A METHOD FOR MONITORING QUALITY IN LONG RUN PRODUCT DEVELOPMENT PROJECTS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

GÜLÇİN ÖZDEN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
INDUSTRIAL ENGINEERING

SEPTEMBER 2019

Approval of the thesis:

A METHOD FOR MONITORING QUALITY IN LONG RUN PRODUCT DEVELOPMENT PROJECTS

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ABSTRACT

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September 2019, 110 pages

For complex products, product development may take a long time. Late delivery and customer dissatisfaction may be inevitable if product quality is not assured from the beginning of the development. The aim of this study is to propose a method to monitor such product development projects from the viewpoint of product quality as well as schedule and cost. The method proposed is built mainly upon Quality Function Deployment (QFD). QFD is already a frequently used approach in relating customer needs to product and process parameters and prioritizing the critical success factors. With the extension that we propose, QFD is used also in predicting customer satisfaction rates by collecting certain realization information throughout the product development. This extension integrates a modification of RAPIDO product maturity assessment method with QFD. At each phase of the project, project managers are able to see the technical requirements fulfillment and customer satisfaction indicators, and compare them to planned ones, so that they can prioritize the tasks accordingly. This method is expected to be useful especially for industries in which development phases may take several years. A hypothetical application of the proposed method in defense industry is presented. Directions for future research are provided.

Keywords: Quality Function Deployment, Project Management, Quality Indicators

ÖZ

UZUN SÜRELİ ÜRÜN GELİŞTİRME PROJELERİNDE KALİTENİN İZLENMESİ İÇİN BİR YÖNTEM

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Tez Danışmanı: Prof. Dr. Gülser Köksal

Eylül 2019, 110 sayfa

Karmaşık ürünlerde, ürün geliştirme süreci uzun olabilir ve ürünün kalitesi geliştirmenin başlamasından itibaren güvence altına alınmazsa geç teslimat ve müşteri memnuniyetsizliği kaçınılmaz hale gelebilir. Bu çalışmanın amacı, bu tür ürün geliştirme projelerini takvim ve maliyet yönüyle olduğu kadar kalite yönüyle de baştan sona izlemek için bir yöntem önermektir. Önerilen yöntem temelde Kalite Fonksiyon Göçerimi (KFG) üzerine kurgulanmıştır. KFG hali hazırda müşteri ihtiyaçlarını ürün ve süreç parametrelerine bağlamak ve kritik başarı faktörlerini önceliklendirmek için sıkça kullanılan bir yöntemdir. Önerdiğimiz açılım ile KFG, belirli gerçekleşme bilgilerini de ürün geliştirme süreci boyunca toplayarak, müşteri memnuniyet oranını da belirlemek için kullanılabilmektedir. Bu açılım, değiştirilmiş RAPIDO ürün olgunluk değerlendirme metodunun KFG ile entegre edilmesiyle oluşturulmuştur. Tüm proje aşamalarında, proje yöneticileri teknik gereksinimlerinin karşılanma oranını ve müşteri memnuniyet göstergesini görebilecek, planlananlarla karşılaştıracak ve böylece etkinlikleri bunlara göre önceliklendirebileceklerdir. Bu metodun özellikle karmaşık ürünlere sahip ve geliştirme sürecinin yıllarca sürebildiği sektörlerdeki projelerde yararlı olması beklenmektedir. Önerilen metodun savunma sanayinde hipotetik bir uygulaması sunulmuştur. İleride yapılabilecek araştırmalara dair yönlendirme yapılmıştır.

Anahtar Kelimeler: Kalite Fonksiyon Yayılımı, Proje Yönetimi, Kalite Göstergeleri

dedicated to my grandparents

ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisor Prof. Dr. Gülser Köksal for her trust in me and her support for almost three years. She never gave up on me even though she had strong reasons for that. She is definitely a role-model for me with her hardworking and caring character. Without her, I wouldn’t be able to complete my work.

I would like to thank my parents Ayten Ersoy and Mustafa Ersoy, for their endless self-devotion all my life.

I would like to thank my beloved husband Burak Şamil Özden, for being such a good partner that makes me thankful every single day.

I would like to thank my sister Burçin Şenol and her husband Osman Erdem Şenol, who inspire me whenever I talk to them.

I would like to thank my second parents Birsel Özden and Hayrettin Özden, and my second sister Başak Özden for all their support and generosity.

And my greatest appreciations are to my grandparents who had built a new life in Turkey from nothing at hand, after they had migrated from Bulgaria. Their hardworking souls have always led us forward.

I would like to thank my company, FNSS Defense Systems Co. Inc., for being such a great place to work. And special thanks to my colleagues Cihan Büyükbayram and Ceyda Elbaşıoğlu Özbay for paving the way for me to study this subject.

Lastly, I would like to thank all my friends, for their patience when I wasn’t attending their organizations. I will catch up with you now.

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ABBREVIATIONS	
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
APC	Armored Personnel Carrier
ASQC	American Society of Quality Control
CI	Consistency Index
CR	Customer Requirement
CR	Consistency Ratio
CS	Customer Satisfaction
DoD	United States Department of Defense
DS	Customer Dissatisfaction
ECQFD	Environmentally Conscious Quality Function Deployment
FAHP	Fuzzy Analytical Hierarchy Process
FMEA	Failure Modes and Effects Analysis
HoQ	House of Quality
IFR	Ideal Final Result
ILS	Integrated Logistics Support
IPDP	Innovative Product Development Process
IRL	Integration Readiness Level
ISO	International Organization of Standards

JSQC	Japanese Society of Quality Control
LTB	Larger-the-better
MCDM	Multiple Criteria Decision-Making
ML	Maturity Level
MRL	Manufacturing Readiness Level
NTB	Nominal-the-best
OPM	Ordinal Prioritization Method
PMBOK	Project Management Body of Knowledge
PMI	Project Management Institute
PMP	Project Management Professional
PP	Product Parameter
RI	Random Inconsistency Index
QFD	Quality Function Deployment
SRVD	System Requirements Verification Document
SSB	T.C. Cumhurbaşkanlığı Savunma Sanayi Başkanlığı (Presidency of the Republic of Turkey - Presidency of Defence Industries)
SRL	System Readiness Level
SRP	System Readiness Potential
STB	Smaller-the-better
TQC	Total Quality Control
TQM	Total Quality Management

TR	Technical Requirement
TRIZ	Theory of Inventive Problem Solving
TRL	Technology Readiness Level
VoC	Voice of Customer
VoS	Voice of Stakeholders
V&V	Verification and Validation

CHAPTER 1

INTRODUCTION

The rate of new product development is increasing every day in parallel to increasing competition in almost every sector. In new product development, a new technology is used to satisfy a need, or incremental improvements are made in order to improve some functions, customize for different customer segments, or decrease the cost of the product or service. To do that, determining the needs or wants of the customers is crucial. Firms, that are more successful than their competitors in terms of understanding customer needs and fulfilling them, outrank their competitors and assure their profits, since a satisfied customer is more likely to buy again, buy more frequently, buy other products or services provided by that company or at least comment positively to her/his network, increasing the potential customer base of the company.

Information age provides new platforms and tools to understand what customers think. On the other hand, it is not easy to satisfy customers as they are more knowledgeable and demanding than they used to be; they ask for customized products and services with the minimum price and fast delivery. Technological advancements both facilitate new product development for the firms but also incite the competition by making all goods and bads visible to everyone, for example making someone else's experience with the product or service accessible to everyone on certain platforms. Overall, this results in reduced tolerance to the defects while developing and serving products.

For companies, it is a difficult task to make the decisions on what new products or services to develop and where to direct their resources or make new investments in order to ensure success of their projects and their profits. It is getting more and more important to make the right decisions in the shortest time possible. Since the decisions taken in development phase have significant impact in product's properties, an effective product development process is vital for the future of the company. Monitoring quality throughout the project lifecycle including product development, and taking decisions accordingly is one of the helpful approaches to support these decisions. Conventionally, monitoring quality is typically left to the production and the following phases. One of the reasons for this is that there is no mature method to monitor and evaluate quality in the product development phases. There is a need of a quality measurement method which can be used right from the start of the project, is as objective as possible and prioritizes the improvement points with regard to schedule and cost.

In this study, the aim is to provide a method to monitor and evaluate the quality aspect of projects, especially those that have long product development phase durations. This method mainly makes use of well-known Quality Function Deployment [1] (QFD) methodology and RAPIDO model [2] in order to define customer requirements better, connect them to design, manufacturing and quality control parameters and finally showing customer satisfaction rate and improvement points with priorities at any step in the project lifecycle, making use of the project calendar.

QFD have been used in directing the design activities, but it lacks giving timely feedback taking into account the realizations. This is where our proposed method steps-in and provides objective information to the project management teams on the current situation and the gaps between the current and planned situations, continuously. This method is expected to be useful especially in projects that are managed in industries such as defense, aerospace and other sectors in which development phases take several years.

In this thesis, a literature review on the methods used to monitor and improve quality in projects is provided in Chapter 2. Chapter 3 describes the proposed method. The application of the proposed method in a hypothetical case in defense industry company is described in Chapter 4. The results with the discussion of the findings are presented in Chapter 5. The conclusion is provided in Chapter 6, with future study suggestions.

CHAPTER 2

LITERATURE REVIEW AND BACKGROUND

Quality has numerous definitions in literature and in practice. ISO 9000:2015 [3] defines quality with these sentences: “The quality of an organization’s products and services is determined by the ability to satisfy customers and the intended and unintended impact on relevant interested parties. The quality of products and services includes not only their intended function and performance, but also their perceived value and benefit to the customer.” It guides companies to exert effort in understanding both written and implied stakeholder expectations. It also implies that quality is tightly connected to understanding the customer (and other stakeholders’) expectations and their satisfaction afterwards.

If we look at what customer satisfaction means, ISO 9000:2015 [3] defines customer satisfaction as “Customer’s perception of the degree to which the customer’s expectations have been fulfilled. (…) It can be that the customer’s expectation is not known to the organization, or even to the customer in question, until the product or service is delivered. It can be necessary for achieving high customer satisfaction to fulfil an expectation of a customer even if it is neither stated nor generally implied or obligatory. (…) Complaints are a common indicator of low customer satisfaction but their absence does not necessarily imply high customer satisfaction. (…) Even when customer requirements (…) have been agreed with the customer and fulfilled, this does not necessarily ensure high customer satisfaction.” To sum up, companies that desire a long-term success should not settle with contract compliance or little/no customer complaint, but should be going further.

As can be seen in these two definitions, quality and customer satisfaction are very close terms and even can be used interchangeably. In the literature, we see a third term, as mentioned in [2] as ‘Product Maturity Degree’. According to Paetzold (2006), as cited in Kandt et al.’s study [2], product maturity degree is “the degree of conformance of customer requirements and additional requirements from engineering view.”

In this chapter, a brief background on project management, quality function deployment with supportive tools to analyze customer requirements, RAPIDO and other product maturity measurement techniques and desirability functions are provided.

2.1. Project Management

Customers of today are more knowledgeable and demanding than in the past and this creates a challenge for organizations. In every sector, the competition is increasing every day. Companies that best catch the customer needs, whether they are explicitly spoken or not, and successfully apply these needs to their product or service design get a competitive advantage over their competitors. These advancements force the organizations to conduct both incremental and radical improvement projects for their portfolio of products and services.

Project Management has gained much importance with respect to this trend, since the lead times are forced to be shortened, costs are forced to be minimized, quality expectations are at the highest level of all times and stakeholder management is also important as well as the product or service itself.

Project Management, mainly deals with forming the optimal settings where all project contributors are able to work in harmony to achieve the shared objective and deliver the project to its customer(s) on time, on budget [4] and with the highest customer satisfaction. Project Management Body of Knowledge (PMBOK, 6th edition) [5] is a widely accepted and applied guide to support project managers achieve project objectives.

As stated by Joslin and Müller [6], project success is a frequently studied topic in project management. There are four main criteria that project managers and executors try to control: Scope, Schedule, Cost and Quality. Scope, time and cost are monitored and controlled more easily when compared to quality. For example; in development phases, the release of drawings can be scheduled and monitored accordingly. The manhours to the tasks can also be measured. However, quality measurements are generally made later in product development projects, i.e. when a physical prototype is created and/or with a first unit production. While scope, cost and schedule can be monitored by well-known methods in projects, quality is not very easy to monitor, especially in the early phases. On the other hand, as the phases advance and designs are released, making changes gets more expensive and sometimes impossible. There are studies mentioning that most defense projects do not finish on schedule, or they are more costly than planned, or not satisfying the customers [7].

