A PRODUCT DESIGN FRAMEWORK FOR ONE-OF-A-KIND PRODUCTION USING INTEGRATED QUALITY FUNCTION DEPLOYMENT AND OPERATIONAL RESEARCH TECHNIQUES

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To my beloved family

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ABSTRACT

The process of product design as an early stage of new product development provides systematic approaches that can lead to the success of a company's competitive strategy in the current turbulent market. By launching an efficient product design procedure can result in the reduction of engineering modifications, cost and production time. One-of-a-Kind Product (OKP) is known as a particular manufacturing system of new product design and development with emphasis on the special order concept. Quality Function Deployment (QFD) is a comprehensive design framework with cross-functional team members that leads to the development of new or improved products. QFD starts with the House of Quality (HOQ) as an organizing matrix to identify the customers' requirements (CR_s) and translate them into the technical attributes (TA_s) of the product and followed by determining the target values for the sets of technical attributes. An evaluation approach to determine the relative importance of CR_s and TA_s should be considered. In previous researches, the traditional methods such as simple scoring method and application of operational research techniques such as Analytic Hierarchy Process (AHP) were reported to weigh the requirements and attributes. Despite the obvious inner-relationships among the elements, considering the HOQ as a hierarchical system may be inefficient. In addition, the contradictory effects of a *TA* on two or more CR_s, is the problem that has been neglected. Here, a mathematical model was developed for calculating the TA_s target values. A case study (dry gas filter, Namdaran Petro-Gas Industries (NPI™)) is presented to exhibit and verify the procedure of OKP product design. Initially, the framework was developed by integrating QFD-operational research (Analytic Network Process (ANP)) as a systematic method for improvement of dry gas filter design. Interview and study of documents were used to identify the CR_s. A robust evaluation on customers' priority and attributes' importance with respect to inner-relationships among criteria/sub-criteria was performed. Furthermore, the effects of TA_s on CR_s with regard to their direction (positive/negative) were considered as the fundamental for developing a Multi-Objective Decision Model (MODM) to be used for determining the TA_s target values. For this purpose, the fuzzy conversion scaling technique followed by formulating the partial satisfaction separately was applied. Modified TOPSIS was used to select the basic design among the available designs for further modification. Later, the process continues with the second phase, translating the TA_s into the key parts. The available options (retailers) to supply the key parts were identified. As the normal procedure of QFD the relative importance's of key parts and the options were determined. Finally, a zero-one goal programming was presented to select the optimum options for each key part subject to the budget constraint. Overall, the developed QFD-ANP framework provides a systematic approach that has the potential to be used for designing OKP product.

ABSTRAK

Proses rekabentuk produk sebagai peringkat awal pembangunan produk baru menyediakan pendekatan sistematik yang boleh membawa kepada kejayaan strategi persaingan syarikat dalam keadaan pasaran semasa yang bergolak. Pelancaran prosedur rekabentuk produk yang berkesan boleh mengakibatkan pengurangan pengubahsuaian kejuruteraan, kos dan masa pengeluaran. Produk lain-daripada-yang-lain (OKP) dikenali sebagai satu sistem pembuatan bagi rekabentuk dan pembangunan produk baru dengan penekanan kepada konsep pesanan khas. Penyebaran fungsi kualiti (QFD) adalah satu rangka kerja rekabentuk yang menyeluruh dengan ahli pasukan dari berbagai fungsi yang membawa kepada pembangunan produk baru atau penambahbaikan produk. QFD bermula dengan Rumah Kualiti (HOQ) sebagai suatu matriks menganjurkan untuk mengenalpasti keperluan pelanggan (CR_s) dan menterjemahkannya kepada sifat teknikal (TA_s) produk dan diikuti dengan menentukan sasaran nilai untuk menetapkan sifat teknikal. Suatu pendekatan penilaian untuk menentukan kepentingan relatif CR_s dan TA_s perlu dipertimbangkan. Dalam penyelidikan terdahulu, kaedah tradisional seperti kaedah pemarkahan mudah dan penggunaan teknik penyelidikan operasi seperti proses hierarki analitik (AHP) telah dilaporkan memberi pemberat kepada keperluan dan sifat. Tambahan pada itu, kesan bertentangan suatu *TA* pada dua atau lebih CR_s, adalah masalah yang telah diabaikan. Di sini, satu model matematik telah dibangunkan untuk mengira nilai sasaran TA_s. Satu kajian kes (penapis gas kering, Namdaran Petro-Gas Industries (NPI ™)) dibentangkan untuk menunjukkan dan mengesahkan prosedur rekabentuk produk OKP. Pada mulanya, rangka kerja dibangunkan dengan mengintegrasikan QFD-penyelidikan operasi (proses rangkaian analitik (ANP)). Temuduga dan kajian dokumen digunakan untuk mengenalpasti CR_s. Penilaian yang teguh terhadap keutamaan pelanggan dan kepentingan sifat berkaitan dengan perhubungan dalaman antara kriteria/sub kriteria telah dilaksanakan. Tambahan pula, kesan TA_s pada CR_s dari segi arah mereka (positif/negatif) dianggap sebagai asas untuk membangunkan suatu model keputusan pelbagai objektif (MODM) untuk digunakan untuk menentukan nilai sasaran TA_s. Untuk tujuan ini, teknik penskalaan penukaran kabur yang diikuti dengan merumuskan kepuasan sebahagian secara berasingan digunakan. TOPSIS diubahsuai telah digunakan untuk memilih rekabentuk asas dari kalangan rekabentuk yang ada untuk pengubahsuaian seterusnya. Proses ini berterusan dengan tahap kedua, menterjemahkan TA_s ke bahagian utama. Seterusnya, pilihan yang ada (peruncit) untuk membekalkan bahagian utama telah dikenalpasti. Sebagai prosedur biasa QFD, kepentingan relatif bahagian utama dan juga opsyen ditentukan. Akhirnya, suatu matlamat pengaturcaraan sifar-satu telah dipersembahkan untuk memilih opsyen yang optimum bagi setiap bahagian utama tertakluk kepada kekangan peruntukan. Secara keseluruhan, rangka kerja QFD-ANP yang dibangunkan berpotensi digunakan untuk merekabentuk produk OKP.

