QFD-Operational Research as an Integrated Method for Developing Product Design Process in One-of-a-Kind Production

Mohaddeseh Ahmadipourroudposht, Noordin Mohd Yusof*, Kuan Yew Wong*
Department of Materials, Manufacturing & Industrial Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

**industrialmanagment@yahoo.com, noordin@fkm.utm.my*

ABSTRACT

The product design process is an early stage of new product development that helps in improving the company competitiveness in the current turbulent environment thus fulfilling the markets requirements in terms of cost, quality and time. Traditional techniques for fulfilling the customer's expectation are less effective in the modern markets due to constraints. Usually, the customer's requirements are not fulfilled by the available product design and it requires significant modification in order to satisfy the customer's needs. This study involves highly systematic methods including quality function deployment (QFD) and operational research such as analytic network process (ANP) and multi-objective decision making (MODM) techniques for enabling a design to be more compatible with future customers' requirements. Initially, the QFD team was established to determine the customer's requirements based on house of quality. These were then prioritized based on the normal procedure of ANP. Later, the customer's requirements were translated into product technical attributes and their relative importance was characterized based on ANP. In the last step of QFD, the technical attributes target values were calculated using a MODM model which refers to the available constraints such as budget and technical limitations. A one-of-a-kind production (OKP) company which is based on the mass-customized production was used as the numerical validation. The selected product was a dry gas filter. The practical results indicated that the design obtained was more compatible with the customer's needs thus

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2017-02-15
Accepted for publication: 2017-09-26
Published: 2018-03-15

requiring fewer modifications and subsequently achieved remarkable saving of production time and cost.
Keywords: *Product design; QFD, ANP, Multi-objective decision making.*

1. Introduction

In the past decade changes in the rate of market and technology has been accelerated. The companies' competitive strategy success in the current turbulent environment is highly dependent to the capacity to develop the new products **[1, 2]**. In the other words, the economic success rate of a company can be determined through new product development (NPD) strategy **[3]**. In order to develop a successful NPD strategy, an emphasis on efficient product design procedure that leads to reduction in the design and development cost/time **[4, 5]**. However, by launching an efficient product design procedure through considering all the manufacturing concerns upstream and customers' requirements, the engineering modifications, inclusive cost and production time can be reduced **[5]**. In order to enhance the NPD procedure, many new techniques have been introduced over the recent decades. The major categories of the current techniques are known as; (i) Quick product specification, (ii) design for excellence (DFX), (iii) rapid prototyping and tooling, (iv) failure mode effect analysis (FMEA), and (v) quality function deployment (QFD) **[6-8]**.

One-of-a-kind production (OKP) is known as any particular type of new product design and development with emphasis on special order concept **[9, 10]**. Against the mass production paradigm that reduced the cost through eliminating the products variations, the OKP can fulfill the requirements of a particular customer **[11, 12]**. Commonly, one-of-a-kind production is related to heavy industries, particularly in developing countries where these industries are usually considered as national industries and are in much more importance than developed countries.

Among the four known manufacturing strategy including: (i) Make-to-stock (MTS), (ii) make-to-order (MTO), (iii) assemble-to-order (ATO), and (iv) engineering-to-order (ETO), mainly one-of-a-kind production is related to the latter two strategies (ETO, ATO), while, most of the researches in the field of production management is related to the first two strategies (MTS, MTO). In other words, although one-of-a-kind production has relatively long history in terms of theoretical research, the mass production and lean manufacturing paradigms neglected the research on this field **[13-15]**. So, theoretical and academic research on issues related to the one-of-a-kind production is very limited and insufficient.

Often the OKP companies have some prepared designs that according to the customer's requirements the most appropriate one is selected and the necessary modification is applied on them, instead of doing complete design of new products based on any particular customer's requirements. Thus, the main objective of this research is to provide a design to be mostly near to the customer's expectation **[16]**.

2. Quality Function Deployment (QFD)

Quality function deployment (QFD) is a very comprehensive and fashionable technique for designing a new product **[17]**. QFD was developed to translate the customer's expectations into the modern manufacturing techniques **[18]**. The QFD technique can be used for both tangible (products) and non-tangible (services), including manufactured goods, service industry, software products, IT projects, business process development, government, healthcare, environmental initiatives and many other applications. Since the growing distance between producers and users is a concern in current industrial society, QFD tries to links the customer's need (end user) with design, development, engineering, manufacturing, and service functions **[19, 20]**. For the first time, in the late 1960s was developed in Japan as a form of cause-and-effect analysis. Later QFD was brought to the United States in the early 1980s **[17, 18]**. It expanded its early popularity as a result of numerous successes in the automotive industry. QFD technique is described as: (i) Acquisition and understanding customer requirements, (ii) Quality systems thinking + psychology + knowledge/epistemology, (iii) Maximizing positive quality that adds value, (iv) Comprehensive quality system for customer satisfaction, and (v) Strategy to stay ahead of the game **[21-23]**.

Traditional quality control planning often considered quality without any failure **[24]**. Against, QFD method defines quality as customer satisfaction and offers proper operational framework for compliance to essentials of this definition. Quality specialists refer to QFD method using many names, including matrix product planning, decision matrices, and customer-driven engineering **[14, 18-20]**. Whatever it is called, QFD is a focused technique to listen to the voice of the customer carefully and then effectively responding to those needs and expectations **[17]**.