In this study it is suggested that the proposed method can be used in project quality management knowledge area, which is the fifth knowledge area of PMI's PMBOK guide [5], together and in close relationship with the other knowledge areas. The all ten knowledge areas are listed as follows:

1. Project Integration Management
2. Project Scope Management
3. Project Time Management
4. Project Cost Management
5. Project Quality Management
6. Project Human Resource Management
7. Project Communications Management
8. Project Risk Management
9. Project Procurement Management
10. Project Stakeholder Management

The detailed explanations for these ten knowledge areas can be found in PMI's PMBOK Guide [5]. Only Project Quality Management Knowledge Area is covered in this study.

There are three main processes suggested by PMBOK, under Project Quality Management; they are:

1. "Plan Quality Management": This process is to plan how quality activities are going to be held throughout the project. The Quality Management Plan prepared as an output of this process may include the quality objectives, roles and responsibilities, the processes that are going to be monitored or audited, the deliverables that are going to be controlled, the standards or methodologies to be used while carrying out the quality activities, and so on. The project team decides whether to deploy QFD or any other method throughout the project in this process.
2. "Manage Quality": This process aims to assure that a mature product that satisfies all the requirements of the customer will unfold at the end of the project by applying various quality assurance activities such as auditing with respect to specific design or manufacturing guidelines, statistical process control, etc. This thesis proposes a methodology that can be used mainly in the scope of this process. Everybody, including the project sponsor and the customer takes part in 'Manage Quality' process.
3. "Control Quality": This process consists of inspection and test activities in order to assess the current quality level of the parts or the product. Inspection activities include the checks and measurements and their recordings. Testing activities are those that are made to see if the parts or the product are in conformance with what the customer wants. The outputs of Control Quality process should be investigated carefully in order to change Manage Quality activities or Quality Management Plan when necessary. Our method proposes to do control activities during the development phases as well as the supply chain phases of a project.

Other knowledge areas are in close relationship with Project Quality Management knowledge area.

From the customers' side, overall behavior of the product is important and effective on their buying decisions. These behaviors are determined by the properties of the product. Hence, determination of the adequate properties that lead to adequate behaviors is necessary [8]. On the other hand, as the complexity of the products increases, the interactions of the components and sustaining transparency and traceability get much more difficult [8], risking the success of the development projects. Therefore, the requirements and interactions of components need visibility to be managed efficiently to assure that the product will have the right set of behaviors when used by customers.

During the product development phase of a project, designers need guidance because of the complexity of the products with their functions and customizations [8]. Throughout the development and the subsequent phases, designers should work closely with specialists from other disciplines such as marketing, sales, manufacturing and quality. The quality or maturity of the product should be monitored closely with the inputs of all the disciplines to prevent any unwanted deviations or to adapt to fast-changing customer needs.

The monitoring of the processes from the very beginning of the project schedule through the satisfied customer has been studied by many scientists and practitioners. They have similar approaches with slightly different jargons and steps. The most common approach is that they all start with understanding the customer very well. Starting from the very beginning of the project, Suh [9] continues with domains, Akao [1] goes with charts, Luft, Krehmer and Wartzack [8] proceed through a procedure model. We are going to focus mostly on Akao's work, Quality Function Deployment, since it is more common and used by many practitioners already.

2.2. Quality Function Deployment

This section includes Quality Function Deployment (QFD) and supportive tools such as Affinity Diagram, Tree Structure, Analytical Hierarchy Process (AHP) and KANO model, that can be used with QFD. These supportive tools are provided where they are needed, while presenting QFD in detail.

QFD is a method to analyze customer requirements and match them to the product or service technical parameters, so that the technical parameters can be ranked according to their importance, and improvement or innovation efforts can be focused to the most promising areas. QFD relates 'why we do this' to 'what we do' and then 'how we do' by making use of numerous matrices. It is also an efficient communication tool that combines different functions in a firm and enables everyone to see the big picture.

According to Akao [1], "Planning is determining what to make; designing is deciding how to make it." QFD method makes all these processes visible and easier to monitor for everyone. According to Sullivan (1986), as cited in the literature review by Chan and Wu [10] on QFD; it is "an overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production". It can be said that QFD was born as a result of the view that sees quality as a controllable dimension throughout the whole lifecycle of a product including development and especially development since although development is just one of the phases in the project, the decisions taken in this phase determine most of the cost of the product and making a change is easiest and cheapest in this phase [11].

The history of QFD begins in 1960s with the Total Quality Control (TQC) movement of Japan [1]. It was in 1972 that Kobe shipyard of Mitsubishi Heavy Industries came up with a matrix to relate customers' needs to the quality characteristics. Dr. Yoji Akao initiated the studies as the founder of QFD Research Committee in Japanese Society for Quality Control (JSQC). Dr. Akao and Dr. Mizuno co-authored a book on

QFD in 1978, in Japan. QFD was first publicized to the world in a journal of American Society for Quality Control (ASQC) in October 1983, by Dr. Akao.

Bob King, Dan Clausing and Lawrence P. Sullivan were among the pioneers in the United States who had learnt QFD and made important contributions to the methodology [12]–[15]. Since then, it has been widely used in various sectors for different product and service design projects, all over the world. A very detailed analysis of the literature can be found in Chan and Wu's literature review [10].

Mazur [16] tells the difference of QFD from traditional quality approaches as, while the latter focus on reducing the number of defects ("negative quality"), the former focuses on maximizing "positive quality" and high rate of customer satisfaction, since your best performance would be 'zero defect' in the traditional approaches. He simply explains that "Nothing wrong" is not equal to "Everything is right".

QFD is regarded as a method to assure quality starting at the early phases of a new product/service development and continuing through the life cycle of it. Product development, quality management, customer needs analysis, product design and planning are the most popular subjects where QFD has been used and proven to be successful. The matrix structure of QFD can also be useful in many areas such as costing and decision making as well as in engineering and other management purposes. The potential use areas of QFD is vast and this study is one other example to these different areas.

QFD is used for the "deployment of quality through deployment of quality functions" [1]. It sees all functions in an organization as contributors to quality, concluding that all have quality functions within themselves. In addition, instead of the traditional "inspected-in quality", it seeks "designed-in quality" [10]. It is a pro-active method, since catching and solving the problems from the very beginning eliminates or decreases the effects of possible problems at the upcoming stages.

QFD uses matrices or charts (or quality charts in Akao's terminology [1]) to achieve identifying and prioritizing all customers' needs and relating them to the quality characteristics created in different functions of the organization. The four main phases/charts of QFD can be seen in Figure 2.1. A comprehensive QFD model [1] is provided in Figure 2.2.

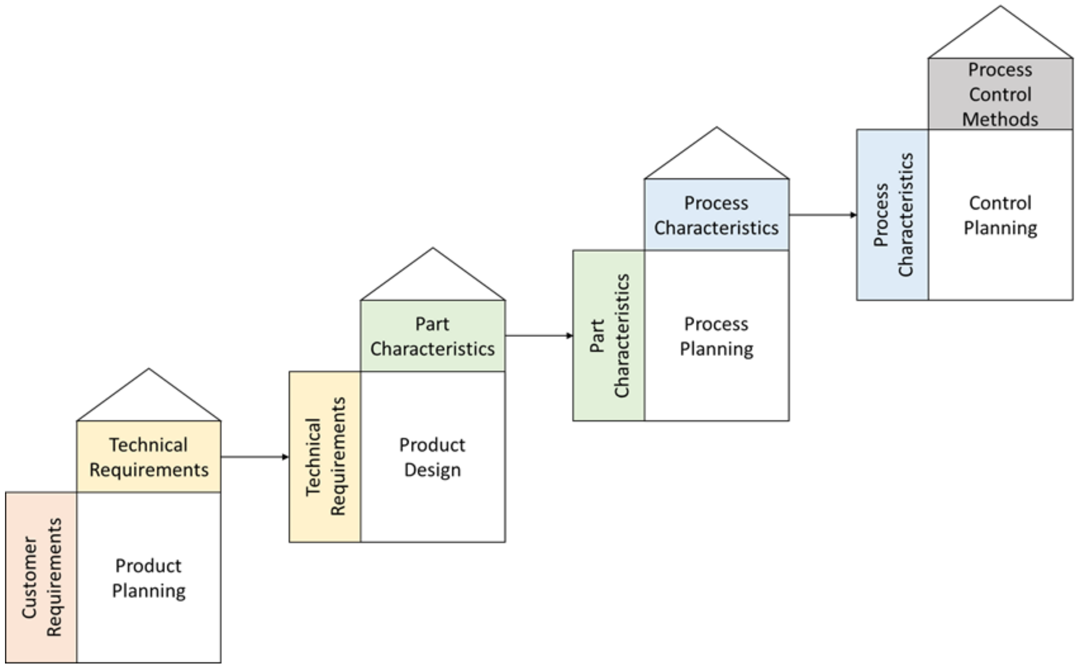


Figure 2.1. Four main phases of QFD

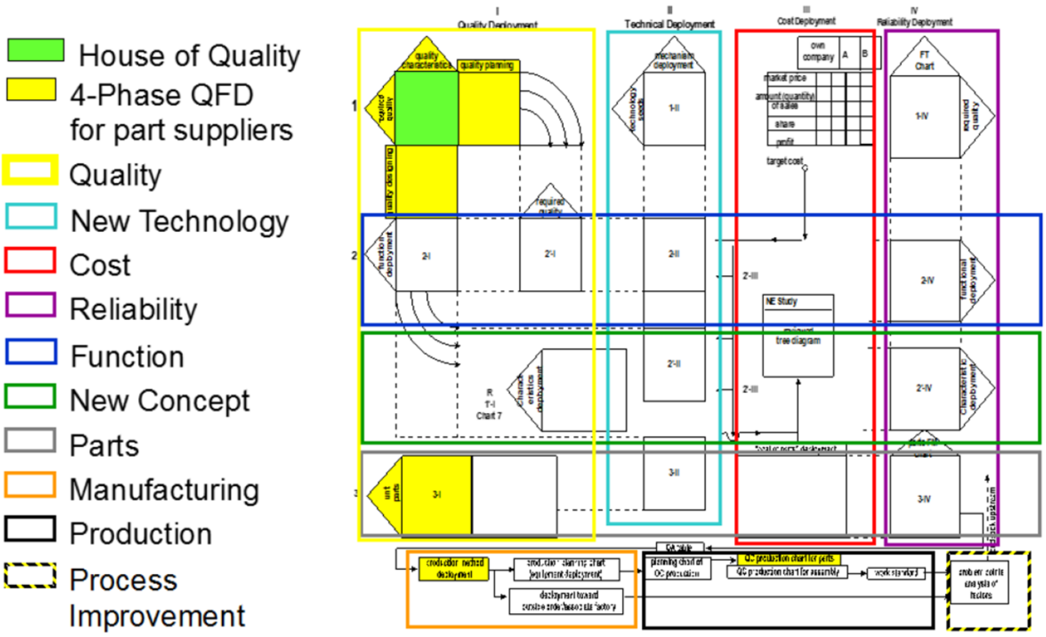


Figure 2.2. Comprehensive QFD [1]

The first chart, which is called House of Quality (HoQ) chart, can be seen in Figure 2.3.

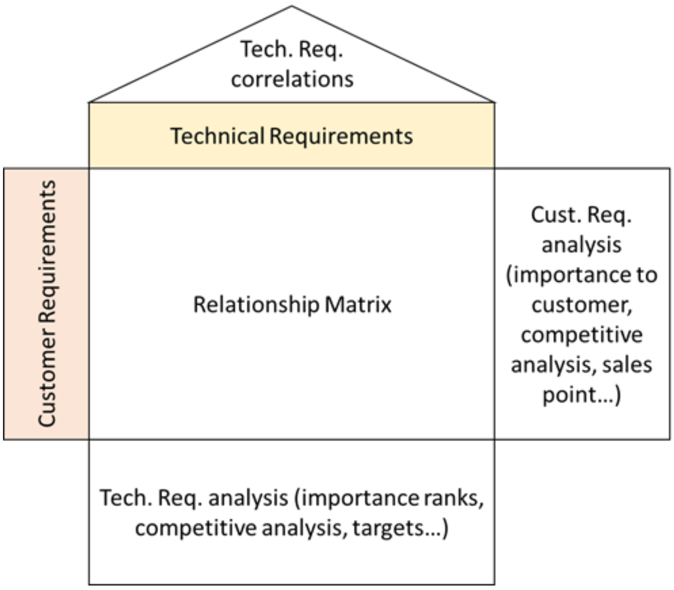


Figure 2.3. House of Quality chart (Product Planning)

A representative HoQ chart that is suggested by ISO 16355 [17] and built in a Microsoft Excel spreadsheet can be seen in Figure 2.4. Grey areas are automatically filled by related formulas.