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LIST OF ABBREVIATIONS

Adj.PVs	-	Adjusted priority vector
Adj.RM	-	Adjusted relationships matrix
AHP	-	Analytic hierarchy process
AMQFD	-	Analytic maintenance quality function deployment
ANP	-	Analytic network process
ATO	-	Assemble-to-order
BD	-	Body diameter
BH	-	Body height
CAD	-	Computer aided design
CD	-	Cartridge durability
CDi	-	Cartridge diameter
CH	-	Cartridge height
CP	-	Cleaning period
CRs	-	Customer’s requirements
CT	-	Cartridge thickness
D	-	Dimension
DEA	-	Data envelopment analysis
DFX	-	Design for excellence
DH	-	Drain height
DRs	-	Design requirements
ELECTRE	-	Elimination and choice expressing reality
EQFD	-	Enhanced quality function deployment
ER	-	Evidential reasoning

ETO	-	Engineering-to-order
FD	-	Filtration density
FFF	-	Free-form fabrication
FMEA	-	Failure mode effect analysis
GCNN	-	Genetic chaotic neural network
HOQ	-	House of quality
ICoDe	-	Integrated concept development
ID	-	Inner diameter
IDEFO	-	ICAM definition
InD	-	Inlet distance
IRI	-	Islamic republic of Iran
IQFD	-	Intelligent quality function deployment
ISM	-	Independent scoring method
ITP	-	Inspection and test plan
MADM	-	Multi-attributes decision making
MEC	-	Means-end chain
MILP	-	Mixed-integer linear programming
MODM	-	Multi-objective decision making
MRI	-	Magnetic resonance image
MTO	-	Make-to-order
MTS	-	Make-to-stock
NDT	-	Non-destructive procedures
NIS	-	Negative ideal solution
NNet	-	Neural network
NPD	-	New product development/design
NPI	-	Namdaran PetroGas™ industry
OKP	-	One-of-a-kind production
OQ	-	Output quality
OR	-	Operational research

PCs	-	Part characteristics
PD	-	Pressure drop
PIS	-	Positive ideal solution
PPs	-	Process parameters
PRs	-	Production requirements
QFD	-	Quality function deployment
R&D	-	Research and development
RP	-	Rapid prototyping
RPN	-	Risk priority number
SAW	-	simple additive weighting
SD	-	System dynamic
SWOT	-	Strength, weakness, opportunities and threats
TAs	-	Technical attributes
TOPSIS	-	Technique order of preference by similarity to ideal solution
TPM	-	Total productive maintenance
TPS	-	Toyota production system
TRIZ	-	Theory of the resolution of invention-related tasks
VOC	-	Voice-of-customer
ZOGP	-	Zero-one goal programming