In order to facilitate the process development, the matrix diagrams are used for organizing the collected data. The diagrams are used to demonstrate the required information about the level to which customers' expectations are being met and the exist resources to fulfill those expectations. The structure in which QFD uses for information organizing is acknowledged as the house of quality. The house of quality should be generated by a team of people with different skills and first-hand knowledge about the company capabilities and the expectations of the customers in order to achieve the goal. Effective use of QFD requires team participation and discipline inherent in the practice of QFD, which has proven to be an excellent team-building experience **[25]**.

Four-phase QFD matrices is an approach that represents four phases in new product development as; (i) Product planning, (ii) part planning/deployment, (iii) process planning, and (iv) process control **[26, 27]**. In this case, product planning phase is the main concern to develop the process of product design. This phase is usually performed by the marketing department. The product planning is also known as the house of quality. Many organizations only get through this phase of a QFD process. This phase documents the customer's needs, data of warranty period, competitive opportunities, product performance measurements, competing product measures, and the technical ability of the organization to fulfill the customer need. Acquisition of appropriate data from the customer in this phase is critical to the success of the entire QFD process **[28, 29]**.

3. Analytic Network Process (ANP)

The ANP is an advanced form of analytic hierarchical process (AHP) that is used in QFD process to determine the priority of criteria and alternatives. Unlike the AHP that decompose the steps into a hierarchical order, ANP consider the whole process as a network and inner dependence of criteria and alternatives are reflected in decision making **[30, 31]**. Usually, decision making using ANP approach consists of four steps: (i) network development to illustrate the objective, (ii) acquisition and prioritization of criteria and alternatives through pairwise comparison, (iii) formation of supermatrix and (iv) ranking of decision alternatives **[19]**. In this case, the purpose of ANP approach was to provide a systematic analysis for customer's requirement prioritization and efficient translation into technical attributes that their target values were obtained through a multi-objective decision model. Thus, formation of supermatrix and ranking of decision alternatives was not considered. Figure 1 depicts the QFD house of quality model and representative ANP network.

The integrated QFD-ANP approach was used as described in the following steps to design a new product based on customers' requirements and priority as well as budget and technical constraints. The customer satisfaction beside the reasonable cost for both manufacturer and customer is as important as quality of the product.

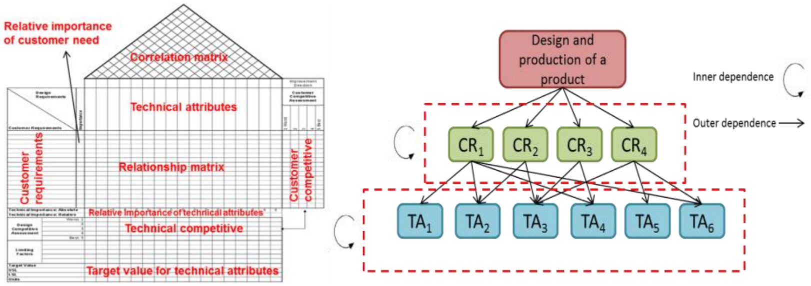


Figure 1: QFD house of quality and representative ANP network

3.1 Determining the customer’s requirements

The QFD team including specialist in various fields was established for acquisitioning and analyzing the customer’s requirements. Commonly, in order to design any product, manufacturers are faced with two types of customer requirements. (I) The first type is the demands which expressed as specified properties with determined standards. This category of customer’s requirements is classified in Kano's basic needs **[32]**. Meeting the customer requirements is essential and manufacturers are not able to modify those demands, while, (II) the second type of customer requirements are not expressed as the specified properties with determined standards and are expressed in customers’ language as qualitative statements. This category of customer’s requirements is classified in Kano's performance needs **[28, 29]**. The manufacturer is able for planning to fulfill these demands within their limitations. Usually in QFD concept in OKP Company, in order to hear the voice of customers a series of instruments such as questioner, interview or particularly customers feedback about the product function, law enforcement reports, obtained data from the warranty period, customers’ complaints and direct observation of the consumer’s behaviour are considered. In the house of quality the customer’s requirements were listed as criteria. The inner relationships among the criteria were considered to determine the customer’s requirements priority.

Based on QFD concept, the customer’s requirements were translated into technical attributes of product. House of quality (HOQ) is the most applicable tool for organizing the QFD procedure. The technical attributes were listed as the alternatives in the house of quality. Here, in the real world definitely there is the inner dependence between technical attributes which cannot be considered hierarchically. Following the QFD principle, the priority of customer’s requirements as well as technical attributes was achieved based on pairwise comparison and ANP approach. The priority of technical attributes must be defined in order to be optimized subject to available constraints based on their importance.

3.2 Pairwise comparison matrix and consistency ratio

In this phase the pairwise comparison matrix of customers' requirements, inner dependence of customers' requirements, technical attributes and inner dependence of technical attributes were conducted and their consistency ratio was checked. The consistency ratio is an index to check the accuracy of experts' opinion in pairwise comparison. The consistency ratio value should be less than 0.1 to be desirable; otherwise the pairwise comparison should be repeated. Consistency ratio was calculated using Equation 1**[33]**:

$$CR = {CI}/_{RI} \tag{1}$$

where, "*CI*" is the consistency index, and "*RI*" is the random index.

The consistency index was calculated using Equation 2:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where, "λ_{max}" is the average of weighted sum (ratio of consistency vector to priority vector) in matrix, and "*n*" is the number of criteria (matrix size).

The random index was obtained from the "*RI*" table was founded by Saaty, **[34]** and tabulated in Table 1.