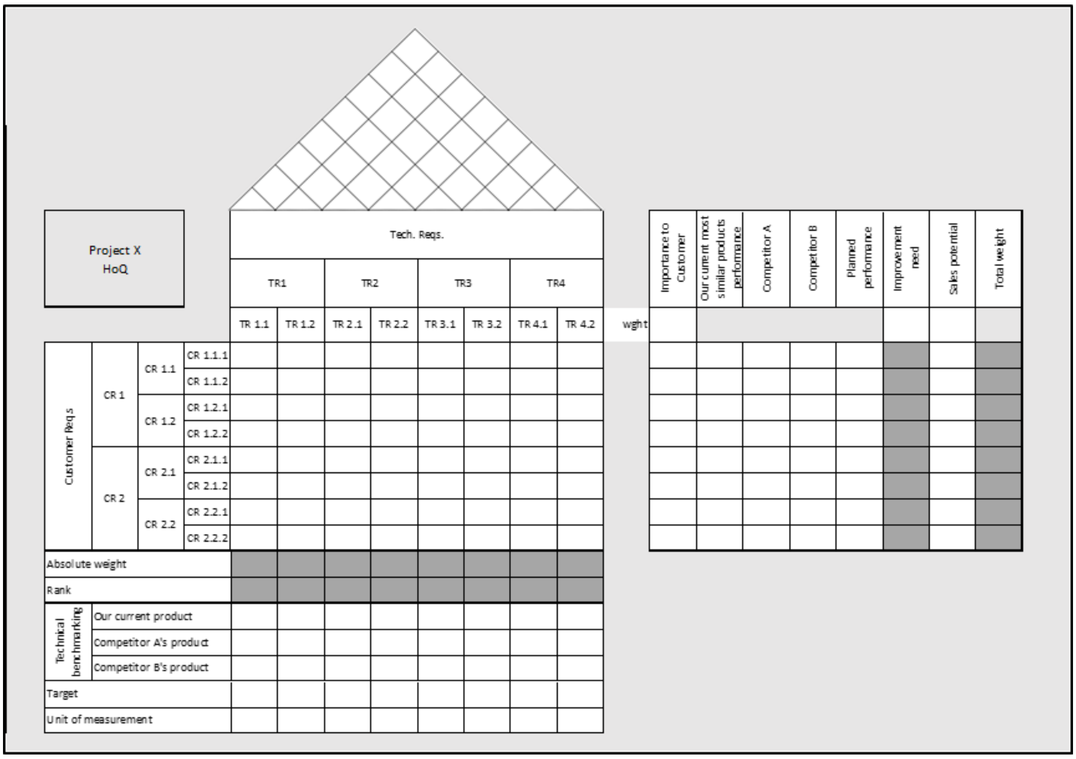


Figure 2.4. Representative HoQ chart

A successful QFD can be conducted by a team that is interdisciplinary, i.e. has members representing different functions of the organization such as marketing, sales, engineering, production, after-sales, quality, purchasing, etc. Bob King states in his book [12] that the ideal number would be 6 – 8, for a QFD team.

Definitions of parameters and variables related to HoQ as provided by Akao [1] and how supportive tools help building a HoQ are presented below:

i: index for customer requirements, $1 \leq i \leq n$

n: total number of customer requirements *j*: index for technical requirements, $1 \leq j \leq m$

m: total number of technical requirements

k: index for the contributors' weights (importance to customer, competitive analysis, sales point) that are used in calculation of total weight of each CR

CR_i: customer requirement *i*

For many products and services, there are more than one customer group or segment. For the QFD study, one or more customer groups can be selected as the target. The selection can be made according to the customer groups' share in revenue, impact on other groups' buying decision, etc. In some QFD studies, the customer segments can be identified after collecting the requirements, considering the differentiation between groups of customers.

To gather customer requirements is called Voice of Customer (VoC) study. To do that, customer requirements are collected through applicable methods such as contracts, surveys, interviews, observation by going to Gemba [16], focus group studies, collecting existing information and customer complaint data. The customers may describe the needs vaguely, but it does not create a problem at this stage. If the list is very long, (this could be the case for complex or high-tech products) grouping them helps to manage them more effectively. The study by Hari, Kasser and Weiss [18] provides how to identify and manage the requirements for complex systems.

Affinity diagram method can be used for grouping customer requirements [19], [20]. It is a method to organize the data by grouping similar entries and it helps to see the missing parts. An affinity diagram example for a vacuum cleaner can be seen in Figure 2.5.

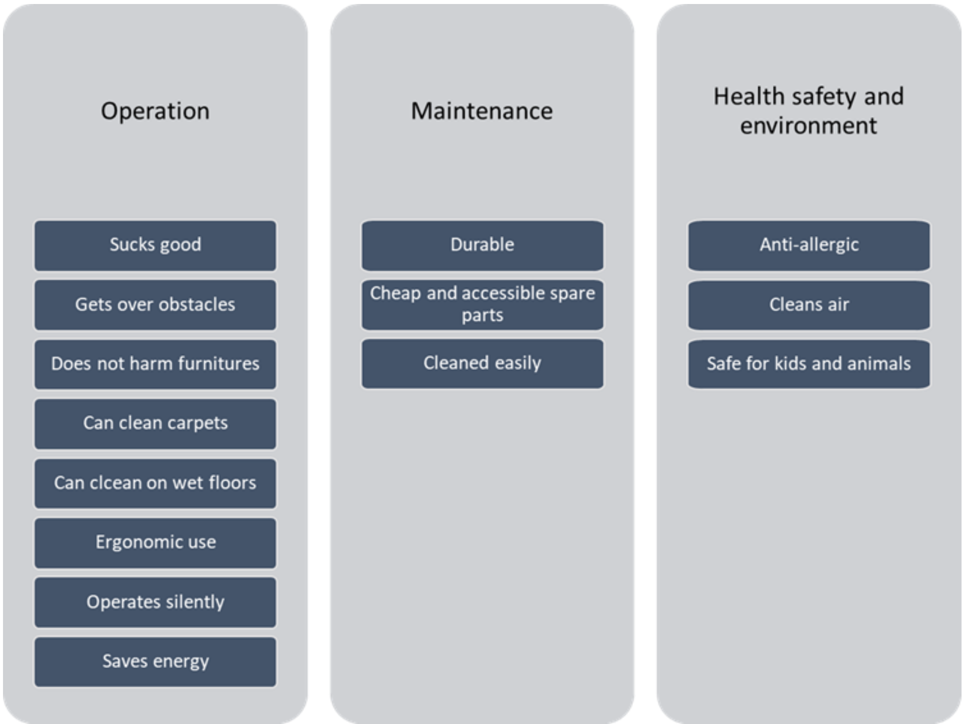


Figure 2.5. An example affinity diagram

For those observations or customer statements which are not understood the same way by each member of the QFD team, more research can be made through applicable methods such as surveys, focus group studies and interviews. It is important that all requirement expressions collected and grouped should be understood in the same way by all the QFD team members. For long-term projects such as those observed in defense industry, preparing a requirements glossary would be beneficial [5], so that it is easier to communicate the requirements with the stakeholders and also to future QFD group members as they can change due to some reasons during the project.

Classification of customer needs or expectations is important, since scarce resources should be used in the best way that maximizes customer satisfaction, revenue and profit. Customers tend to have an overall idea of a product or service, based on a few significant attributes [21]. To choose which customer requirements are to be satisfied and up to what level is a major activity in product planning stage. Also, it is hard for customers to foresee and express their expectations from a product and the degree of that expectation. It is a profession to reveal these expectations and classify them in terms of their effect on overall customer satisfaction.

In 1984, Kano with his colleagues [22] have showed the nonlinearity of requirement fulfillment and customer satisfaction. Not all requirements/attributes are equal, not all are causing satisfaction of the customer when met and dissatisfaction when unmet. Different classes of attributes are acting on customer satisfaction in a different way. The categories they suggest are “must-be, performance, excitement, indifference and reverse”.

- Must-be (basic) attributes: When unmet, they cause serious customer dissatisfaction; when met, they do not result in much satisfaction. They are already expected by the customer. Example: Being leak-proof for a dishwasher.
- Performance (one-dimensional) attributes: They are in almost linear relationship with customer satisfaction. The better we do them, the more satisfied is the customer; failing to fulfill leads to customer dissatisfaction. Example: Maximum speed of a car.
- Excitement (attractive) attributes: Opposite to the must-be requirements, when unmet, they do not cause customer dissatisfaction; but when met, they result in high level of customer satisfaction. They are unexpected by the customer and even though a detailed interview with the customer is made, the customer may not speak of these attributes. So, they are usually found out by observation and creativity. Example: Pre-heating of seats by the remote control for a car.
- Indifference attributes: Whether or not they are fulfilled, they do not cause significant customer satisfaction or dissatisfaction. One must be aware of these attributes in order to shorten development durations and do cost savings by not wasting time and effort with these attributes. Example: The surface roughness of the inner side of the hood for a car.

- Reverse attributes: Their fulfillment causes dissatisfaction while their absence causes satisfaction. By rewording these attributes, one can consider them under performance attributes.

The different effects of these categories on customer satisfaction can be seen in Figure 2.6. Indifference and reverse attributes are not shown in this graph.

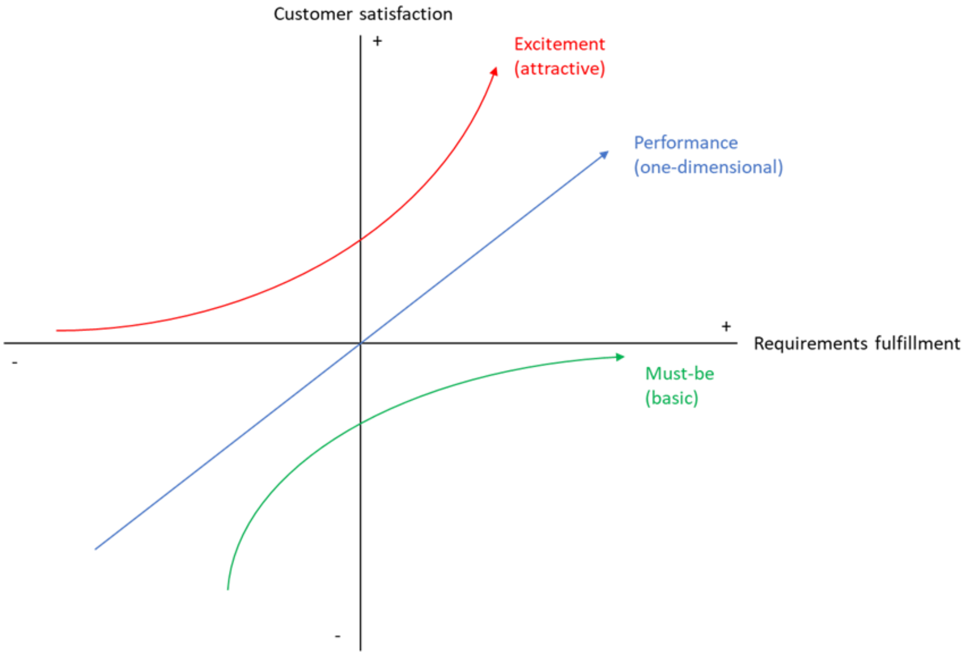


Figure 2.6. Graph representation of Kano model

Kano et al. [22] proposes the questioning methodology to determine in which category a requirement is. For each customer requirement, the customer is asked two questions; one positive, one negative. For example, let's say the requirement is the silence of a PC while working. The customer is asked:

a) How would you feel if the PC works silently?
b) How would you feel if the PC works with a cooling fan sound?

The first question is called a functional question and the other is the dysfunctional question. The answer of each surveyee to these two questions together is placed in the relevant cell of Table 2.1, which is prepared for each attribute questioned. Looking at the majority of the checks in a cell, an attribute is classified as must-be, performance, excitement, indifference or reverse. The classification equivalence of each cell is shown as circles in the cells, with the initials of the category names and Q for Questionable (not logical). For the silence attribute asked above, it is seen in Table 2.1 that it is an excitement attribute for the customers.

Table 2.1. *Kano model - evaluation table for an attribute (M: must-be, P: performance, E: excitement, I: indifference, R: reverse, Q: questionable)*

Attribute X		Answer to dysfunctional question				
		I'd like it	It should be so	Neutral	I can live with it	I wouldn't like it
Answer to functional question	I'd like it	Q	E	/ E	////// E	/ P
	It should be so	R	I	// I	// I	/// M
	Neutral	R	I	/ I	I	M
	I can live with it	R	I	I	I	M
	I wouldn't like it	R	R	R	R	Q

A key thing when preparing these questions is that, they should be in a format that reflects the customers' benefits from that product or service. In other words, it should not be like "How would you feel if there is sound insulation material in the PC?", instead, one should ask as "How would you feel if the PC works silently?".