LIST OF SYMBOLS

W_j^{ANP}	-	Weight of j^{th} technical attributes based on ANP approach
R_{ij}	-	Relationship between i^{th} CR_s with j^{th} TA_s
d_i	-	Importance of i^{th} customer's requirements
W_{21}	-	Priority vector obtained from customer's requirements
W_{22}	-	Inner-dependence matrix of customer's requirements
W_{32}	-	Relationships matrix between TA_s and CR_s
W_{33}	-	Inner-dependence matrix of technical attributes
I	-	Identity matrix
PV_{CRs}	-	Priority vector of customer's requirements
S_i	-	Customer's satisfaction function refer to i^{th} requirements
Di^+	-	Euclidean distance from positive values
Di^-	-	Euclidean distance from negative values
CL_i^*	-	Closeness index
$Adj.PV_{CRs}$	-	Adjusted priority vector of customer's requirements
$Adj.RM_{TAs}$	-	Adjusted relationships matrix of technical attributes
T_{ij}	-	Weight of technical attribute "j^{th}" refer to CR_i
x_j^{max}	-	Upper licensed variation limits for technical attributes
x_j^{min}	-	Lower licensed variation limits for technical attributes
d_i^+	-	Excess deviation variables
d_i^-	-	Slack deviation variables
V_i	-	Weight of i^{th} customer's requirements
C_j	-	Cost of j^{th} technical attribute

B	-	Budget
K_{ij}	-	Converted scale value
r_{ij}	-	Weighted elements of matrix
R_e	-	Euclidean distance attribute
W_F	-	Final weight of key parts
W_{KP}	-	Weight of key part
$W_{Opt.}$	-	Weight of key parts' options
CI	-	Consistency index
RI	-	Random index
CR	-	Consistency ratio

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CHAPTER 1

INTRODUCTION

1.1 Overview of the Research

In the past decade changes in market requirements and technology advancements have accelerated. Companies' competitive strategy success in the current turbulent environment is highly dependent on the capability to develop the new or improved products (Hoyer *et al.,* 2010; Gmelin and Seuring, 2014). In other words, the economic success rate of a company can be determined through new product development (NPD) strategy (Chang and Taylor, 2016). Companies should continuously improve their NPD strategy in order to fulfill both the markets requirements and compete with the other companies (Yeniyurt *et al.,* 2014; Gopalakrishnan *et al.,* 2015; Suleymanova, 2015). New product is cited as the key to the success of a company. In 1980s, new product contributed to around 33% of companies' profit (Takeuchi and Nonaka 1986). During 1990s, this value has raised to 50% (Slater, 1993). However, related studies show that the NPD strategy is also failing at an alarming rate. Usually, the rate of success in NPD is less than 60% (59.8% in Japan, 59% in United States of America, 54.3% in United Kingdom and 49% in Iran) (Griffin *et al.,* 1997; Nezam *et al.,* 2016; de Waal *et al.,* 2016). In order to launch a successful NPD strategy, emphasis on efficient product design procedure can lead to a reduction in the design and development cost/time. Launching an efficient product design procedure that considers all the manufacturing concerns upstream and customers' requirements can result in the reduction of engineering modifications, cost and production time. (Li *et al.,* 2011a; Wassick *et al.,* 2012; Zhong *et al.,* 2013; Huang *et al.,* 2016; Mei *et al.,* 2016b). In order to enhance the

NPD procedure, many new techniques have been introduced over the recent decades. The major categories of the current techniques used 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) (Coman *et al.,* 2013; Jovičić *et al.*, 2014; Mohammadi *et al.,* 2014; Sarkar, 2015; Santolaya *et al.,* 2016).