Table 1: Random index (*RI*) table for (n≤10) (Saaty, 1977)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

3.2.1 Ranking the customer's requirements weights using ANP approach

In order to rank the customer's requirement priorities, initially the inner dependence flow chart of the criteria (customer's requirements) was determined based on experts' opinion. Later as normal procedure of ANP, the criteria based on their influence on every main target were compared together using pairwise comparison questionnaire. Pairwise comparison was done based on what is explained in Saaty **[35]**. Briefly, a 1-9 scale of comparison is used to measure the dominance of two elements. The respondents were asked to rank between two elements according to 1-9 scale of Saaty. 30 customers were selected to fill the questionnaires in order to get appropriate sample size. Table 2 tabulated the pairwise comparison scale as the reference for judging. The pairwise comparison matrix for customer's requirements was formed by putting the geometric means of the values obtained from the 30 filled questionnaires. This matrix was normalized and the local priority vector was obtained (W_{21}).

Table 2: 1-9 scale of comparison

Importance rate Definition	Values
Equally Preferred	1
Equally to Moderately Preferred	2
Moderately Preferred	3
Moderately to Preferred	4
Preferred	5
Preferable to Strongly Preferred	6
Strongly Preferred	7
Very Strongly Preferred	8
Extremely Preferred	9

On the other hand, based on the inner dependence flowchart, the criteria (which have relationship to each other) were compared pairwise based on a criteria as the control. The obtained matrices were normalized for achieving the priority vector. Later those vectors were combined to conduct the dependence matrix of customer's requirements (W_{22}). The eigenvector (customer's requirements priority) was obtained using Equation 3 **[35]**:

$$E_v = W_{21} \times W_{22} \tag{3}$$

where, "E_v" is the eigenvector, "W_{21}" is the local priority vector obtained from customer's requirements and "W_{22}" is the inner-dependence matrix.

<u>3.2.2 Ranking the technical attributes weights using ANP approach</u>

Likewise, the related technical attributes to each customer's requirements were compared pairwise refer to each customer's requirements as the control. The pairwise comparison matrices were conducted and priority vectors were obtained through normalizing the matrices. Later the priority vectors were combined together to conduct the matrix of relationship between customer's requirements and technical attributes (W_{32}). The Saaty 1-9 scale and pairwise comparison questionnaire was used.

On the other hand, based on the inner dependence flowchart of the technical attributes, the alternative (which have relationship to each other) were compared pairwise, normalized and combined to conduct the inner dependence matrix of technical attributes (W_{33}). The adjusted relationship matrix was obtained using Equation 4:

$$Adj._{RM} = W_{32} \times W_{33} \tag{4}$$

where, "$Adj._{RM}$" is the adjusted relationships matrix, "W_{32}" is the relationships matrix between customer's requirements and technical attributes, and "W_{33}" is the inner-dependence matrix.

Finally, the priority of technical attributes was obtained through multiplying the adjusted relative matrix by eigenvector of customer's requirements as Equation 5:

$$TA_{Priority} = Adj._{RM} \times E_v \tag{5}$$

where, "$Adj._{RM}$" is the adjusted relationships matrix, and "E_v" is the eigenvector of customer's requirements.

3.2.3 Multi-objective decision model

The last step in the first house of quality was to determine the target values for each technical attribute of the product **[35, 36]**. Here, based on the concurrent engineering approach, despite the technical constraints, the budget and competitive constraints were the involved factors in determining the target values, as well. Thus application of mathematical programming was necessary to model the function. In QFD cases, it is likely that a technical attribute may have different positive and negative effect on two different customer's requirements. Thus, increase/decrease the value of that technical attribute in order to meet a customer's requirements, may leads to promote/decrease of one while decrease/promote of the other one. This was the point that has never been considered in previous researches. In the other word, If the attribute number "j" in set of technical attributes be effective on customer demand number "i" and also on customer demand number "$i+n$", so this is possible that increasing/decreasing the value of attribute number "j", simultaneously have resulted on promoting/reducing the customer satisfaction from demand number "i" and reducing/promoting the customer satisfaction from demand number "$i+n$", respectively. In order to overcome this limitation, the partial satisfactions of customer's requirements were modelled separately in the objective function. The partial satisfactions function was as Equation 6:

$$S_i = \sum_{j=1}^{n} T_{ij} \frac{K_j}{x_j^{max} - x_j^{min}} \tag{6}$$

where, "S_i" is the partial satisfaction refer to CR_i, the "T_{ij}" is the weight of technical attribute "j^{th}" refer to CR_j, the "x_j^{max} and x_j^{min}" are the upper and lower licensed variation limits for technical attributes, respectively and "K_j" is defined as Equation 7:

$$\begin{cases} K_j = x_j^{max} - x_j & \text{Attributes with positive effect} \\ K_j = x_j - x_j^{min} & \text{Attributes with negative effect} \end{cases} \quad (7)$$

Conversion scaling changed the values within [0, 1], which (0) value indicated the exact match with positive ideal value and (1) indicated the exact match with negative ideal value. Thus, the exact match of all the attributes with ideal values makes the "S_i" equal to zero.

The partial satisfaction functions were transformed to ideal constraints through defining the 'zero' as the goal value for the objective functions, and adding the slack and excess deviation variables of goal (Equation 8):

$$S_i = \sum_{j=1}^{n} T_{ij} \frac{K_j}{x_j^{max} - x_j^{min}} + d_i^- - d_i^+ = 0 \quad (8)$$

where, d_i^- and d_i^+ are the slack and excess deviation variables, respectively.