Kano categories are dynamic with respect to time, i.e. what is an excitement attribute of today may become a performance attribute of tomorrow, or even a must-be attribute. This is intuitive, as with the advancements in technology, what is a novelty today becomes a standard as time goes by. Practitioners should be taking this into account and not use old survey data for their studies. This fact also emphasizes the importance of bringing the innovative products to market in the shortest possible time [23], as excitement attributes may lose their excitement factor and become performance or must-be type.

Kano facilitates understanding the customer requirements and customer segments. It is useful when there has to be a trade-off between fulfilling more than one requirement, and forces development teams to include excitement attributes to the product or service which could strengthen the customer satisfaction and loyalty.

Kano's model has been found very lean and easy to understand, became very popular and is frequently used by many practitioners. However, it has been criticized for its inherent subjectivity, not differentiating attributes that are in the same category, and difficulty of implementation in reality. ISO 16355 [17] proposes the use of a 'new Kano model', with regard to these criticisms. In literature, there are many Kano model extensions mostly proposing an extension to make it more analytical, especially the classification criteria. For example, Brandt [24] suggests penalty-reward contrast analysis, using "dummy regression model" to identify the impact of each attribute to customer satisfaction level and to categorize the attribute by looking at the regression coefficients. Lin et al. [25] suggest "moderated regression approach" to have a more accurate classification of the attributes. Vavra [26] brings the concepts of implicit and explicit importance and evaluation of them on an "importance grid" and categorizing the attributes accordingly. Wang and Ji [27] use S-CR relationship (relationship between customer requirement fulfillment and customer satisfaction) functions with the help of calculated CS (customer satisfaction) and DS (customer dissatisfaction) values, in order to tell the category of each attribute. Chen [28] proposes another regression model that evaluates the relationship between customer satisfaction and attribute fulfillment levels to determine categories. Kim and Yoo [29] use big data analysis to detect the raising opinions about a product and present it as an attractive attribute. An assessment covering numerous studies on Kano and extensions to it can be found in Mikulic and Prebezac's [30], and Violante and Vezzetti's [31] works which are both helpful to decide which approach would suit the needs of a manager or team. Madzik [20] suggests a Type IV Kano model after the aforementioned propositions, which argues to give more accurate classification of requirements without adding difficulty to the study.

Kano model has also been used with QFD. Matzler and Hinterhuber [32] use Kano classifications as a basis in QFD study to give weights to the customer requirements in terms of the satisfaction and dissatisfaction they could create. Shen et al. [22] explain how Kano approach forces QFD team to include all categories of Kano in the customer requirements section of the HoQ to exceed customer expectations and be competitive. Nordin and Razak [33] apply QFD and Kano integration in healthcare sector. He et al. [34] balance customer satisfaction and enterprise satisfaction (with respect to costs of reaching the targets) by integrating modified Kano model into QFD and apply the method to a home elevator design. Ji et al. [35] integrate qualitative and quantitative Kano results into QFD, maximize customer satisfaction considering cost and technical constraints and validate the method to notebook computers. Haber, Fargnoli and Sakao [36] apply QFD, Kano and fuzzy FAHP (Fuzzy Analytical Hierarchy Process) in medical device development, using only performance and excitement attributes as input to QFD process, since must-be attributes are mandatory to be satisfied and do not provide additional customer satisfaction when improved. Garibay, Gutierrez and Figueroa [37] use this integration for a digital library, and Hashim and Dawal [38] use it for a workstation in a school workshop in terms of ergonomics.

There are also many case studies applying Kano in the literature. For example; Bilgili, Erciş and Ünal [39] apply Kano in new jewelry product development. Zobnina and Rozhkov [40] use Kano to identify the parameters affecting hotel selection. Madzik and Pelantova [41] use Kano approach for validation of a website, emphasizing that the curve character, i.e. the Kano category of the attribute, is a useful input to optimize improvement efforts by identifying improvement prioritizations considering Kano outputs. Their work is a good example on using Kano for different purposes other than just classification of requirements and providing insight to marketing and business development teams.

Integration of Kano and FMEA (Failure Modes and Effects Analysis) [42], [43], integration of Kano and robust design approach [44], integration of fuzzy Kano with fuzzy AHP [45] are other extension areas to Kano, currently.

After categorizing with respect to Kano, preparing a tree-structure for the final list of CRs would help visualize the leveling of the CRs. An example tree-structure for a vacuum cleaner is shown in Figure 2.7.

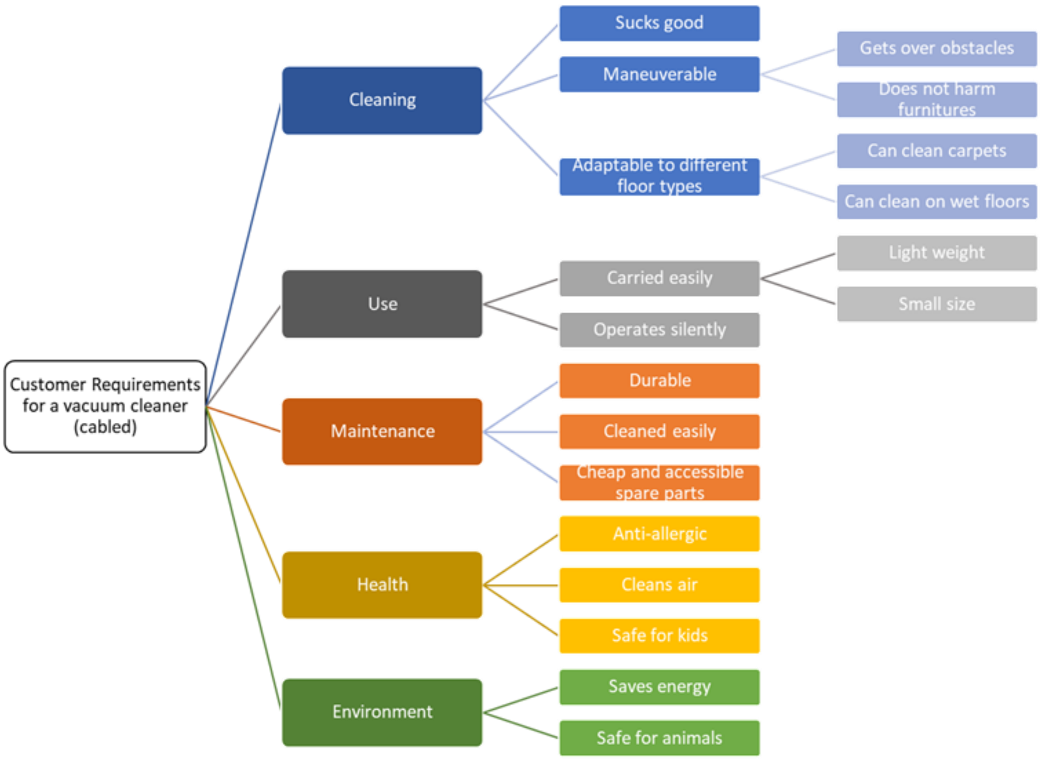


Figure 2.7. An example tree structure to group customer requirements

It is generally advised to prepare a 3-level structure. After a review of the tree structure and assuring that all customer needs are covered, the customer requirements are placed in the left-most columns of the first matrix, House of Quality.

After determining the customer requirements and assuring that they are well-understood by the QFD team members, AHP, developed by Saaty in 1990 [46], can be used to determine the customer importance weights. ISO 16355 [17] recommends weighing customer requirements using AHP to have ratio scale weights at hand, instead of assigning ordinal scale numbers or symbols as in the traditional QFD methodology [1]. An example AHP table is given below in Table 2.2. Grey cells are calculated automatically.

Table 2.2. *An example AHP calculation table*

	CR_1	CR_2	CR_3	CR_4	N_1	N_2	N_3	N_4	Row sum	Normalized sum
CR_1	1	3	1/5	1	0.136	0.214	0.130	0.136	0.617	0.154
CR_2	1/3	1	1/7	1/3	0.045	0.071	0.093	0.045	0.255	0.064
CR_3	5	7	1	5	0.682	0.500	0.648	0.682	2.512	0.628
CR_4	1	3	1/5	1	0.136	0.214	0.130	0.136	0.617	0.154
totals	7.333	14.000	1.543	7.333	1.000	1.000	1.000	1.000	4.000	1.000

ICR_{41} $NICR_{41}$ $CWCR_1$

The calculation steps are as follows.

i: index for row number

h: index for column number

ICR_{ih}: The value that answers the question: "How much CR_i in the row is more important than the CR_h in the column for a given hierarchy in the tree structure of CRs?" The value is between 1-9 on the basis of Table 2.3.

Table 2.3. *AHP importance rates [47]*

Verbal answer	Grade
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9

The diagonal cells in Table 2.2 contain 1's, since they are self-comparison. The other cells in grey in columns CR_1 to CR_4 are calculated automatically by taking the inverse of their symmetrical values. Columns N_1 to N_4 are the normalized values for the columns CR_1 to CR_4. They are found by:

$$\mathrm{NICR}_{ih} = \frac{\mathrm{ICR}_{ih}}{\sum_{h=1}^{n} \mathrm{ICR}_{ih}} \tag{1}$$

The customer importance weights are found by the sum of the normalized columns N_1 – N_4.

$CWCR_i$: 'importance to customer' weight of CR_i.

$$\mathrm{CWCR}_i = \frac{\sum_{h=1}^{n} \mathrm{NICR}_{ih}}{\sum_{i=1}^{n} \sum_{h=1}^{n} \mathrm{NICR}_{ih}} \tag{2}$$

$$\sum_{i=1}^{n} \mathrm{CWCR}_i = 1 \tag{3}$$

When the importance data are gathered from several customers, the cells of Table 2.2 would include geometric mean of values aspired by the customers [47].

Before using the results, a consistency test should be done. For this, Saaty [48] proposes a method. First, a Consistency Index (CI) as in Equation 4 is calculated where λ_{max} is the highest value for the eigenvalues of the AHP matrix. Then, Consistency Ratio (CR) is calculated as the ratio of CI to Random Inconsistency Index (RI) as in Equation 5.

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n-1} \tag{4}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{5}$$

Saaty [48] suggests that CR values > 0.10 means that there is high inconsistency and it is better to revisit the pairwise evaluations.

The consistency check of Table 2.2 is made. λ_{max} is found to be 4.074 and a CR value of 0.027 is found which indicates a consistent enough AHP table to be used in further analysis.

AHP method can be used to prioritize customer requirements in QFD studies. But it is not the only way to do that. There are also other methods that can be used, such as weighted sum method, TOPSIS, ELECTRE III, PROMETHEE II, etc. Weighted sum method, its use and its deficiencies can be found in Marler and Arora's study [49].

TOPSIS is the abbreviation for 'Technique for Order Preference by Similarity to Ideal Solution'. It uses positive-ideal and negative-ideal solutions to choose among the alternatives that has the minimum distance to the former and the maximum distance to the latter. It is first proposed by Hwang and Yoon in 1981 [50]. A detailed review of this method and several applications can be found in Behzadian et al.'s study [51].

A comprehensive literature review on ELECTRE method is provided by Govindan and Jepsen [52]. It uses pair-wise comparisons to outrank alternatives. It is first developed by Benayoun, Roy and Sussman [53], and then many extensions to it have been studied under the names ELECTRE II, III, IV, TRI, etc.

PROMETHEE is the abbreviation for 'Preference Ranking Organization Method for Enrichment Evaluations'. It is developed by Brans in 1982 [54] and similar to ELECTRE it uses pair-wise comparisons of alternatives for each criterion. Many extensions to this method are studied with names PROMETHEE I, II, III, IV, V, VI, GDSS, GAIA, etc. A detailed review on PROMETHEE can be found in Behzadian et al.'s study [55].

These methods, together with AHP are compared in the recent study of Kokaraki et al. [56]. It is seen that AHP performs as well as the other methods mentioned. Also, a larger group of methods are compared under a fuzzy environment in the study of Zamani-Sabzi et al. [57] where it is proposed that AHP performed well among other methods that performed well. According to Zanakis et al. [58], as the number of alternatives to choose from increases, methods that they compare tend to result in dissimilar rankings. This is one of the criticisms for the different multiple-criteria decision making (MCDM) methods, along with rank reversal phenomenon which is that when a new alternative is introduced to the list of alternatives, the rankings may change for the old list of alternatives.