One-of-a-kind product (OKP) manufacturing system is known as a particular system of new product design and development with emphasis on special order concept (Bernard, 2014; Mei *et al.,* 2016b). Compared to the mass production paradigm that reduces the cost by eliminating products variations; OKP can fulfill the customized requirements of any particular customer (Koskela *et al.*, 2013; Li and Xie, 2013). The characteristics of OKP can be briefly summarized as: (i) high customization, (ii) great uncertainties in production control, (iii) complicated and dynamic supply chain, and (iv) dynamic production system. Despite the high importance of OKP research scope, it has been neglected for long time due to the inconsistency with the mass production paradigm (which is known as dominant paradigm in production management research). A better strategy for the manufacturing sector to survive and grow is to strengthen the OKP while reducing the cost (Tu and Dean, 2011). Commonly, one-of-a-kind production is related to the heavy industries, particularly in developing countries where these industries are usually considered as national industries and are much more important than in the developed countries (Berggren *et al.*, 2015; Schöggl *et al.,* 2017). OKP usually uses sophisticated software to perform the product development process such as; (i) customer's requirements acquisition, (ii) modelling and identification of design, and (iii) planning and controlling of production process (Mei *et al.,* 2016b). This process must be done to identify the optimum product design based on the customer's requirements. The optimal product is determined by evaluating customer's satisfaction in terms of performance and cost. The numbers of the active researchers in this scope is too few and a new researcher (after a while of investigation the related industries) can easily get familiar with the researchers' concerns. Information systems (Barata and Cunha, 2015; Galambos *et al.,* 2015) computer-aided design (CAD) and manufacturing (Tu *et al.,* 2000; Zhong *et al.,* 2013; Bonev *et al.*, 2015), virtual enterprises and flexible structures (Tu, 1997; and Fung *et al.,* 2006) and their roles in one-of-a-kind production have already been considered by researchers. One of the main concerns of researchers that are reflected in subsequent articles of Rahman Abdul Rahim and Shariff Nabi Baksh, (2003a), is the absence of a general model for designing and developing one-of-a-kind production (Rahman Abdul Rahim and Shariff Nabi Baksh, 2003b; Rahman Abdul Rahim and Shariff Nabi Baksh, 2003c). It can be concluded that the lack of a model which is able to explain the design and development process of OKP at the overall level, will limits the thinking activities in this field. Despite the many competitive advantages of OKP, the low efficiency and high costs associated with OKP companies have threatened to push their business opportunities into the hands of cheaper overseas suppliers (Tu and Dean, 2011b). One-of-a-kind production introduces a novel strategy and technology to help OKP companies to efficiently produce mass customized products. In one-of-a-kind production, usually case studies from OKP companies are used to validate the feasibility and effectiveness of the OKP strategy and technology (Garuti and Spencer, 2007).

In this research the manufacturer of one-of-a-kind product are the companies which are known as OKP in the literature. OKP companies have the following characteristics:

i. Their products are produced according to the customers' order each time.
ii. Product design, testing and production will be done concurrently.
iii. Final products are produced by either modifying or combining available primary products or standard units and parts.

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), one-of-a-kind production is related to the latter two strategies (ATO, ETO), while, most of the researches in the field of production management is related to the first two strategies (MTS, MTO). In other words, one-of-a-kind production has a relatively long history in terms of theoretical research, while currently the mass production and lean manufacturing paradigms are the real interests of most of the practical researches (Hilletofth, 2009; Li and Womer, 2012; Lee and Lee, 2014; Wagner and Ryan, 2016). So, theoretical and academic researches on issues related to one-of-a-kind production are very limited and insufficient.

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 (Shahin *et al.,* 2013; Gustavsson *et al,* 2016). 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 (Taboli and Soltani, 2014; Kern *et al.,* 2015). This may capable the manufacturer for planning to fulfill these demands within their limitations. 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, a certain number of existing designs are often fully provided the first type of customer requirements (Kano's basic needs). Since these proposed designs have different costs, they can just provide different levels of second type of customer's requirements while reasonable level of cost is acceptable for the customer. In these types of companies, desirable design selection is the most important part in order to satisfy the customers (Xie and Tu, 2011; Zheng *et al.,* 2016, Varl *et al.,* 2016).

After selecting the desirable design, the most important factor influencing the performance of the product is the selection of key parts (Akao and Mazur, 2003; Aghlmand *et al.,* 2010; Lindemann *et al.,* 2015). Often for these key parts, there are several different options. For example, different types of transformer manufactured by different companies can be installed on a fluorescent lamp but the output may be different. Obviously, the selecting of the different key parts is effective on product performance and customer satisfaction aspects. On the other hand, the different price of different choices makes it essential to reconsider the cost limitations prior to key part selection (Chan and Wu, 2002).

