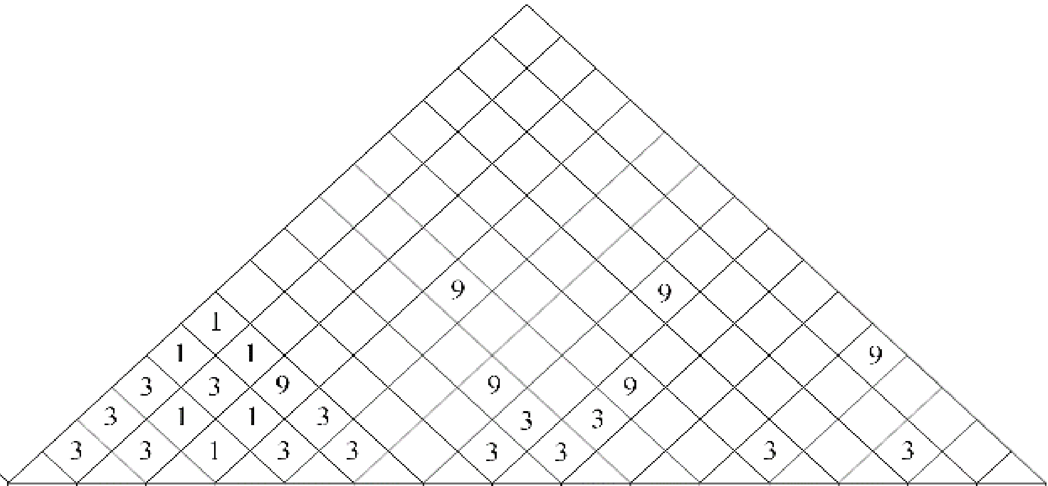
Then, the other normalization procedure (Eq. (1)) was employed to the normalized weights. The normalization results were arranged in the relationship matrix of the HOQ. The example of normalization for R_{33} is as follows:

$$R_{33}^{norm} = \frac{R_{33}.\gamma_{33} + R_{36}.\gamma_{63} + R_{39}.\gamma_{93}}{R_{33}.\gamma_{33} + R_{36}.\gamma_{63} + R_{39}.\gamma_{93} + R_{33}.\gamma_{63} + R_{36}.\gamma_{66} + R_{39}.\gamma_{96} + R_{33}.\gamma_{93} + R_{36}.\gamma_{69} + R_{39}.\gamma_{99}}$$

$$R_{33}^{norm} = \frac{(0.4*1) + (0.32*9) + (0.28*9)}{(0.4*1) + (0.32*9) + (0.28*9) + (0.4*9) + (0.32*1) + (0.28*9) + (0.4*9) + (0.32*9) + (0.28*1)}$$

Later, the absolute importance for the EC_j (that is A_j) were computed for all j (Eq. (4)). For example: $A_1 = (0.228 * 0.128) + (0.164 * 0.035) = 0.035$.

Then, the complete HOQ matrix could be developed as shown by Figure 2.



Normalized Importance		EC_1	EC_2	EC_3	EC_4	EC_5	EC_6	EC_7	EC_8	EC_9	EC_{10}	EC_{11}	EC_{12}	EC_{13}	EC_{14}	EC_{15}
CR_1	0.228	0.128	0.128	0.248	0.139	0.139	0.204									0.013
CR_2	0.19							0.162	0.353		0.129	0.357				
CR_3	0.206			0.305			0.339			0.356						
CR_4	0.212													0.468	0.371	0.161
CR_5	0.164	0.035	0.035	0.131	0.035	0.35	0.131	0.126	0.057	0.143	0.025	0.078	0.009	0.13	0.031	
Absolute Importance		0.035	0.035	0.141	0.037	0.037	0.138	0.051	0.076	0.097	0.029	0.081	0.001	0.121	0.084	0.037

Figure 2. The complete HOQ for a dining chair design

Table 5. Optimal solution

Variable	Value	Variable	Value
T_1	5 cm	X_1	0%
T_2	5.376 cm	X_2	18.784%
T_3	39.5 cm	X_3	100%
T_4	7 cm	X_4	100%
T_5	7 cm	X_5	100%
T_6	39.5 cm	X_6	100%
T_7	53.6 cm	X_7	0%
T_8	42.4 cm	X_8	0%
T_9	1.2 cm	X_9	0%
T_{10}	23 cm	X_{10}	100%
T_{11}	30.7 cm	X_{11}	100%
T_{12}	9.1 cm	X_{12}	0%
T_{13}	46.6 cm	X_{13}	100%
T_{14}	59.9 cm	X_{14}	100%
T_{15}	100°	X_{15}	100%