A literature review prepared by Vaidya and Kumar [59] covers many applications of AHP. They observed that AHP has been used in engineering quiet often in an increasing trend. Because of its simplicity and being known widely, AHP is chosen to be applied, together with QFD in this study. Franceschini et al. [60] proposes an alternative way to the prioritization of technical requirements when the customer requirements have ordinal weights. They prioritize technical requirements in a more objective way than the classical QFD prioritization using their Ordinal Prioritization Method (OPM). This method is especially useful when the number of customer requirements are high and making customers evaluate them with AHP would be exhaustive or trying to give them exact weights (independent scores) in ratio scale would be difficult. Singh and Kumar [61] used QFD combined with Analytical Network Process (ANP), which is a tool for decision making that is a more general form of Analytical Hierarchy Process (AHP).

Kamvysi et al. [62] use QFD with fuzzy AHP and linear programming in order to design an optimal academic course, taking into consideration the students' needs and wants as objectively as possible.

The next part in HoQ covers the competitive analysis of the CRs. It includes evaluating your own product (or most similar product of yours) and also one or more of your competitors' products for each customer requirement. A scale between 1-5 can be used; 5 means a high score representing the industry leader and 1 is the lowest score that represents a bad performance. Considering the achievements of your competitors and your company, a target value for each customer requirement is determined. The competitive analysis weight for each customer requirement is calculated and then normalized.

FCR_i: Company's current product's performance value for CR_i in the market as perceived by the customers. (i: index for CRs)

$$1 \leq \text{FCR}_i \leq 5 \tag{6}$$

ACR_i: Competitor A's performance value for CR_i

$$1 \leq \text{ACR}_i \leq 5 \tag{7}$$

BCR_i: Competitor B's performance value for CR_i

$$1 \leq \text{BCR}_i \leq 5 \tag{8}$$

TCR_i: Target performance value for the new/improved product for CR_i. This value is assigned by looking at the company's and its competitors' performances.

$$1 \leq \text{TCR}_i \leq 5 \tag{9}$$

To assign competitive analysis weights considering the improvement need as a gap between current product performance and target performance, again AHP method can be used in order to have ratio scale weights. The competitive analysis weight values that are used in [63] and [64] are used in the same way in this study, as shown in Equation 10. Since the values are in ratio scale, they can be used in calculations.

$CAWCR_i$: competitive analysis weight of CR_i (improvement need).

$$\text{CAWCR}_i = \begin{cases} 0.558 & \text{if TCR}_i \text{ is much better than FCR}_i \\ 0.263 & \text{if TCR}_i \text{ is somehow better than FCR}_i \\ 0.122 & \text{if TCR}_i \text{ is almost equal to FCR}_i \\ 0.057 & \text{if FCR}_i \text{ is better than TCR}_i \end{cases} \tag{10}$$

NCAWCR$_i$: normalized competitive analysis weight of CR$_i$ (improvement need)

$$\text{NCAWCR}_i = \frac{\text{CAWCR}_i}{\sum_{i=1}^{n} \text{CAWCR}_i} \tag{11}$$

SPCR$_i$: sales point coefficient for CR$_i$. The sales point values that are used in [63] and [64] are used also in this study, similar to the competitive analysis weight. These sales point values were derived in these studies by using AHP. Since the values are in ratio scale, they can be used in calculations.

$$\text{SPCR}_i = \begin{cases} 0.633 & \text{if CR}_i \text{ has a major contribution to sales} \\ 0.260 & \text{if CR}_i \text{ has minor contribution to sales} \\ 0.106 & \text{if CR}_i \text{ does not contribute to sales significantly} \end{cases} \tag{12}$$

It is important to distribute these points in a balanced way. Too many judgements of ‘significant contribution to sales’ would not prioritize one or two important CRs.

NSPCR$_i$: normalized sales point coefficient for CR$_i$

$$\text{NSPCR}_i = \frac{\text{SPCR}_i}{\sum_{i=1}^{n} \text{SPCR}_i} \tag{13}$$

Total weight of each customer requirement can now be found by the weighted sum of the three values: importance to customer, improvement need and sales points. To do that, weights indicating importance degrees of these three inputs are assigned by the QFD team.

w$_k$: weights to be used in weighted sum calculation of the total weight of CR$_i$

$$\sum_{k=1}^{3} \text{w}_k = 1 \tag{14}$$

TWCR$_i$: total weight of CR$_i$

$$\text{TWCR}_i = (\text{w}_1 \times \text{CWCR}_i) + (\text{w}_2 \times \text{NCAWCR}_i) + (\text{w}_3 \times \text{NSPCR}_i) \tag{15}$$

$$\sum_{i=1}^{n} \text{TWCR}_i = 1 \tag{16}$$

Since all contributing values are normalized, the total weights of CRs sum up to 1, so there is no need to normalize TWCR$_i$ values.

After analyzing the customer requirements, the process can continue with defining and analyzing the technical requirements.

TR_j: technical requirement j

Technical requirements are derived by the engineers. They are performance metrics for the product's functions. In other words, they are how the engineers describe this product [13], in measurable terms. Leveling them by tree-structure, as in CR leveling can be useful in order to organize and place them into HoQ.

Technical requirements can be in correlation with another technical requirement. For example, weight and braking distance are negatively correlated technical requirements of a vehicle, while weight and protection level are positively correlated. In the roof of the HoQ, the triangle is filled with 0's for no correlation, 1's for positive correlations and -1's for negative correlations. The possible correlation values are shown as in Equation 17.

c_{jl}: correlation value between technical requirements j and l

$$c_{jl} = \begin{cases} +1 & \text{if } \mathrm{TR}_j \text{ and } \mathrm{TR}_l \text{ correlate positively} \\ 0 & \text{if } \mathrm{TR}_j \text{ and } \mathrm{TR}_l \text{ do not correlate} \\ -1 & \text{if } \mathrm{TR}_j \text{ and } \mathrm{TR}_l \text{ correlate negatively} \end{cases} \tag{17}$$

Investigating the negative correlations between TRs, if exists, is essential for the success of the project. It is better if technical requirements are defined ensuring no negative correlation between them. However, when it is not possible to do so, re-engineering studies can be started as soon as possible to save time and solve these contradictions. TRIZ methodology is a good option to solve contradictions.

TRIZ is the acronym of Theory of Inventive Problem Solving in Russian and was found by Altshuller and his colleagues [65]. Yamashina, Ito and Kawada [66] use QFD with TRIZ. Brief information on TRIZ can be found in the paper of Ilevbare, Probert and Phaal [67]. By using TRIZ techniques, the unwanted correlations of the technical requirements can be solved and difficult targets of important technical requirements can be reached. Yamashina and his colleagues propose IPDP (Innovative Product Development Process) technique to systematically apply both QFD and TRIZ together. Vinodh, Kamala and Jayakrishna [68] use environmentally conscious QFD (ECQFD), TRIZ and AHP together to determine alternatives (by ECQFD), solve contradictions (by TRIZ) and choose the best design alternatives. They test their approach in an automotive component design. Other perspectives of TRIZ methodology can be found in Appendix A.

Continuing with the HoQ; to connect TRs to CRs, relationship values are needed. Each relationship value indicates how a TR is effective on a CR in terms of fulfilling the requirement.

r_{ij}: relationship value between CR_i and TR_j. Relationship values can be assigned with respect to two methods [17]:

1) Classical QFD: 0 or blank means no relation, 1-3-9 are assigned for weak to strong relationships respectively.

$$\mathrm{r}_{ij} = \begin{cases} 0 \text{ or blank} & \text{if } \mathrm{CR}_i \text{and } \mathrm{TR}_j \text{ have no relation} \\ 1 & \text{if } \mathrm{CR}_i \text{and } \mathrm{TR}_j \text{ have a weak relation} \\ 3 & \text{if } \mathrm{CR}_i \text{and } \mathrm{TR}_j \text{ have medium relation} \\ 9 & \text{if } \mathrm{CR}_i \text{and } \mathrm{TR}_j \text{ have strong relation} \end{cases} \qquad (18)$$

2) Modern QFD: Instead of ordinal scale as in Classical QFD, Modern QFD makes use of ratio scale when assigning relationship values [17]. Ordinal scales cannot be used in mathematical operations, while ratio scale can. Relationship values can be assigned according to the Tables 2.4 and 2.5 below, Table 2.4 for a 5-point scale and Table 2.5 for a 9-point scale. Choosing whether to use 5-point scale or 9-point scale depends on the QFD team's preference.

Table 2.4. *5-point scale relationship values table*

Relationship - qualitative	**Relationship – ratio scale**
Weak	0.069
Moderate	0.135
Strong	0.267
Very Strong	0.518
Extremely Strong	1.000

Table 2.5. *9-point scale relationship values table*

Relationship - qualitative	**Relationship – ratio scale**
Weak	0.059
Weak-to-Moderate	0.079
Moderate	0.112
Moderate-to-Strong	0.162
Strong	0.237
Strong-to-Very strong	0.344
Very Strong	0.498
Very Strong-to-Extremely Strong	0.712
Extremely Strong	1.000

$AWTR_j$: Absolute weight of TR_j

$$\mathrm{AWTR}_j = \sum_{i=1}^{n} (\mathrm{r}_{ij} \ x \ \mathrm{NTWCR}_i) \tag{19}$$

$NWTR_j$: Normalized weight of TR_j

$$\mathrm{NWTR}_j = \frac{\mathrm{AWTR}_j}{\sum_{i=1}^{m} \mathrm{AWTR}_j} \tag{20}$$

$$\sum_{j=1}^{m} \mathrm{NWTR}_j = 1 \tag{21}$$

RTR_j: Rank of TR_j

RTR_j is found by sequencing TRs according to the NWTR values, from largest to smallest. The TR with the largest NWTR has RTR value of 1.

FTR_j: The current product's performance value for TR_j according to the definition of the technical requirement

ATR_j: Competitor A's performance value for TR_j

BTR_j: Competitor B's performance value for TR_j

TTR_j: Target value for the new/improved product for TR_j

Lastly, the units are entered to the last row of the HoQ.

A major output of a HoQ is the prioritized technical requirements and their target values. The next chart can be created using these prioritized technical requirements and deriving product parameters.

The HoQ with its relationship matrix provides also opportunities to detect redundancies or missing technical requirements. For example, if a customer requirement does not have any relation with the technical requirements, there is a risk that the final product will not be satisfying that particular customer requirement or it can be interpreted as an opportunity to improve the product by additional technical requirements. On the other hand, if a technical requirement does not have any relation with any of the customer requirements, it may either be a redundant technical requirement, or we are lacking at least one customer requirement in the matrix.

HoQ helps managing changes since it shows the relations in multiple dimensions. The impact of a change in customer demands are reflected easily on the technical requirements. A constraint in a technical requirement may trigger a re-engineering project to ensure satisfaction of the related customer requirement(s). Also, the roof of the HoQ shows the correlations of technical requirements and they may indicate points where trade-off analysis is necessary.

QFD is also a tool that improves communication between people from different disciplines and perspectives. Their skills are focused for one common objective: satisfying the customer and making them purchase the company’s products continually [13]. Marketing people, designers, manufacturers, quality controllers and sales people should be working together and in harmony to achieve it. QFD provides us the platform to make this possible.

Researchers and practitioners who study QFD agree that there are no hard rules or must-be symbols or structures for QFD studies. As long as the main principle behind the method is there, every QFD team can adapt it to their own conditions and preferences [13]. On the other hand, an ISO standard, called ISO 16355 [17], [47], [69]–[72] is released that covers “application of statistical and related methods to new technology and product development process”, its main emphasize being the QFD methodology. This descriptive standard is written to guide practitioners using QFD in their professions.

Gavareshki, Abbasi and Rostamkhani [73] use QFD with Value Engineering (VE) and Lean methodology. Value Engineering was first announced by Lawrence D. Miles [74] in 1940’s in General Electric, to reduce costs by reconsidering the materials of the products. The proposed procedure consists of determining the control parameters at the end of four main matrices of QFD and then prioritizing these control tests using VE and lean methodologies. Using QFD with VE was proposed by Bob King [12], too.

Matorera and Fraser [75] propose the use of QFD and Six Sigma together. Six Sigma is a philosophy, first found in 1980s Motorola and General Electric, and is a combination of tools that aims to decrease variance in processes, decreasing rate of defects to as little as 3.4 per million.

Kivinen [76] proposes that project requirements could be improved by using QFD and it positively affects project management as the decisions are based on solid justifications. Dinçer [77] proposes use of QFD outputs with goal programming to get maximum customer satisfaction considering the constraint(s).