Quality function deployment (QFD) is a very comprehensive and fashionable technique for designing a new product. QFD was developed to translate the customer's particular needs to modern business and manufacturing. 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. As a result of the growing distance between producers and users which is a concern in current industrial society, QFD tries to link the customer's need (end user) with design, development, engineering, manufacturing, and service functions. For the first time, in the late 1960s, QFD was developed in Japan as a form of cause-and-effect analysis. Later QFD was brought to the United States in the early 1980s. It expanded its early popularity as a result of numerous successes in the automotive industry (Jahnukainen *et al.*, 1999; Jiang *et al.*, 2001; Kim *et al.*, 2000). 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
v. Strategy to stay ahead of the game

The implementation of psychology and knowledge an (epistemology) element in system thinking allows QFD to provide a comprehensive development system for (Goetsch and Davis, 2014):

i. Differentiating between “real” customer's needs and the customer's view
ii. Knowing what “value” means to the customer in terms of the customer's view
iii. Understanding how customer becomes interested, select, and are satisfied
iv. Analyzing how do suppliers know the customer's requirements
v. Determining what attributes/properties to include

vi. Defining what level of performance to deliver

vii. Effectively relating the customer's need with design, development, engineering, manufacturing and service operation

QFD is defined as a systematic link between the customer's requirements and different business operations/organizational processes (such as marketing, design, quality engineering, production, manufacturing and sales) in order to line up the entire company towards achieving a common goal (Govers *et al.*, 2001; Kuo and Che, 2011; Franceschini, 2016; Zheng *et al.*, 2016). The companies are able to empower their expectation level through determining the positive opportunities in terms of quality and business, and translate those into design and manufacturing using prioritization and analytical techniques.

Traditional quality control planning often considered quality without any failure (Andersen *et al.*, 2005). On the other hand, QFD method defines quality as customer satisfaction and offers proper operational framework for complying with the essentials of this definition. Quality specialists refer the QFD method using many names, including matrix's product planning, decision matrices, and customer-driven engineering (Cristiano *et al.*, 2000; Lin *et al.*, 2008; Chen, 2014). 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.

QFD is a theoretical framework that starts the design and development activities of a new product by obtaining customer feedback. With a focus on quality arrangements it offers clear solutions for a variety of organizational tasks in the process of design and development of new products (Zaim *et al.*, 2014; Marini *et al.*, 2016). Hence, this framework can be the basis of a prescriptive model for organizing the process of a new one-of-a-kind product design and development. Theoretical subjects in the theory of decision making helps to solve traditional computational flaws in QFD and experiences obtained from the combinational application of mathematical programming and QFD have resulted in the improvement of operational accuracy (Chen *et al.*, 2013; Sperry, 2014). So by referring to the previous experiences from the application of combined QFD and operational research (OR) techniques, it has the capacity to be used as the proper method for one-of-a-kind production design and development and can also proposed a preliminary order for streamlining (Nixon *et al.*, 2013; Zaim *et al.*, 2014).

In order to facilitate the development process, 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 resources available to fulfill those expectations. The structure (template) which QFD uses for organizing the information is acknowledged as the house of quality (HOQ). In its broadest sense, the QFD house of quality exhibits the relationship between dependent (what) and independent (how) variables (Xie and Tu, 2011; Zheng *et al.*, 2015). Figure 1.1 shows the typical house of quality template.

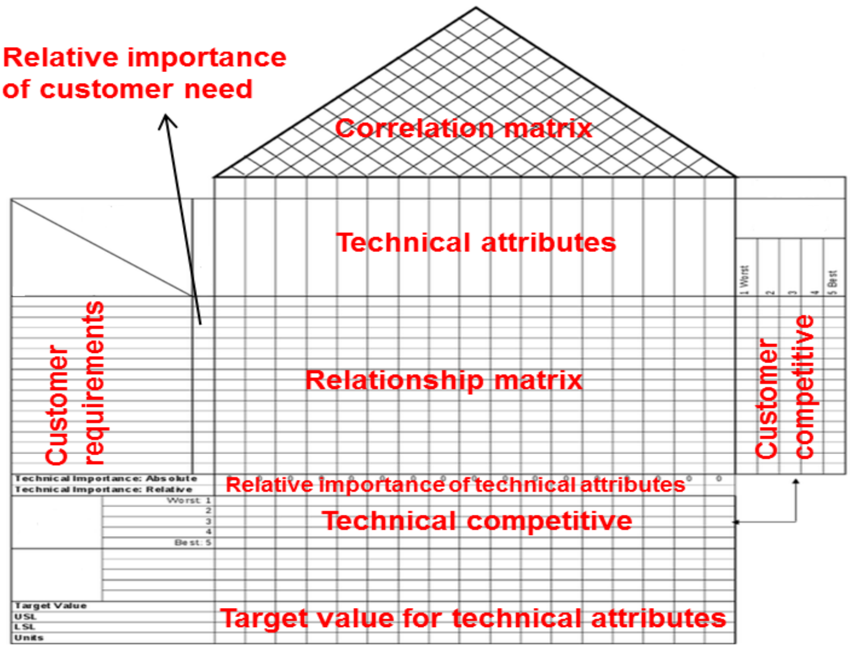

Figure 1.1: Typical template of house of quality (Chaudha *et al.*, 2011)

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 (Tu *et al.*, 2010; Pitman *et al.*, 2013; Chen *et al.*, 2016).