The objective was to reduce the undesired deviation variable (d_i^+). Through dedicating the weights of each partial satisfaction, the total objective function and model (goal programming) is defined as Equation 9:

$$Min\ Z = \sum_{i=1}^{m} V_i d_i^+$$

$$S_i = \sum_{j=1}^{n} T_{ij} \frac{d_j}{x_j^{max} - x_j^{min}} + d_i^- - d_i^+ = 0$$

ST.

$$x_j^{min} < x_j < x_j^{max}$$

$$\sum_{j=1}^{n} C_j x_j \leq B$$

(9)

where, "V_i" is the weight of customer's requirements, "T_{ij}" is the weight of technical attributes, "x_j^{max} and x_j^{min}" are the upper and lower licensed variation limits for technical attributes, "C_j" is the cost of technical attribute and "B" is the budget.

4. Case Study

The Parto Petro-Gas Industry.™ (PPI) started activities in 2005 in the field of oil, gas, petrochemical equipments manufacturing as well as steel and power plants industry. The company achieved the mission in terms of providing the maximum satisfaction of the customer's requirements. The dry gas filter among the company's product was selected to be redesigned using QFD-operational research techniques.

All the gas flow pipelines have dry contaminants (such as pipe scale, dirt, and rust) that will damage or even destroy the downstream equipment. Thus using a dry gas filter is necessary to remove all forms of dry contamination in order to lengthening the durability of the compressor vanes and saving thousands of dollars in maintenance costs and downtime. Dry gas filter is one of the main components of gas transfer system that are particularly used in pressure drop stations. The dry gas filter operation can be defined as scrubber to remove the existed solid particles in the gas flow through crossing from a porous element. PPI™ dry gas filter product is designed with multiple elements for removing dust and other solids from gas stream with a minimum drop in pressure and heat of combustion. PPI gas scrubber uses centrifugal force to effectively remove solid particles from the gas flow.

The filter is a horizontal/vertical cylindrical tube that has an inlet and outlet valve. The gas flow goes through the filter and the solid particles are separated and the filtered gas flow obtained from outlet valve. The main component of the dry gas filter is the cartilage that through a centrifugal force separates the solid particles. The particles are accumulated at the bottom of the tube. A drain is designed at the bottom of tube to remove the residue. At the top of the chamber, a closure is designed that is used to remove the cartilage for cleaning/changing purpose. The dimensions of the body height/diameter, cartilage height/diameter, inner diameter, thickness, inlet distance, drain height and others are the specifications that can be modified according to the application and customer's expectations. Figure 2 illustrates the structure of a vertical dry gas filter.

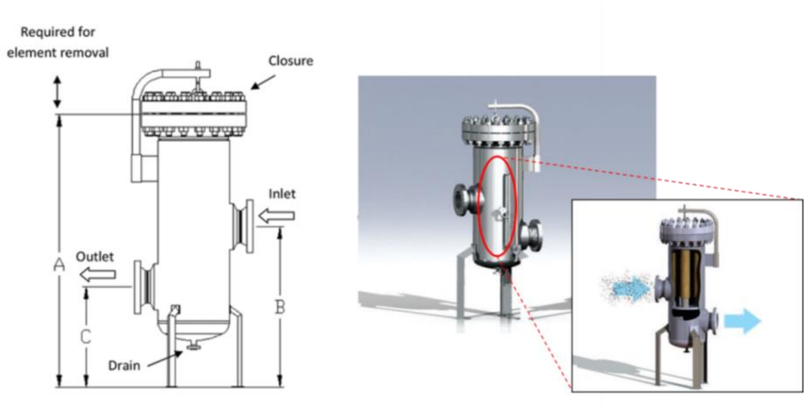


Figure 2: Schematic of exterior and interior of a vertical dry gas filter

5. Results and Discussion

The QFD team member including sales/aftersales manager, technical manager, quality control supervisor and two PhD student in the field of industrial and mechanical engineering (in association with R&D unit) through several interview sessions with the customers and other documents such as customer's feedback on product performance, warranty period results, customer's complaint, law enforcements report identify and categorized the customer's requirements into 5 main group. Quality of the gas output (QO), pressure drop (PD), dimensions (D), cartilage durability (CD), and cleaning period (CP) were the customer's requirements. Thus, the house of quality criteria number was five.

5.1 Prioritize the customer's requirements

The pairwise comparison questionnaire was designed and the experts and customers were asked to determine their priority between two particular criteria. The criteria were compared pairwise and the data was collected. The geometric mean of the data obtained was calculated and insert into the matrix as depicted in Table 3. Later, the matrix was normalized and the priority vector was obtained as Table 4 (Matrix W_{21}). The consistency ratio was 0.07 which is less than 0.1 and desirable. Currently, the weights obtained are based on AHP technique. In order to change the AHP to ANP, inner dependence should be considered. After this in order to minimize the paper volume, the pairwise comparisons matrices after normalization are used and normalization procedure was done but exempt from showing.