The third step is formulating the optimization model. The appropriate mathematical model is presented by Eq. (8) to Eq. (24).

$$\begin{aligned}\text{Max } Z = {} & 0.035X_1+0.035X_2+0.141X_3+0.037X_4 \\ & +0.037X_5+0.138X_6+0.051X_7+0.076X_8 \\ & +0.097X_9+0.029X_{10}+0.081X_{11}+0.001X_{12} \\ & 0.121X_{13}+0.121X_{14}+0.037X_{15}\end{aligned} \quad (8)$$

Subject to

$$X_1 = (T_1 - 5)/(7 - 5) \quad (9)$$

$$X_2 = (T_2 - 5)/(7 - 5) \quad (10)$$

$$X_3 = |(T_3 - 41.5)/(41.5 - 39.5)| \quad (11)$$

$$X_4 = (T_4 - 5)/(7 - 5) \quad (12)$$

$$X_5 = (T_5 - 5)/(7 - 5) \quad (13)$$

$$X_6 = |(T_6 - 41.5)/(41.5 - 39.5)| \quad (14)$$

$$X_7 = (T_7 - 53.6)/(58.6 - 53.6) \quad (15)$$

$$X_8 = (T_8 - 42.4)/(45 - 42.4) \quad (16)$$

$$X_9 = (T_9 - 1.2)/(4 - 1.2) \quad (17)$$

$$X_{10} = |(T_{10} - 24.5)/(24.5 - 23)| \quad (18)$$

$$X_{11} = |(T_{11} - 33.7)/(33.7 - 30.7)| \quad (19)$$

$$X_{12} = (T_{12} - 9.1)/(10.8 - 9.1) \quad (20)$$

$$X_{13} = (T_{13} - 43)/(46.6 - 43) \quad (21)$$

$$X_{14} = (T_{14} - 55.3)/(59.9 - 55.3) \quad (22)$$

$$X_{15} = (T_{15} - 90)/(100 - 90) \quad (23)$$

$$\begin{gathered}2312.02X_1+2312.02X_2+(-881.7X_3)+2312.02X_4 \\ +2312.02X_5+(-881.7X_6)+20047.35X_7+15858.35X_8 \\ +8067.864X_9+(-395.595X_{10})+(-711.24X_{11}) \\ +1222.436X_{12}+3837.169X_{13}+3974.722X_{14} \\ +(0)X_{15} \leq 10000\end{gathered} \quad (24)$$

Lingo 19.0 was used to solve the optimization model to derive the optimal specifications. T_j and the associated X_j, for all j, are shown in Table 5.

The optimal specifications lead to the customer satisfaction score of 71.15%. The graphical representation of the dining chair with optimal specifications is shown by Figure 3.