Four-phase QFD matrices approach represents the four phases in new product development via; (i) product planning, (ii) part planning/deployment, (iii) process planning, and (iv) production planning (Zhang, 1999; Karsak *et al.*, 2003; Karsak and Dursun, 2104; Franceschini and Maisano, 2015).

(i) ***Phase 1, product planning***: Building the house of quality. This phase is usually performed by the marketing department. The product planning is also known as the house of quality (HOQ). 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 phase 1 is critical to the success of the entire QFD process (Corti and Portioli-Staudacher, 2004; Dursun and Karsak, 2013).

(ii) ***Phase 2, part planning***: This phase is led by the engineering department. Part planning requires creativity and innovative team ideas. Product concepts are created during this phase and part specifications are documented. Parts that are determined to be most important to meeting customer needs are then deployed into process planning (Ertay *et al.*, 2005; Browning *et al.*, 2006).

(iii) ***Phase 3, process planning***: Process planning comes next and is performed by manufacturing engineering department. During the process planning, manufacturing processes are flow charted and process parameters (or target values) are documented (Bayraktaroglu and Özgen, 2008).

(iv) ***Phase 4, production planning***: Finally, in production planning, performance indicators are created to monitor the production process, maintenance schedules, and skills training for operators. Also, in this phase decisions are made as to which process poses the most risk and controls are put in place to prevent failures. The quality assurance department in association with manufacturing leads this phase (Qattawi *et al.*, 2103; de Fátima Cardoso *et al.*, 2015).

However, upon considering the importance of selecting the appropriate design and the key parts, this research focus on the process of product design and development in OKP companies that taken into account in the product planning and part planning matrices. Figure 1.2 illustrates the four phases of QFD.

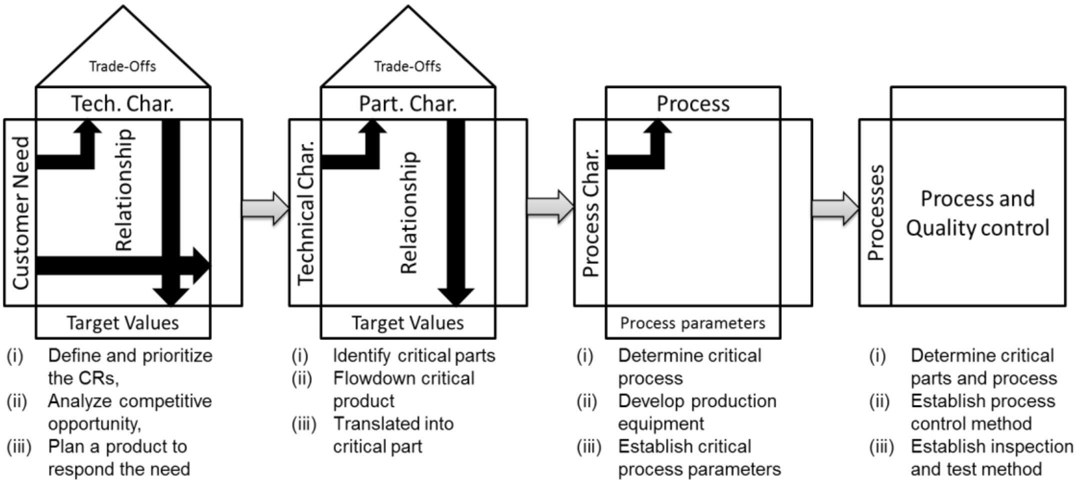

Figure 1.2: Four-phase matrices approach of QFD (Chen and Ko, 2010)

Totally, organizing the process of product design of these companies (OKP) can be reduced to identifying the customer's requirements, presenting a method for selecting an optimum design of the existing designs and then selecting the key parts within the four-phase QFD matrices framework, while always considering customer satisfaction and cost constraints as a goal (Hong *et al.*, 2010; Li *et al.*, 2011b; Bernard, 2014).