Table 3: Pairwise comparison results between customer's requirements

	QO	PD	CD	CP	D
Quality of output (QO)	1.000	5.000	4.000	5.000	7.000
Pressure drop (PD)	0.200	1.000	0.333	1.000	5.000
Cartilage durability (CD)	0.250	3.000	1.000	1.000	5.000
Cleaning period (CP)	0.200	1.000	1.000	1.000	5.000
Dimension (D)	0.142	0.200	0.200	0.200	1.000

Table 4: Normalized matrix and priority vector of customer's requirements

	QO	PD	CD	CP	D	Priority vector
QO	0.5578	0.4902	0.6122	0.6098	0.3043	0.5149
PD	0.1116	0.0980	0.0510	0.1220	0.2174	0.1200
CD	0.1394	0.2941	0.1531	0.1220	0.2174	0.1852
CP	0.1116	0.0980	0.1531	0.1220	0.2174	0.1404
D	0.0797	0.0196	0.0306	0.0244	0.0435	0.0396

*.Consistency ratio (CR) = 0.07< 0.1

5.1.1 Inner dependence of customer's requirements

Figure 3 illustrates the inner dependence flowchart of customer's requirements. The pairwise comparison was done. For example Table 5 tabulated the pairwise comparison and priority vector refer to quality of output as the control. Likewise, 3 more matrices were conducted, normalized and priority vectors were obtained and combined to achieve the inner relationship matrix of customer's requirements as Table 6 (Matrix W_{22}). Since there is no relationship between any criteria on dimension, the values were all equal to zero. The eigenvector of customer's requirements (priority) was obtained using Equation 3 as tabulated in Table 6.

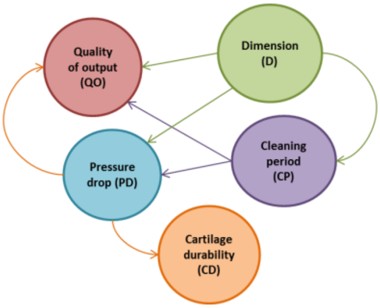


Figure 3: Flowchart of inner relationship of customer's requirements

Table 5: Pairwise comparison matrix and priority vector based on "QO"

Quality of Output	QO	PD	CP	D	Priority vector
Quality of output (QO)	1.000	9.000	7.000	7.000	0.6816
Pressure drop (PD)	0.111	1.000	3.000	3.000	0.1683
Cleaning period (CP)	0.142	0.333	1.000	1.000	0.0750
Dimension (D)	0.142	0.333	1.000	1.000	0.0750

*.CR= 0.0907< 0.1

Table 6: Inner relationship matrix of customer's requirements (Matrix W_{22})

Matrix W_{22}	QO	PD	CD	CP	D	Eigen vector
Quality of output	0.681	0.000	0.000	0.000	0.000	**0.3509**
Pressure drop	0.168	0.776	0.111	0.000	0.000	**0.2004**
Cartilage durability	0.000	0.000	0.888	0.000	0.000	**0.1646**
Cleaning period	0.075	0.154	0.000	0.875	0.000	**0.1801**
Dimension	0.075	0.068	0.000	0.125	1.000	**0.1040**

5.2 Prioritize the technical attributes

Following the QFD concept, the customer's requirements were translated into technical attributes of the product. The technical attributes were the nine alternatives in the network. The technical attributes were listed in the house of quality as: (i) Cartilage height (CH), (ii) body diameter (BD), (iii) cartilage diameter (CDi), (iv) inner diameter (ID), (v) cartilage thickness (CT), (vi) filtration density (FD), (vii) inlet distance (InD), (viii) drain height (DH), and (ix) body height (BH). Table 7 illustrates the positive/negative relationship of technical attributes on customer requirements. The (⬀) represents the positive, (⬂) represents the negative and (●) represents the no-relationship between attributes and requirements.

Table 7: Relationship between technical attributes and customer's needs

	CH	BD	CDi	ID	CT	FD	InD	DH	BH
QO	⬀	●	⬀	●	⬀	⬀	⬀	●	●
PD	⬀	⬂	⬀	⬂	⬂	⬂	●	●	●
CD	⬀	⬀	⬀	⬀	⬂	⬂	⬀	⬀	●
CP	●	⬀	●	●	●	●	●	⬀	●
D	●	⬀	●	●	●	●	⬀	⬀	⬂

Base on the relationship (neglect the positive/negative effect) between technical attributes and requirements, the technical attributes were compared pairwise using Saaty 1-9 scale. For this purpose the relative importance (priority vector) of technical attributes refer to each customer's requirements were defined and was then combined into a relationship between customer's requirements and technical attributes matrix (Matrix *W32*). For example Table 8 tabulated the pairwise comparison matrix of technical attributes on "criteria: quality of output" as customer requirement. Likewise, 4 more matrices were conducted, normalized and priority vectors were obtained. The priority vectors were combined as depicted in Table 9.

Table 8: Pairwise comparison of technical attributes (Criteria: QO)

Criteria: Quality of output	CH	CDi	CT	FD	InD	Priority vector
Cartilage height (CH)	1.000	1.000	3.000	4.000	7.000	0.3600
Cartilage diameter (CDi)	1.000	1.000	3.000	5.000	6.000	0.3677
Cartilage thickness (CT)	0.333	0.333	1.000	1.000	3.000	0.1208
Filtration density (FD)	0.250	0.200	1.000	1.000	3.000	0.1048
Inlet distance (InD)	0.142	0.166	0.333	0.333	1.000	0.0467

*.CR= 0.0161< 0.1

Table 9: Relationship matrix among technical attributes and customer's needs

	QO	PD	CD	CP	D
CH	0.3600	0.2651	0.1879	0.0000	0.0000
BD	0.0000	0.0610	0.0519	0.5000	0.3747
CDi	0.3677	0.0579	0.1984	0.0000	0.0000
ID	0.0000	0.0579	0.0278	0.0000	0.0000
CT	0.1208	0.2651	0.2207	0.0000	0.0000
FD	0.1048	0.2931	0.2019	0.0000	0.0000
InD	0.0467	0.0000	0.0643	0.0000	0.0745
DH	0.0000	0.0000	0.0471	0.5000	0.1569
BH	0.0000	0.0000	0.0000	0.0000	0.3939

5.2.1 Inner dependence of technical attributes

The technical attributes inner relationships are depicted in a flowchart as Figure 4. The pairwise comparison matrix of inner dependence of technical attributes on body height (BH) was conducted, normalized and the priority vector was obtained as shown in Table 10. The obtained priority vector was put into the inner relationship matrix of technical attributes (Matrix W_{33}). Here, due to no other inner dependence of technical attributes there was only one priority vector for body height column and obviously, the other elements in the inner relationship matrix column of technical attributes were following the identity matrix (I). Table 11 represents the inner relationship matrix between technical attributes.