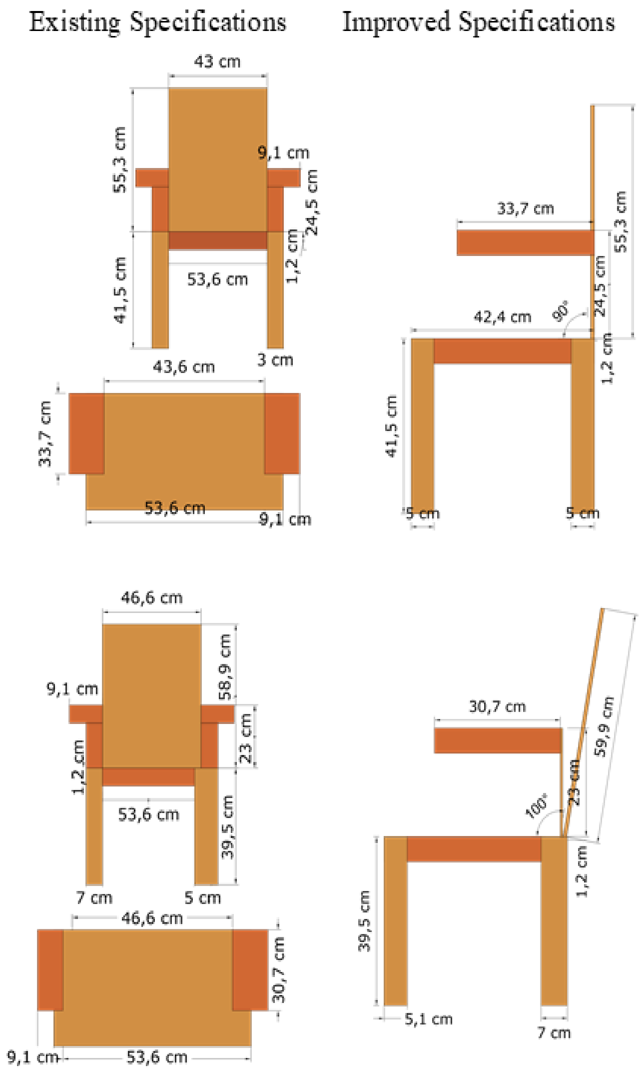


Figure 3. Existing and improved design

4. ANALYSIS AND DISCUSSION

In the formation of HOQ matrix, several pieces of information are required, namely customer needs, customer importance weights, technical characteristics, CRs and ECs relationships, ECs relationships and absolute importance. The relationship ratings between ECs have been normalized. With this normalization, it is expected that new priorities can be formed as it accommodates the relationships between engineering characteristics. For example, comfortable back of seat (*CR_4*), which is related to engineering characteristic backrest position (*EC_{15}*), before normalization, *EC_{15}* was the dominant characteristic influencing *CR_4* with a rating value of 0.435. However, after normalization, *EC_{15}* becomes non-dominant, with a value of 0.16. This is because *EC_{15}* does not have a relationship with other engineering characteristics (in this case, *EC_{13}* and *EC_{14}*).

To determine customer satisfaction level, it has been expressed with mathematical Eq. (5). X_j represents the percentage of technical improvement of EC_j with values ranging from 0 to 1, and A_{ij} is the absolute priority rating of the EC_j . The maximum value obtained for customer satisfaction is 1 (100%). The range constraint of EC_j is established with Eq. (6), where T_i represents the technical target of EC_j with lower and upper limit of the improvement range. Another main constraint is the product development cost represented by Eq. (7). If there is no improvement in EC_j, then the value of C_i for that EC_j will be 0.

We can see from Table 5 the optimal solution, it is apparent that for X_1, X_7, X_8, X_9, and X_{12}, the values are 0, indicating that their performance is within the minimum range of characteristics or equal to the initial characteristics. Conversely, X_3, X_4, X_5, X_6, X_{10}, X_{11}, X_{13}, X_{14}, and X15 are within the performance range of maximum characteristics.

The sensitivity analysis was conducted to determine the change in budget towards customer satisfaction. Table 6 illustrates the contribution of budget changes for every increase of 1000 IDR towards the improvement of customer satisfaction. In this numerical example, the given budget is 10000 IDR, resulting in a customer satisfaction level of 71.15% at this budget.

Table 6. Sensitivity analysis on budget change to customer satisfaction improvement

Budget (IDR)	Customer Satisfaction (%)	Delta
1000	54.77	
2000	56.88	2.11
3000	58.99	2.11
4000	61.11	2.12
5000	63.19	2.08
6000	64.79	1.60
7000	66.39	1.60
8000	67.99	1.60
9000	69.59	1.60
10000	71.15	1.56
11000	72.67	1.52
12000	74.19	1.52
13000	75.70	1.51
14000	77.20	1.50
15000	78.47	1.27
16000	79.67	1.20
17000	80.88	1.21
18000	82.08	1.20
19000	83.28	1.20
20000	84.48	1.20
21000	85.68	1.20
22000	86.89	1.21
23000	87.55	0.66
24000	88.03	0.48
25000	88.51	0.48
26000	88.99	0.48
27000	89.47	0.48
28000	89.95	0.48
29000	90.43	0.48
30000	90.91	0.48

Table 6 indicates that an increase in the budget by 1000 IDR results in a customer satisfaction improvement of approximately 2%. However, when the budget exceeds 23000 IDR, the increase in customer satisfaction becomes insignificant, reaching only 0.48%.

5. CONCLUSIONS

This paper has proposed a formal HOQ technique to determine the technical target of ECs. The swing method and Wasserman's normalization procedure was employed to obtain better relationship ratings. A mathematical model was developed to maximize customer satisfaction, subject to available organizational resources. The proposed procedure was applied in designing a wooden dining chair and has improved the customer satisfaction. A sensitivity analysis has been conducted to obtain the optimal budget to yield customer satisfaction.

Several contributions to the body of knowledge have been obtained to offer a new mathematical model. First, this study contributes to the using of weighted average of the importance rating to convert the customer requirements to engineering characteristics. Second, this study contributes to the engineering characteristics relationship ratio to incorporating the effect of dependencies. Also, contributions to product development practitioners by providing mathematical models and their procedures facilitate practitioners in translating consumer desires into technical characteristics to achieve optimal consumer satisfaction within technical specifications and cost constraints, with detailed numerical example.

However, the proposed technique still used ratings which were measured on interval (even on ordinal scale) i.e. CRs' importance ratings and correlation between ECs. For future research, better weighting methods need to be employed to assess those values.

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