1.2 Research Problem Statement

Designing and developing high-tech equipment used in heavy industries can be considered as a national interest worldwide. Particularly, in the Middle East developing countries, whose economy is mostly dependent on the oil and gas, very high-tech OKP equipments are required for extracting and the subsequent processing of the natural resources. OKP products in this field are the most important sectors of national industries and have strategic importance. Therefore, any attempt to improve the capability of these industries can be considered as a national interest. Acquiring the required technology for designing and manufacturing of these types of products can obviously increase the development speed where billions of dollars can be saved within the countries instead of purchasing that product from overseas. Thus, providing a general framework for new product design and development based on the aforementioned considerations can help the countries progress.

The abovementioned inconsistency between mass production paradigm and one-of-a kind production (OKP) makes the use of traditional QFD approach unreliable (Baldwin and von Hippel, 2011; Li *et al.*, 2011a; Tseng and Hu, 2014). In traditional QFD in order to determine the customer's requirement/attributes priority, independent scoring method (ISM) had been used and the interrelationship between customer's requirements/attributes and their effects on relative importance (priority) were neglected (Braglia *et al.*, 2007; Karsak and Özogul, 2009; Nahm *et al.*, 2013). In addition, in order to determine the technical attributes' target values, experience-based knowledge had been used. Here, a novel approach of integrated QFD-operational research techniques such as ANP and MODM were used to develop a systematic procedure.

In addition, during the translation of customer's requirements into technical attributes, a table is drawn (to shows the relationships between customer's requirements and technical attributes) which is used for designing the pairwise comparison questionnaire and later modern and systematic techniques (such as analytic hierarchy process (AHP) and analytic network process (ANP)) are used to find the customer's requirements/attributes relative importance. Currently, this table is used just for showing either there is any relationships, while it is possible in some cases that a technical attribute to have a relationship with two criteria of customers' requirements but having different effects on these two criteria. Correspondingly, increasing the value of that technical attribute will result in increasing the customers' satisfaction for one criteria while will lead to a decrease in the other one. For example if the 'j^{th}' technical attribute has simultaneous influence on 'i^{th}' and '$(i+1)^{th}$' customer's requirements, it is possible that increasing of 'j^{th}' technical attributes has resulted in increasing the 'i^{th}' customer requirements, while will lead to a decrease in '$(i+1)^{th}$' customer's requirements. In other words, technical attributes conflicting effects on customer demands are assumed to be negligible in previous mathematical models in order to determine the target values (Morgan and Liker, 2006; Wheelwright, 2010; Pahl and Beitz, 2013; Gmelin and Seuring, 2014; Roy *et al.,* 2014; Pramanik *et al.,* 2015). So this problem was considered in this research in order to justify the contradictory effects through the use of a new multi-attributes decision making (MADM) model. The world predicted that OKP can be a promising and competitive production mode for manufacturing and tries to identify a new product planning and design framework for manufacturing companies in the future. This research presents a new model for determining target values of technical attributes based on goal programming which is known as the multi objective decision making (MODM) approach which considers contradictory effects of technical attributes on customer's needs which was previously not considered in OKP company.

Furthermore, in OKP the general designs of products which are in the same product domain usually have the same fundamental features. So the OKP manufacturer prefers to select one of the designs in that product domain (that is already in production) and do the required modification based on new customer's requirements. Thus, a design which mostly matches the customer's requirements should be selected in order to minimize modification. Among the various MADM techniques, the TOPSIS method seems to be the most appropriate one to be used in this case (Li *et al.,* 2014; Pramanik *et al.,* 2015). Usually the technical attributes have a specific variation limits with different scales. In this case, the ideal values are not provided in the decision matrix and are the output of a mathematical model that is used to determine the target value of technical attributes, thus the current norm of TOPSIS method is not able to justify this problem and a modified TOPSIS in terms of fuzzy conversion scaling technique is required (Ashrafzadeh *et al.*, 2012; Mousavi *et al.*, 2013; Onar *et al.*, 2016).

1.3 Research Questions

i. What is an effective method to translate the voice of customer into the technical attributes, the technical attributes into key parts and then prioritize those?
ii. What is the desirable model to determine the technical attributes target values?
iii. How to validate the framework and model obtained?
iv. How to select the desirable design as the basic design?
v. How to select the best choice of key parts in order to optimize the final product in terms of quality and cost/time?