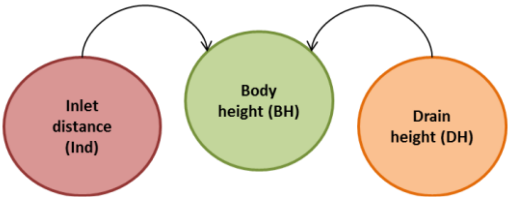


Figure 4: Flowchart of inner relationship of technical attributes

Table 10: Pairwise comparison matrix and priority vector of technical attributes on "body height"

Control: Body height	InD	DH	BH	Priority vector
Inlet distance (InD)	1.0000	3.0000	0.1429	0.1549
Drain height (DH)	0.3333	1.0000	0.1111	0.0685
Body height (BH)	7.0000	9.0000	1.0000	0.7766

*.CR= 0.0708< 0.1

The results of matrix of inner relationship technical attributes (Table 11) multiple by matrix of relationship between technical attributes and customer's requirements (Table 9) provided the adjusted relationship matrix as Table 12. Finally in order to find the technical attribute relative importance, the adjusted relationship matrix was multiplied by relative importance of customer requirements (eigenvector obtained in Table 6). The relative importance (priority) of technical attributes using ANP technique was listed as Table 13.

Table 11: Inner relationship matrix between technical attributes (Matrix W_{33})

	CH	BD	CDi	ID	CT	FD	InD	DH	BH
CH	1.00	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.0000
BD	0.00	1.00	0.00	0.000	0.000	0.000	0.000	0.000	0.0000
CDi	0.00	0.00	1.00	0.000	0.000	0.000	0.000	0.000	0.0000
ID	0.00	0.00	0.00	1.000	0.000	0.000	0.000	0.000	0.0000
CT	0.00	0.00	0.00	0.000	1.000	0.000	0.000	0.000	0.0000
FD	0.00	0.00	0.00	0.000	0.000	1.000	0.000	0.000	0.0000
InD	0.00	0.00	0.00	0.000	0.000	0.000	1.000	0.000	0.1549
DH	0.00	0.00	0.00	0.000	0.000	0.000	0.000	1.000	0.0685
BH	0.0	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.7766

Table 12: Adjusted relationship matrix between technical attributes and customer's requirements

	Quality of output	Pressure drop	Cartilage durability	Cleaning period	Dimension
CH	0.3600	0.2651	0.1879	0.0000	0.0000
BD	0.0000	0.0610	0.0519	0.5000	0.3747
CDi	0.3677	0.0579	0.1984	0.0000	0.0000
ID	0.0000	0.0579	0.0278	0.0000	0.0000
CT	0.1208	0.2651	0.2207	0.0000	0.0000
FD	0.1048	0.2931	0.2019	0.0000	0.0000
InD	0.0467	0.0000	0.0643	0.0000	0.1355
DH	0.0000	0.0000	0.0471	0.5000	0.1839
BH	0.0000	0.0000	0.0000	0.0000	0.3059

Table 13: Relative importance of technical attributes using ANP approach

CH	BD	CDi	ID	CT	FD	InD	DH	BH
0.2104	0.1497	0.1733	0.0162	0.1319	0.1288	0.0411	0.1169	0.0318

5.3 Determining the technical attributes target value using MODM model

The technical attributes target value was determined using proposed MODM model. For this purpose, the licensed variation limits of the technical attributes are tabulated in Table 14. The budget for production of one product estimated as 10,000 USD. Based on Equations (6 to 8) the partial satisfactions (customer's requirements) were converted to scale less value and formulated separately. For example the partial satisfaction with "quality of output" as criteria is shown in Equation 10.

Table 14: Licensed variation limits of the technical attributes (cm, g/cm^3)

	CH	BD	CDi	ID	CT	FD	InD	DH	BH
Upper Limit	2000	370	220	170	100	200	100	400	3000
Lower Limit	200	270	190	145	23	100	20	100	900
Variation Limit	1800	100	30	25	78	100	80	300	2100

$$-0.0002\times CH-0.0123\times CDi-0.0016\times CT-0.001\times FD-0.0006\times InD-d_1^{+}+d_1^{-}=-3.5139 \quad (10)$$

Likewise, 4 more Equations were formulated for each customer's requirements and all were put into the objective function. The LINGO software© was used to programming the model. The technical constraints and budget constraint were added to the model. The final model is shown in Equation 11:

$$MinZ = 0.3509 \times d_1^{+} + 0.2004 \times d_2^{+} + 0.1646 \times d_3^{+} + 0.1801 \times d_4^{+} + 0.104 \times d_5^{+}$$