There are also numerous case studies in the literature, using QFD for different purposes in different sectors, products and services. A few examples to these works are covered here. Köksal, Kasnakoğlu and Wasti [78] gather the voice of stakeholders (VOS) and improve services of a technopark, using Blitz QFD approach. Walters and Seyedian [79] use QFD for improving the academic advising program in a business school. Kurtulmuşoğlu and Pakdil [80] use it to increase service quality in lodging while Gharakhani and Eslami [81] prioritize the requirements of the customers of an hotel. Jandaghi, Amiri and Mollaee [82] use QFD in public sector, forming a strategy for an HR department. Bulut, Duru and Huang [83] apply multi-layer QFD to improve services in an international airport by considering the voice of different customer segments. Lin and Pekkarinen [84] use QFD in logistic service design. Hussain et al. [85] improve customer satisfaction in telecom industry and Gupta and Srivastava [86] analyze online banking services using QFD. Hadidi [87] assesses contractors of a firm in terms of their customer requirements' satisfaction performances, with the help QFD method. LePrevost and Mazur [88] discuss the use of QFD to prioritize IT projects and manage resources accordingly. Dror and Barad [89] modify HoQ as HoS (House of Strategy) and Eliezer and Dror [90] modify HoQ as HoPS (House of Project Success) in order to modify the structure keeping the main principles of the HoQ matrix.

QFD is also frequently used in education area. Using QFD, Franceschini and Terzago [91] design an industrial training course, and Aytaç and Deniz [92] design a curriculum of a vocational school while Köksal and Eğitman [18] improve industrial engineering education quality in a university. Hwarng and Teo [93] study other areas in higher education and use QFD to improve systems such as an online registration system, research grant application.

As can be seen from these few examples and rest of the literature on QFD, the method has been applied in various areas and with different purposes, and by many modifications that are made regarding the specific needs of the users. However, there is no study that adds the actual situation of a project into the system to evaluate it further. In other words, QFD feeds teams on what the important requirements or parameters are. It does not consider actual quality, schedule and cost performances to better guide the project managers in their decision making throughout the project lifecycle.

2.3. Product Maturity Assessment

This study proposes to provide quality indicators that can be calculated starting from the very beginning of product development throughout the lifecycle of the product. So, it is beneficial to review relevant methods that could be similar to or inspiring for our problem. For this reason, studies on maturity levels and product maturity assessment methods are reviewed and they will be summarized in this section.

Product maturity assessment is an attractive area for many scientists and practitioners, as the growing competition in the world is enforcing organizations to have shorter product development lead times while increasing customer satisfaction rates at the same time.

The challenge affects both the design organizations as well as acquisition parties like government agencies. For example, Azizian et al. [7] states in their study that USA Government Accountability Office has declared having difficulties in the acquisition programs in terms of schedule, cost and other performance metrics. They state that it is because of immature technologies, manufacturing capabilities or designs.

To mitigate the risks of failures in the later phases, technical project managers have to monitor the development phases closely. When the systems are not complex, it is easier to assess the maturity level of the system. When the systems get more complex, which is actually the case, as, while products look leaner, they in fact get more complex inside, a formal and repeatable method is needed. [94]

There are several methodologies in the literature to determine the maturity degree of a product. Among these methodologies, only RAPIDO will be detailed in this section, while other methodologies such as TRL and its variants, TRIZ and Property Based Product Development are provided in Appendix A.

RAPIDO method, proposed by Kandt et al. [2], is a product maturity assessment method which takes the relative importance of requirements, the degree of fulfillment of the requirements and the uncertainty of this requirement fulfillment evaluation as inputs to do the maturity assessment. In other words, it uses three criteria for the assessment: importance of the technical requirement ("significance index"), probability that the requirement is satisfied ("uncertainty of requirements fulfillment") and how certain we are in declaring the satisfaction of the requirement ("uncertainty of the used decision data basis"). The first two parameters can be judged to be more straightforward as most approaches suggest to compare the current fulfillment degree of the requirements with the planned fulfillment and taking their importance into account. The third parameter is a useful additional contributor in RAPIDO model because when the project is at its first stages, there are mostly expert opinions at hand. Since expert opinions have high uncertainty, the maturity level is not high at the initial phases of the project.

The assessment table is shown in Table 2.6 and possible scaling criteria for parameter A (method uncertainty) of RAPIDO model is given in Figure 2.8.

Table 2.6. *Rating scale for the three RAPIDO criteria [2]*

Values for A, B and U	B: How important is TR_i?	U: What is your decision for the fulfillment of TR_i?	A: How did you decide on fulfillment of TR_i?
0-3	“Nice to have” requirements	Requirement presumably accomplishable, test/simulation passed	Test
4-7	Intern requirements	Requirement fulfillment uncertain	Simulation
8-10	Customer or legal requirements	Requirement presumably not accomplishable, test/simulation failed	Expert knowledge

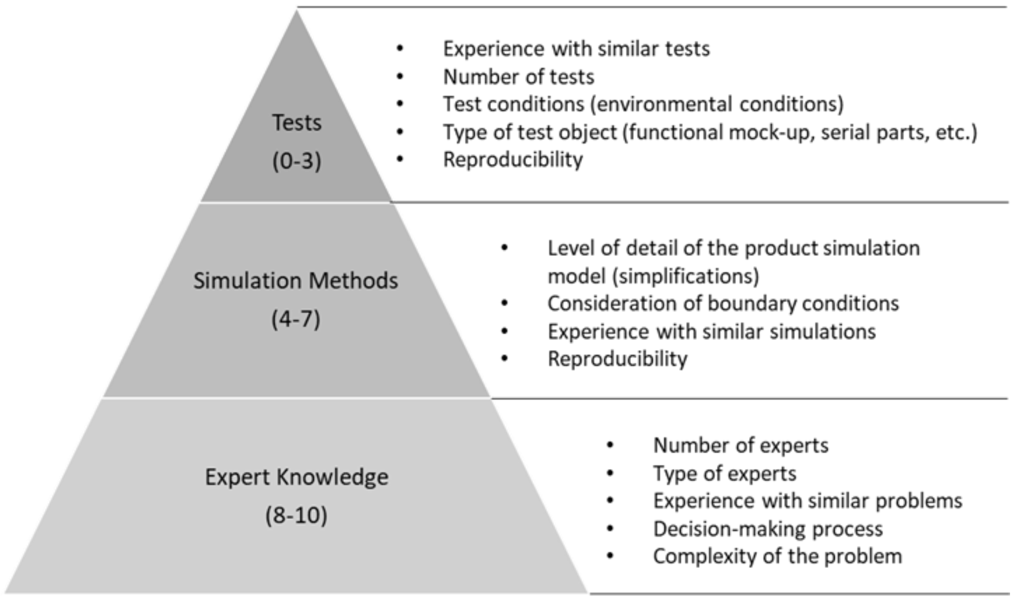


Figure 2.8. Pyramid of verification and validation (V&V) method details used to decide about fulfillment of technical requirements [2]

The maturity calculation equation is shown in Equation 22. Equation 23 is used to calculate the maximum possible maturity level if the planned verification & validation methods at that step of the project have been applied. Equation 24 is used to calculate the maximum possible maturity level, if the planned achievement rates are used instead of real achievement rates for the requirements.

$$\mathrm{ML}_{real}[\%] = 100 - \sum_{j=1}^{m} \frac{\mathrm{A}_j + \mathrm{U}_j}{2} \times 10 \times \frac{\mathrm{B}_j}{\sum_{j=1}^{m} \mathrm{B}_j} \quad (22)$$

$$\mathrm{ML}_{A,p}[\%] = 100 - \sum_{j=1}^{m} \frac{\mathrm{A}_{p,j} + \mathrm{U}_j}{2} \times 10 \times \frac{\mathrm{B}_j}{\sum_{j=1}^{m} \mathrm{B}_j} \quad (23)$$

$$\mathrm{ML}_{U,p}[\%] = 100 - \sum_{j=1}^{m} \frac{\mathrm{A}_j + \mathrm{U}_{p,j}}{2} \times 10 \times \frac{\mathrm{B}_j}{\sum_{i=1}^{n} \mathrm{B}_j} \quad (24)$$

where

j: index for technical requirements

m: total number of technical requirements

TR_j: Technical Requirement j

A_j: Uncertainty rate of the used decision data basis for TR_j

$A_{p,j}$: Uncertainty rate of the planned decision data basis for TR_j

U_j: Uncertainty of the fulfillment level of TR_j

$U_{p,j}$: Uncertainty at the planned fulfillment level of TR_j

B_j: Significance index for TR_j

ML_{real}: Real (or current) Maturity Level

$$0 \leq \mathrm{ML}_{\mathrm{real}} \leq 100 \quad (25)$$

$ML_{A,p}$: Maximum Possible Maturity Level if planned verification and validation methods are used (Value of A may be different than that used in the calculation of ML_{real})

$$0 \leq \mathrm{ML}_{\mathrm{A,p}} \leq 100 \quad (26)$$

$ML_{U,p}$: Maximum Possible Maturity Level if planned fulfillment rates are used instead of real fulfillment rates (Value of U may be different than that used in the calculation of ML_{real})

$$0 \leq ML_{U,p} \leq 100 \quad (27)$$

To be able to comment on the maturity level, the value of ML_{real} is compared with $ML_{A,p}$ and $ML_{U,p}$ values. If $ML_{A,p}$ is larger than ML_{real}, than it can be said that the planned verification and validation (V&V) methods are not used currently, which means that the product is not as mature as it is planned for the current phase of the project. If $ML_{U,p}$ is larger than ML_{real}, than it can be said that the planned fulfillment rates for the technical requirements are not achieved currently, which means that the product is not as mature as it is planned for the current phase of the project. For the cases where ML_{real} is larger or equal to $ML_{A,p}$ and $ML_{U,p}$, it can be concluded that the project is progressing as planned or even better.

All three values used in the calculation of ML values are in ordinal scale. However, RAPIDO method uses them in calculations, which makes this method prone to criticisms on objectivity. Instead of parameter U (fulfillment rate of TR) using desirability functions can be considered in the proposed method. An overview of desirability functions is provided in Section 2.4.

RAPIDO method assumes that the technical requirements are already defined properly. Making this evaluation on the customer requirements is not easy, since the requirements can be vague, subjective or too many. Also, customer requirements are sometimes mixed with technical requirements or even with product parameters. Hence, the requirements to be used in RAPIDO model is assumed to be technical requirements. The advantage of RAPIDO is that it has an easy to understand logic behind, and also it covers all requirements, evaluating each of them one by one.

Using QFD at first and applying RAPIDO logic to assess the broken-down requirements would be an integral method, and it would also prevent the aforementioned shortcomings in application. That is why RAPIDO approach is chosen as a complimentary part of QFD in this study.

2.4. Desirability Functions

Desirability functions are generally used for problems where the responses to a certain condition is not linear. A desirability function maps a certain response value to a desirability value between 0 and 1. It is first studied by Harrington [95] and then modified by Derringer and Suich [96]. In this study, for the customer requirements, the fulfillment of the requirements does not necessarily cause satisfaction of the customer in a linear mode. Hence, use of desirability functions is considered.

Figure 2.9 shows representative desirability function graphs for different type of requirements. In these graphs the parameters L, U and w represent parameters of the desirability function, determined by the decision maker according to his/her preferences.

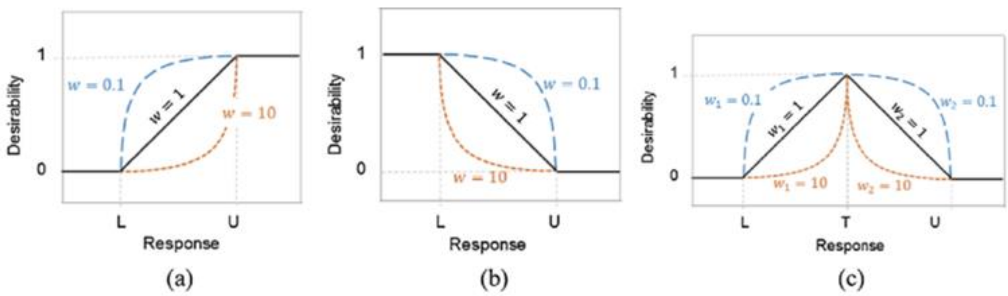


Figure 2.9. Desirability functions for larger-the-better (LTB), smaller-the-better (STB) and nominal-the-best (NTB) type of functions [97]

The studies of Akteke-Öztürk, Köksal and Weber [98]–[100] can be referred to, for more information and different uses of desirability functions.

CHAPTER 3

THE PROPOSED METHOD

In this study, the aim is to provide a method to monitor and evaluate the quality aspect of projects that have long product development phase durations. This method is expected to be useful especially for projects, in which development phase takes several years. Those are typically make-to-order type of businesses, where production and even the detailed design usually begin after the order is received from the customer.