1.4 Research Aim and Objectives

The overall purpose of this research is to develop a method for organizing the product design process by applying operational research (OR) techniques in OKP companies within the four-phase QFD matrices approach. In order to achieve the said goal the following objectives are set:

i. To determine the priority of customers' requirements and technical attributes through integration of QFD approach and operational research (AHP and ANP) techniques.
ii. To model a new multi-objective decision making (MODM) function for determining the technical attributes target values subjects to technical/budget constraints.

iii. To validate the theoretical framework using a real case study (gas filter).
iv. To modify the TOPSIS method in order to select a basic design by comparing the technical attributes values of the available designs and target values obtained.
v. To implement the part planning phase for determining the key/spare parts and develop a zero-one goal programming subject to parts importance level/budget constraint for optimum supplier selection among the possible retailers option.

1.5 Research Scopes

The research scope is limited to investigating the one-of-a-kind production (OKP) system in terms of the development of product design process within four-phase matrices of QFD. Since the desirable design and key parts selection are highly correlated to the customers' satisfaction in these types of companies, so this research focused specially on:

i. The first two matrices of the four-phase matrices of QFD; (I) product planning and (II) part planning were considered to develop a desirable product design to be used as the basic design of the company.
ii. The customer's requirements were determined through interview by the sales/aftersales and technical managers based on the 30 documents such as warranty reports, customer's complaint, performance of product and etc.
iii. The customer's requirements and attributes were prioritized using AHP and ANP techniques.
iv. The multi-objective decision making approach was used to model the technical attributes target value determination.
v. The research methodology in this case was limited to application of concurrent engineering concept and mathematical programming where

the design, production and testing were done concurrently in these types of companies.

vi. The product in this research is the dry gas filter which is used in the pressure reducing station to remove the solid particles with size >3**μ**m. It has a capacity to accommodate a gas flow of 50,000 m^3/h.

vii. The research case study was conducted at NamdaranPetroGas Ind.™ Company. Since 2005, the company specializes in the design, production and installation of regulating and metering stations, dry gas filters, filter separator, and gas scrubbers.

viii. The budget of the company to produce a particular product (dry gas filter) was 10,000 $ (USD).

ix. Some technical constraint in terms of product design was applied to the model. The licensed variation limits for technical attributes was based on product domain (dry gas filter) documents.

x. The basic design was selected based on modified TOPSIS technique.

xi. Key/spare parts selection (among the available options) was done based on a zero-one mathematical model according to the cost constraint.

xii. The new design influences scope was based on customer's satisfaction in terms of cost and time.

1.6 Significance of Research

According to the visible and clear trend of markets to shift to the customer-orientation policies and also development of technology, it is predicted that one-of-a-kind production will be a dominant production model in future factories (Tu and Dean, 2011; Bernard, 2014; Zheng *et al.,* 2017). Regardless of the accuracy of such forecasts, this type of production has been widely accepted in heavy industries such as shipyards, petrochemicals, oil and gas industries, and so on. In fact one-of-a-kind production is considered a traditional form of production in heavy industries. Nevertheless, the literature of this subject and the theoretical researches surrounding it should be found in literature of the newest paradigm that called agile manufacturing. However, theoretical and academic researches on issues related to the

OKP are very limited and insufficient. Heavy industries in developing countries, particularly in oil and gas fields which are the most important sectors of national industries, have strategic importance. Therefore, any attempt to improve the quality of these industries can be considered as a national interest. Application of operational techniques such as AHP and ANP makes the identification of customer's requirements and attributes more systematic that leads to the proposal of a sustainable design. The OKP are currently produced in the mass-customized principle and is a time consuming and costly procedure. Thus, developing a systematic and desirable design in OKP can help the companies to reduce the cost and time of production while meeting the customer's requirements.

1.7 Organization of Thesis

In the first chapter of this thesis, general information of the research, problem statement, objectives and scope are provided. In the second chapter, the literature reviews of the OKP Company and QFD in terms of mathematical programming and operational research techniques (AHP and ANP) are described as well as the previous investigation on four-phase matrices of QFD. Chapter 3 starts with research framework and detailed explanation of each phase in order to show how the research was conducted. Chapter 4 describes the case study and the product (dry gas filter) properties in detail to exhibits the technical specifications of the product and also the available constraint (either budget or technical) to design a dry gas filter. Chapter 5 provides the results and detailed discussion on the findings of this research. This chapter is divided into three main sections; (i) the customer's requirements/attributes identification and prioritization, (ii) determining the technical attributes' target value and selection of basic design, and (iii) key parts selection. In Chapter 6, the conclusion was presented according to the assumptions/objectives made and the results obtained.

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