Subject to:

$$-0.0002 \times CH - 0.0123 \times CDi - 0.0016 \times CT - 0.001 \times FD - 0.0006 \times InD - d_1^{+} + d_1^{-} = -3.5139$$

$$0.00061 \times BD + 0.0012 \times ID + 0.0034 \times CT + 0.0029 \times FD - 0.00015 \times CH - 0.0019 \times CDi - d_2^{+} + d_2^{-} = 0.1513$$

$$0.0028 \times CT + 0.002 \times FD - 0.0001 \times CH - 0.0005 \times BD - 0.0066 \times CDi - 0.0005 \times ID - 0.0008 \times InD - 0.00016 \times DH - d_3^{+} + d_3^{-} = -1.9218$$

$$-0.005 \times BD - 0.0017 \times DH - d_4^{+} + d_4^{-} = -2.5167$$

$$0.0001 \times BH - 0.0006 \times DH - 0.0017 \times InD - 0.0037 \times BD - d_5^{+} + d_5^{-} = -1.6698$$

- $200 \le CH \le 2000$; $270 \le BD \le 380$; $190 \le CDi \le 220$; $145 \le ID \le 170$
- $23 \le CT \le 100$; $100 \le FD \le 200$; $20 \le InD \le 100$; $100 \le DH \le 400$
- $900 \le BH \le 3000$
- $\sum_{j=1}^{n} C_j x_j \le 10{,}000$ (11)

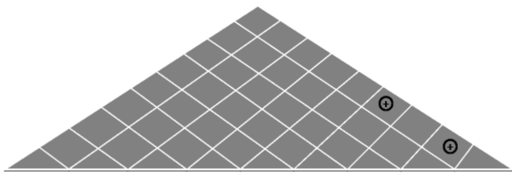
The model results (target values of technical attributes) were obtained as represented in Table 15. The obtained results were used for production of a gas filter and seem to satisfy the customer's expectation.

Table 15: Results of MODM model for technical attributes' target values (cm, g/cm^3)

CH	BD	CDi	ID	CT	FD	InD	DH	BH
200	304.8	190	127	63	100	79.61	400	900

The systematic analysis using operational research technique leads to find a series of optimum values for the technical attributes that may satisfy most the customer's requirements, so required modification on design to manufacture a product will be least and subsequently reduce the production cost. The investigation by the Company sales and production department refer to new values of technical attributes indicated an estimation of roughly 900USD reduction of the production cost.

Figure 5 illustrates the QFD template of case study house of quality as a summary. The customer's requirements, technical attributes as well as their relative importance, their inner relationships and other valuable information can be easily reachable from the HOQ template.



Customer Requirements	Customer Priority	Cartilage height	Body diameter	Cartilage diameter	Inner diameter	Cartilage thickness	Filtration density	Inlet distance	Drain height	Body height
Output Quality	0.3509	0.3600	0.0000	0.3677	0.0000	0.1208	0.1048	0.0467	0.0000	0.0000
Pressure Drop	0.2004	0.2651	0.0610	0.0579	0.0579	0.2651	0.2931	0.0000	0.0000	0.0000
Cleaning Period	0.1646	0.1879	0.0519	0.1984	0.0278	0.2207	0.2019	0.0643	0.0471	0.0000
Cartilage Durability	0.1801	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000
Appearance Dimension	0.1040	0.0000	0.3747	0.0000	0.0000	0.0000	0.0000	0.1355	0.1839	0.3059
weight of Technical attributes		0.2104	0.1497	0.1733	0.0162	0.1319	0.1288	0.0411	0.1169	0.0318
Technical constraints:					Technical Assessment					
Upper Limits		2000	370	220	170	100	200	100	400	3000
Lower Limits		200	270	190	145	23	100	20	100	900
Target Value of Technical attributes		200	304.8	190	127	63	100	79.61	400	900

Figure 5: House of quality for case study

6. Conclusion

The new product design process is the early stage of new product development that highly influences on the output of the Company in term of cost, time and quality. In OKP product (also known as mass-customized production) the production is started based on customer’s order. Usually in OKP Company there are some available designs (that production was done based on them) that the manufacturer used them and applied the required modification refer to each customer expectations instead of lunching the new process of product design. Thus, importance of an accurate design to reduce the required modification helps the Company to increase the efficiency. This research proposed application of integrated QFD-operational research techniques that systematically analyzed the procedure. Unlike the traditional techniques, mathematical multi-objective model with consideration of constraints was developed to obtain more accurate target values. The model is able to include the contradictory effect of technical attributes on customer’s requirements. The practical part of this research was performed to develop the basic design for a PPI™ Company that is suffering from high cost of production to satisfy the customer’s requirements. The expectation of new proposed design is to reduce the production cost around 900USD per product.