Preliminary requirements that the proposed method is based on are stated as follows:

1) There is an actual or a potential customer.
2) There is a project that aims to develop a product or a service that would fulfill the needs and wants of the customer.
3) There is a team assigned for the project.
4) The project is managed using a proper project management method such as PMI/PMBOK, Prince2, etc. There is at least a project schedule with defined latest finish dates and precedence relations for workpackages.
5) Requirements management process exists and efforts are exerted to understand the customer needs. At least, the project management has the will to do so.
6) Training about the proposed method is given to the project team.
7) There is top management support on the use of a method to monitor and evaluate quality right from the start of the project.

The proposed method is presented under two phases; Initiation and Monitoring. The initiation phase is mostly a proper execution of product planning based on HoQ. The only difference is that the Kano classification is added to the customer requirements evaluation part. Monitoring consists of monitoring quality and interpreting the results by taking into account data on schedule and cost. Monitoring quality, cost and schedule are the major contributions of this study and a modified and complemented version of the RAPIDO method is used for this phase.

The application of the proposed method in a hypothetical case in a defense industry company is provided in Chapter 4.

3.1. Initiation

Initiation phase consists of forming a team, collecting voice of customer (VoC) and building the HoQ in its most recommended way such as in [13]. The matrix to be filled in this part is shown in Figure 3.1. Grey cells are calculated automatically. The notation is the same used in Section 2.2.

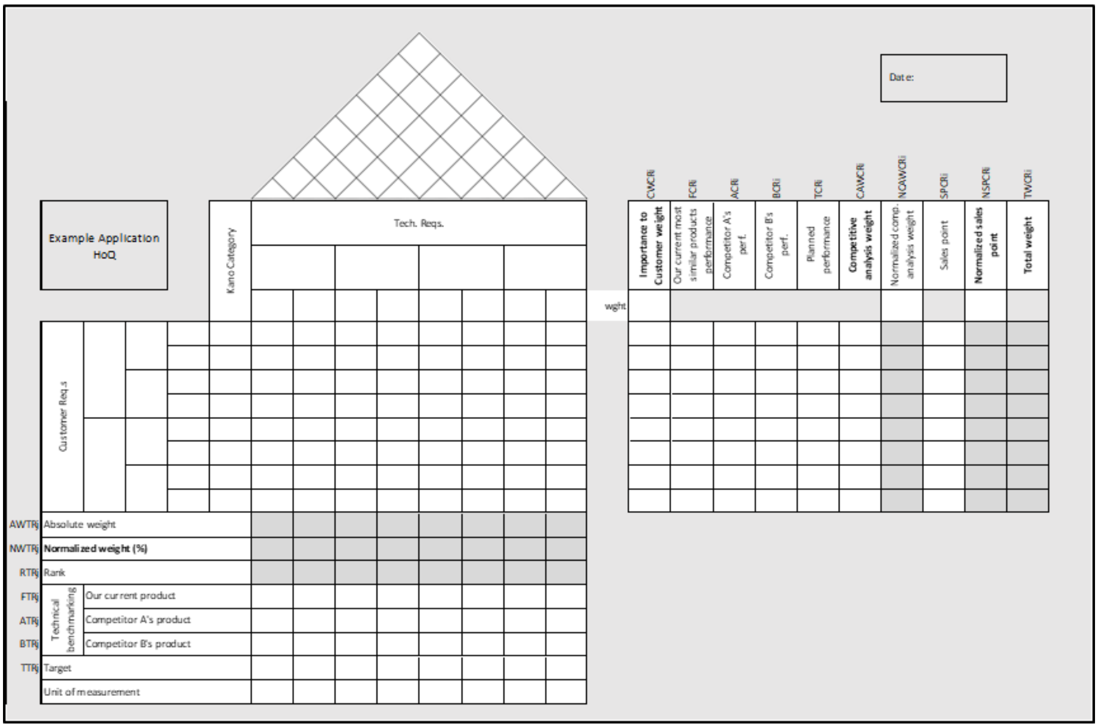


Figure 3.1. Initiation phase HoQ

3.2. Monitoring

After building the HoQ, quality feedback can be provided by integrating a modified RAPIDO method. Monitoring means collecting data, updating the indicators with respect to it and analyzing the situation by comparing it to the planned performances. Monitoring can be done continuously or in defined periods such as monthly, quarterly, or in project milestones that are defined in project schedule. In many projects, such as those in defense industry, project milestones that partition the project into phases are defined in the beginning of the project and reviews are done in these milestones. For convenience, monitoring quality can also be done in these milestones with actual data. Monitoring part of the proposed method is as follows.

1) For the "Significance Index" in RAPIDO model, normalized weight of TR_j ($NWTR_j$) is used. It provides a more objective evaluation, when compared with the 0-10 scale suggested by Kandt et al. [2], as $NWTR_j$ is connected to the weights of CRs and the relationship levels of each TR to each CR.
2) For the "Uncertainty of Requirements Fulfillment" in RAPIDO model, instead of using a 0-10 scale as suggested by Kandt et al. [2], actual fulfillment rates of TRs can be designated using desirability functions.

   Let the best guess value of TR_j be $AVTR_j$. Then, the actual fulfillment rate of TR_j ($AFRTR_j$) can be found by using desirability functions as follows:

   Let L_i, U_i and T_i be the lower, upper, and target values, respectively, that are desired for response $AVTR_i$. ($L_i \leq T_i \leq U_i$). For $w = 1$, the desirability function increases linearly towards T_i; for $w < 1$, the function is convex, and for $w > 1$, the function is concave, as shown in Figure 2.9 in Srction 2.4. For LTB and STB type of requirements, there is no target (T_i) value.

   Let $AFRTR_j$ is the actual fulfillment rate for TR_j.

   If a TR is 'larger-the-better' type, then the $AFRTR_j$ is found by:

$$\mathrm{AFRTR}_j = \mathrm{d}(\mathrm{AVTR}_j) = \begin{cases} 0 & \text{if } \mathrm{AVTR}_j < \mathrm{L}_j \\ \left(\frac{\mathrm{AVTR}_j - \mathrm{L}_j}{\mathrm{U}_j - \mathrm{L}_j}\right)^w & \text{if } \mathrm{L}_j < \mathrm{AVTR}_j < \mathrm{U}_j \\ 1 & \text{if } \mathrm{AVTR}_j > \mathrm{U}_j \end{cases} \quad (28)$$

   For instance, assume that one of TRs in the constructed HoQ is the maximum speed of the vehicle. This is a larger the better type of requirement; in other words, a faster vehicle is more desirable for the customer. However, for speed values above 100 km/hr, the customer is indifferent, meaning that the increase in the speed does not increase the satisfaction degree of the customer. And, the customer may not accept a maximum speed under 60 km/hr, which means that all actual values under 60 km/hr have zero degree of satisfaction on the customer side. Assume the change of desirability between 60 km/h and 100 km/h is linear (w=1). Then for an actual performance value of 80 km/hr for this TR, actual fulfillment rate (AFRTR) is found by:

$$\text{AFRTR} = \left(\frac{80-60}{100-60}\right)^1 = 0.5$$

Instead of using 0-10 scale as in original RAPIDO method or using a simple ratio such as 80/100 for fulfillment rate of a TR, using desirability functions represents better the real satisfaction degree of the customer.

This part can also be made as part of the initiation part of the proposed method, since it can be evaluated as part of the analysis of TRs.

As opposed to the RAPIDO's uncertainty (of requirements fulfillment) rating, this ratio is more like certainty rating since it increases as the actual value is closer to target value, while U_j in RAPIDO was a decreasing function of fulfillment rate of TR_j, as can be seen in Table 2.6 in Section 2.3. In cases where assigning a performance value is difficult or not preferred, a probability of achieving the target rate can be provided. Let P_j be the probability that $AVTR_j$ is better than or equal to TTR_j. P_j can be used interchangeably with $AFRTR_j$ whereas in the hypothetical case study provided in Chapter 4, $AFRTR_j$ is used.

The RAPIDO model maturity level assessment formulas will be modified considering these modifications as described in Step 4.

3) For the "Uncertainty of the Used Decision Data Basis" in RAPIDO model, a verification and validation (V&V) methods list similar to Kandt et al.'s proposal shown in Figure 2.8 in Section 2.3 is prepared, which should be specific to the sector, company or project. These methods can be expert opinion, analysis, simulation, test, and so on, depending on the company and

project. In a project, as the phases progress, methods used to verify/validate requirements change, typically in a positive way.

Instead of using the ordinal scale rates proposed by RAPIDO, ratio scale values can be found by using AHP method as described in Section 2.2. Assuming the best method provides 100% resemblance of the real situation (for example, it can be ‘test in a true environment’), a V_j value of 1 is assigned to this V&V method. Assuming the method that provides the least certainty has 50% resemblance of the real situation (for example, it can be ‘expert opinion’), a V_j value of 0.5 is assigned to this V&V method. The other methods are assigned V_j values in proportion to these two end-values by using the interpolation equation below.

Let,

L: minimum AHP score

M: maximum AHP score

X_j is the AHP score of TR_j

Then,

$$V_j = 0.5 + \left[\frac{0.5}{(M-L)} \times \left(X_j - L\right)\right] \tag{29}$$

This equation assures that the ratio of V_j values are proportional to the AHP values for each TR.

The type of the requirements (LTB, STB or NTB), upper and lower limits, linearity parameter value and the actual fulfillment rates for TRs and the V&V method used to decide about the fulfillment rates of TRs are added to the HoQ.

4) The original formula of Maturity Level in RAPIDO is:

$$ML_{real}[\%] = 100 - \sum_{i=1}^{n} \frac{A_i + U_i}{2} \times 10 \times \frac{B_i}{\sum_{i=1}^{n} B_i} \tag{30}$$

Instead of A_i (uncertainty of the used decision data basis) in the original RAPIDO formula, we now have V_j (certainty rate of the used method) that is found by AHP and linear interpolation.

Instead of U_i (uncertainty of fulfillment of requirement *i*) in the original RAPIDO formula, we now have $AFRTR_j$ (actual fulfillment rate of TR_j).

Instead of B_i (significance index for requirement *i*) in the original RAPIDO formula, we now have $NWTR_j$ (normalized weight of TR_j) that is found by Equation 20 in Section 2.2, utilizing QFD method.

Let ML' be the maturity level found by the modified RAPIDO model. ML' is a monotonically increasing function whereas ML in RAPIDO is a monotonically decreasing function. Hence, the subtraction operation is cancelled.

Modified Maturity Level (ML') Assessment formula would then be:

$$\mathrm{ML'}_{\mathrm{real}} = \sum_{j=1}^{m} \left(\mathrm{V}_j \times \mathrm{AFRTR}_j \times \mathrm{NWTR}_j \right) \tag{31}$$

$$0\% < \mathrm{ML'}_{\mathrm{real}} < 100\% \tag{32}$$

In the original RAPIDO, for a TR that is said to be not fulfilled at all with the best method in terms of certainty, taking the average of fulfillment rate and the method uncertainty increases the degree of ML. Let's say there are only two requirements; TR_1 and TR_2, with the same importance weights; $B_1 = B_2 = 5$.

A test in real conditions is made and found out that both TRs are not satisfied at all. TR_1 has a U_1 value 10 and A_1 value 0. The same way, TR_2 has a U_2 value 10 and A_2 value 0.

Then,

$$\mathrm{ML}_{\mathrm{real}} = 100 - \left[\left(\frac{0 + 10}{2} \times 10 \times \frac{5}{10} \right) + \left(\frac{0 + 10}{2} \times 10 \times \frac{5}{10} \right) \right] = 50$$

It means that maturity level halfway achieved. It is not intuitive to have a ML of 50, for $0 \leq \mathrm{ML} \leq 100$, when neither of the requirements are satisfied at all.

To calculate $\mathrm{ML'}_{\mathrm{real}}$, the parameters would then be $AFRTR_1 = AFRTR_1 = 0$, V1 = V2 = 1, NWTR1 = NWTR2 = 0.5. $\mathrm{ML'}_{\mathrm{real}}$ would be:

$$\mathrm{ML'}_{\mathrm{real}} = (1 \times 0 \times 0.5) + (1 \times 0 \times 0.5) = 0$$

It is a more intuitive result than $\mathrm{ML}_{\mathrm{real}}$ because TRs are not fulfilled at all.

ML'_{real} shows where we are in the technical requirements fulfillment as a percentage. This is the first proposed quality indicator. It is meaningful to compare this indicator with the potentially best ML' values for the specific phase of the project. As explained in Section 2.3, there are two indicators that show us possible two potential maturity levels. Their calculations are also adapted to the changes to the original performed as in Equation 30.