References

1. Gmelin, H. and S. Seuring, *Determinants of a sustainable new product development.* Journal of Cleaner Production, 2014. **69**: p. 1-9.
2. Hoyer, W.D., et al., *Consumer cocreation in new product development.* Journal of Service Research, 2010. **13**(3): p. 283-296.
3. Chang, W. and S.A. Taylor, *The effectiveness of customer participation in new product development: a meta-analysis.* Journal of Marketing, 2016. **80**(1): p. 47-64.
4. Gopalakrishnan, M., et al., *The effect of cost goal specificity and new product development process on cost reduction performance.* Accounting, Organizations and Society, 2015. **42**: p. 1-11.
5. Suleymanova, U., *New Product Development.* 2015.
6. Yeniyurt, S., J.W. Henke Jr, and G. Yalcinkaya, *A longitudinal analysis of supplier involvement in buyers' new product development: working relations, inter-dependence, co-innovation, and performance outcomes.* Journal of the Academy of Marketing Science, 2014. **42**(3): p. 291-308.
7. Takeuchi, H. and I. Nonaka, *The new new product development game.* Harvard business review, 1986. **64**(1): p. 137-146.
8. Slater, S.F., *Competing in high-velocity markets.* Industrial Marketing Management, 1993. **22**(4): p. 255-263.
9. Bernard, A., *One-of-a-kind production.* Production Planning & Control, 2014. **25**(16): p. 1400-1401.
10. Mei, Y., J. Ye, and Z. Zeng, *Entropy-weighted ANP fuzzy comprehensive evaluation of interim product production schemes in one-of-a-kind production.* Computers & Industrial Engineering, 2016. **100**: p. 144-152.
11. Li, B. and S. Xie, *Product similarity assessment for conceptual one-of-a-kind product design: A weight distribution approach.* Computers in Industry, 2013. **64**(6): p. 720-731.
12. Koskela, L., T. Bølviken, and J. Rooke. *Which are the wastes of construction?* in *Proceedings for the 21st Annual Conference of the International Group for Lean Construction.* 2013.
13. Lee, J.H. and J. Lee, *Features of data management in PLM customised for ship design adopting engineering to order strategy.* International Journal of Product Lifecycle Management, 2014. **7**(4): p. 292-317.

14. Hilletofth, P., *How to develop a differentiated supply chain strategy.* Industrial Management & Data Systems, 2009. **109**(1): p. 16-33.
15. Wagner, C.-M. and C. Ryan, *Physical and Digital Integration Strategies of Electronic Device Supply Chains and Their Applicability to ETO Supply Chains.* Supply Chain Strategies and the Engineer-to-Order Approach, 2016: p. 224.
16. Tu, Y. and P. Dean, *One-of-a-kind Production*. 2011: Springer Science & Business Media.
17. Akao, Y., *Quality function deployment.* 2004.
18. Akao, Y. and G.H. Mazur, *The leading edge in QFD: past, present and future.* International Journal of Quality & Reliability Management, 2003. **20**(1): p. 20-35.
19. Li, M., L. Jin, and J. Wang, *A new MCDM method combining QFD with TOPSIS for knowledge management system selection from the user's perspective in intuitionistic fuzzy environment.* Applied soft computing, 2014. **21**: p. 28-37.
20. Rahmani, K., K. Emamisaleh, and R. Yadegari, *Quality Function Deployment and New Product Development with a focus on Marketing Mix 4P model.* Asian Journal of Research in Marketing, 2015. **4**(2): p. 98-108.
21. Zhang, F., M. Yang, and W. Liu, *Using integrated quality function deployment and theory of innovation problem solving approach for ergonomic product design.* Computers & Industrial Engineering, 2014. **76**: p. 60-74.
22. Ko, W.-C. and L.-H. Chen, *An approach of new product planning using quality function deployment and fuzzy linear programming model.* International Journal of Production Research, 2014. **52**(6): p. 1728-1743.
23. Galankashi, M.R., et al., *An efficient integrated simulation–Taguchi approach for sales rate evaluation of a petrol station.* Neural Computing and Applications, 2016: p. 1-13.
24. Galankashi, M.R., et al., *Performance evaluation of a petrol station queuing system: a simulation-based design of experiments study.* Advances in Engineering Software, 2016. **92**: p. 15-26.
25. Fung, R., et al., *Product design resources optimization using a non-linear fuzzy quality function deployment model.* International Journal of Production Research, 2002. **40**(3): p. 585-599.
26. Bhattacharya, A., B. Sarkar*, and S.K. Mukherjee, *Integrating AHP with QFD for robot selection under requirement perspective.* International journal of production research, 2005. **43**(17): p. 3671-3685.
27. Vezzetti, E., F. Marcolin, and A.L. Guerra, *QFD 3D: a new C-shaped matrix diagram quality approach.* International Journal of Quality & Reliability Management, 2016. **33**(2): p. 178-196.

28. Zheng, P., X. Xu, and S.Q. Xie. *Integrate product planning process of OKP companies in the cloud manufacturing environment*. in *IFIP International Conference on Advances in Production Management Systems*. 2015. Springer.
29. Varl, M., J. Duhovnik, and J. Tavčar, *Towards a model for robust design and design process in one-of-a-kind production of large power transformers.* International Journal of Agile Systems and Management, 2016. **9**(1): p. 67-88.
30. Lam, J.S.L. and K.-h. Lai, *Developing environmental sustainability by ANP-QFD approach: the case of shipping operations.* Journal of Cleaner Production, 2015. **105**: p. 275-284.
31. Marini, C., et al. *Product Development using QFD, MCDM and the Combination of these Two Methods*. in *IOP Conference Series: Materials Science and Engineering*. 2016. IOP Publishing.
32. Shahin, A., et al., *Typology of Kano models: a critical review of literature and proposition of a revised model.* International Journal of Quality & Reliability Management, 2013. **30**(3): p. 341-358.
33. Kou, G., D. Ergu, and J. Shang, *Enhancing data consistency in decision matrix: Adapting Hadamard model to mitigate judgment contradiction.* European Journal of Operational Research, 2014. **236**(1): p. 261-271.
34. Saaty, T.L., *That is not the analytic hierarchy process: what the AHP is and what it is not.* Journal of Multi-Criteria Decision Analysis, 1997. **6**(6): p. 324-335.
35. Saaty, T.L., *Decision making—the analytic hierarchy and network processes (AHP/ANP).* Journal of systems science and systems engineering, 2004. **13**(1): p. 1-35.
36. Chankong, V. and Y.Y. Haimes, *Multiobjective decision making: theory and methodology*. 2008: Courier Dover Publications.