1. $ML'_{V,p}$: Potential maturity level when the planned V&V methods are executed. The planned V&V methods' rates should have been determined by the Project Management in the Project Plan.

$$\mathrm{ML'}_{\mathrm{V,p}} = \sum_{j=1}^{m} \left(\mathrm{V}_{\mathrm{p},j} \times \mathrm{AFRTR}_{j} \times \mathrm{NWTR}_{j} \right) \tag{33}$$

$$0\% < \mathrm{ML'}_{\mathrm{V,p}} < 100\% \tag{34}$$

2. $ML'_{AFRTR,p}$: Potential maturity level when the planned levels of fulfillment are achieved for all TR_j. The planned requirement fulfillment for the specific project milestone should have been determined by the Project Management in the Project Plan.

$$\mathrm{ML'}_{\mathrm{AFRTR,p}} = \sum_{j=1}^{m} \left(\mathrm{V}_{j} \times \mathrm{AFRTR}_{\mathrm{p},j} \times \mathrm{NWTR}_{j} \right) \tag{35}$$

$$0\% < \mathrm{ML'}_{\mathrm{AFRTR,p}} < 100\% \tag{36}$$

If $ML'_{real} < ML'_{V,p}$; it shows that the V&V methods that were planned for this phase of the project are not used while evaluating the requirement fulfillment rates. This may be due to a delay in schedule or any other reason. Project team has to investigate and make sure the reasons are identified and necessary actions such as crashing and fast-tracking [5] are taken.

If $ML'_{real} < ML'_{AFRTR,p}$; it shows that the planned fulfillment rates of TRs are not achieved yet. This may be due to technical struggles, resource shortages, wrong material selection, variation in processes, and so on. It is important that the project team understands the underlying reasons well and take appropriate corrective actions in compliance with the root causes.

Each of these two measures are needed in order to be able to see if the project is performing as expected in terms of execution of verification and validation activities as planned and in terms the fulfillment rates of requirements as planned, separately.

These additional information to the HoQ of the Initiation part makes up the first extension that we propose in the Monitoring Part of the proposed method.

5) Another quality indicator alternative is the customer satisfaction level which is the rate of fulfillment of the CRs. It can be calculated through the fulfillment rates of TRs and their relationships with CRs. In other words, it is a backward calculation. At the beginning of QFD, TRs are weighed by CRs; now, the CR performances are evaluated by TR performances.

Let satisfaction level of any CR_i be CS_i. CS_i is calculated as:

$$\mathrm{CS}_i = \frac{\sum_{j=1}^{m}(\mathrm{r}_{ij} \times \mathrm{V}_j \times \mathrm{AFRTR}_j)}{\sum_{j=1}^{m} \mathrm{r}_{ij}} \tag{37}$$

$$0\% < \mathrm{CS}_i < 100\% \tag{38}$$

Total rate of customer satisfaction (TCS) is calculated as:

$$\mathrm{TCS} = \sum_{i=1}^{n} \mathrm{CS}_i \times \mathrm{TWCR}_i \tag{39}$$

$$0\% < \mathrm{TCS} < 100\% \tag{40}$$

$$\mathrm{TCS}_{\mathrm{V,p}} = \sum_{i=1}^{n}\left(\frac{\sum_{j=1}^{m}(\mathrm{r}_{ij} \times \mathrm{V}_{\mathrm{p},j} \times \mathrm{AFRTR}_j)}{\sum_{j=1}^{m} \mathrm{r}_{ij}} \times \mathrm{TWCR}_i\right) \tag{41}$$

$$\mathrm{TCS}_{\mathrm{AFRTR,p}} = \sum_{i=1}^{n}\left(\frac{\sum_{j=1}^{m}(\mathrm{r}_{ij} \times \mathrm{V}_j \times \mathrm{AFRTR}_{\mathrm{p},j})}{\sum_{j=1}^{m} \mathrm{r}_{ij}} \times \mathrm{TWCR}_i\right) \tag{42}$$

Similar to ML' value that was compared to potential ML' values, TCS value can also be compared to potential TCS for that phase of the project.

If $TCS_{real} < TCS_{V,p}$; it shows the effect of not being able to apply the V&V methods that were planned for this phase of the project on customer satisfaction rate. This may be due to a delay in schedule, lack of capability to apply the method, and so on. Project team has to investigate and make sure the reasons are identified and necessary actions are taken such as revising the plan, crashing the project activities, etc.

If $TCS_{real} < TCS_{AFRTR,p}$; it shows the effect of not achieving the planned fulfillment rates of TRs on CRs. This may be due to technical struggles, resource shortages, etc. It is important that the project team understands the underlying reasons well and take appropriate corrective actions in compliance with the root causes.

Choosing which indicator to use - ML' or TCS - depends on the preference of the project manager. Whichever convenient can be selected. It should be noted that choosing TCS might be of help when fulfillment rates of a specific group of CRs with the same Kano categories are investigated separately. For example, if the fulfillment rate for the set of must-be CRs is important or preferred to be watched separately, it is more convenient to go with TCS indicator as the quality indicator of the project, since the Kano categorization is made for CRs, not TRs.

Now that we have indicators for the quality performance of the project, we know the strong and weak points in our project in terms of quality. In addition to this information, we can also have information about cost and schedule. That would support us while making decisions about the project. Choosing ML' as quality indicator might be of help when schedule and cost is also monitored together with quality, as described in Steps 6 - 9.

This part is the second extension that we propose.

6) The third extension in the Monitoring phase is the Project Management part. This part is designed for Project managers to support them with their decisions throughout the project. Write once more the $NWTR_j$ and $AFRTR_j$ values.

7) Identify the cost scale (C_j) for each TR_j, the money needed to reach to target from the actual status. To facilitate, a scale can be developed or by using AHP, related rates can be assigned.

   Table 3.1 shows an example scale for money need to reach TTR_j. Here, the mid-points of the intervals are used and linear interpolation is applied to normalize the values.

Table 3.1. *Example scale for money need*

Money need	**Value**
> 100k	0.721
< 100k	0.180
< 50k	0.072
< 10k	0.018
< 5k	0.007
< 1k	0.001

One example to the use of AHP is shown on Table 3.2. The question asked is "How much is the situation in the row more important than the situation in the column?" According to this table, if the money needed is known or predictable, it can be an evaluation criterion. A similar table can be built for person day needed if it is predictable, such as in Table 3.3. If money needed or person day needed is neither known nor predictable, technical difficulty criterion can be used such as in Table 3.4.

Table 3.2. *Cost scale example AHP table*

Money need (ex. labor) ($)	> 100k	< 100k	< 50k	< 10k	<5k	<1k	AHP rates
> 100k	1	3	5	7	7	8	0.440
< 100k	1/3	1	3	5	6	7	0.247
< 50k	1/5	1/3	1	3	4	7	0.143
< 10k	1/7	1/5	1/3	1	3	5	0.084
< 5k	1/7	1/6	1/4	1/3	1	5	0.059
< 1k	1/8	1/7	1/5	1/5	1/5	1	0.028

Table 3.3. *Person day criteria example*

Person day need	<1 pday	< 5 pday	< 10 pday	< 50 pday	< 100 pday	< 200 pday

Table 3.4. *Technical difficulty criteria example*

Technical diff.	-we did before, we have data	-we did before, but no data	-we never did but know how to	-we can learn easily	-we can learn with a lot of effort	-we cannot do

8) Identify the schedule scale (S_j) for each TR_j reaching the target. To do that, project schedule can be used. Work packages in the project schedule should have a link to at least one TR. As an approach, when a specific TR is filtered among all work packages, the maximum of the latest finish time of the related work packages can be taken as the remaining time to satisfy the TR; 'latest finish time' – 'today' can give the remaining time left. Similar to cost values, schedule can also be evaluated by designing a scale or by using AHP.

For the scale option, intervals for 'time left' are identified and the mid-points of the intervals are used to assign values by linear interpolation, as in Table 3.5. The values in the table are presented as today + how many weeks/months/years left to satisfy TR.

Table 3.5. *Example scale for time left*

Time left	Value
Passed	0.571
< 1w	0.245
< 1m	0.122
< 6m	0.048
< 1y	0.012
< 2y	0.001
> 2y	0.000

To evaluate using AHP, a table similar to Table 3.6 can be used. The question asked is: "How much is the time left in row more pressing than the situation in column?"

Table 3.6. *Schedule scale example AHP table*

Schedule status	Passed	< 1w	< 1m	< 6m	< 1y	< 2y	> 2y	AHP rates
Passed	1	3	5	7	7	8	9	0.398
< 1w	1/3	1	3	5	6	7	8	0.234
< 1m	1/5	1/3	1	3	4	7	8	0.147
< 6m	1/7	1/5	1/3	1	3	5	6	0.090
< 1y	1/7	1/6	1/4	1/3	1	5	7	0.073
< 2y	1/8	1/7	1/5	1/5	1/5	1	4	0.036
> 2y	1/9	1/6	1/7	1/4	1/7	1/4	1	0.022

9) Observe the technical requirements and choose the ones which are most important and need the urgent attention of the project team. Those that are important in terms of satisfying CRs ($NWTR_j$), with low actual fulfillment rates ($AFRTR_j$), require higher cost, have less time left need attention of the project management. They can be red colored to draw attention.

It is expected that project managers or the team members plan actions, looking at the results of the monitoring phase. For example, if a TR is far from its target and little time is left in the schedule, increasing resources or hiring subject-matter experts can be planned. Or, when the target of a TR is almost achieved and there is plenty of time left, allocated resources for that TR can be used in another area. These outputs help decision making for the project management and also the top management of the company.

The decisions can change from project to project or according to the different roles of the people responsible for decision making. For example, for a project manager, the riskiest items, i.e. the big problems with little time can be a consideration; for another group of experts, high costs associated with TRs may be the area of attack in order to make cost savings. Every member of the team can see the situation according to their roles and responsibilities. A procedure or guideline to support decision making for the stakeholders can be prepared within the company.

A sample decision flow-chart is provided in Figure 3.2. According to this chart, iterations continue until decisions are given for all TRs. The iterations start with the TR that has the highest weight. Any chart prepared in the company or specific to the project would be somehow generic and the decisions would have to be customized for each TR. For example, for a TR that has high importance weight, if there is little time left and to reach the target is costly, every opportunity to reach the target would be exploited whereas for a TR with low importance weight, a decision in such a condition would be to cancel fulfillment of that TR by negotiating with the customer.

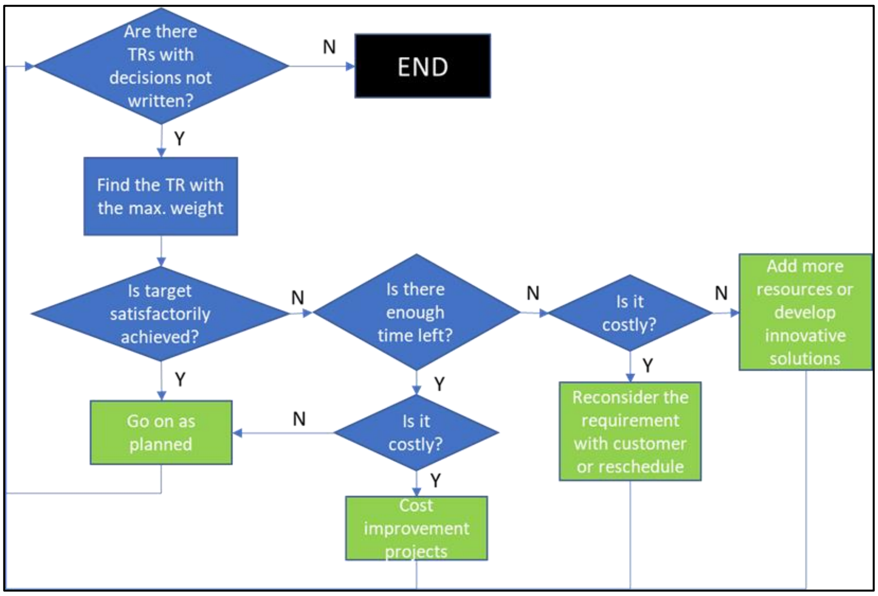


Figure 3.2. Sample decision flowchart

This sample flowchart in Figure 3.2 is designed as independent evaluations for each TR. However, for TRs that are correlated, the decisions made for one TR might affect the TRs that it is correlated with. To avoid such a case, the correlated TRs can be evaluated together as a bundle. Evaluating the current situation of both, the best decision can be given that would maximize the improvement of one TR while minimizing the potential adverse effects on the other TRs.

Monitoring is made by the project team. At any time, *t*, the model will be reflecting the actual status, as long as all the data are up-to-date. It is important to collect data in a disciplined way from the team members or other technical specialists and decide with the up-to-date data. Ensuring healthy information flow throughout the project lifecycle is a challenge for the project managers who want to monitor quality.

The HoQ with modified RAPIDO and project management extensions looks like the chart shown in Figure 3.3. The parts that are added in the monitoring part of the proposed method is shown in Figure 3.4.

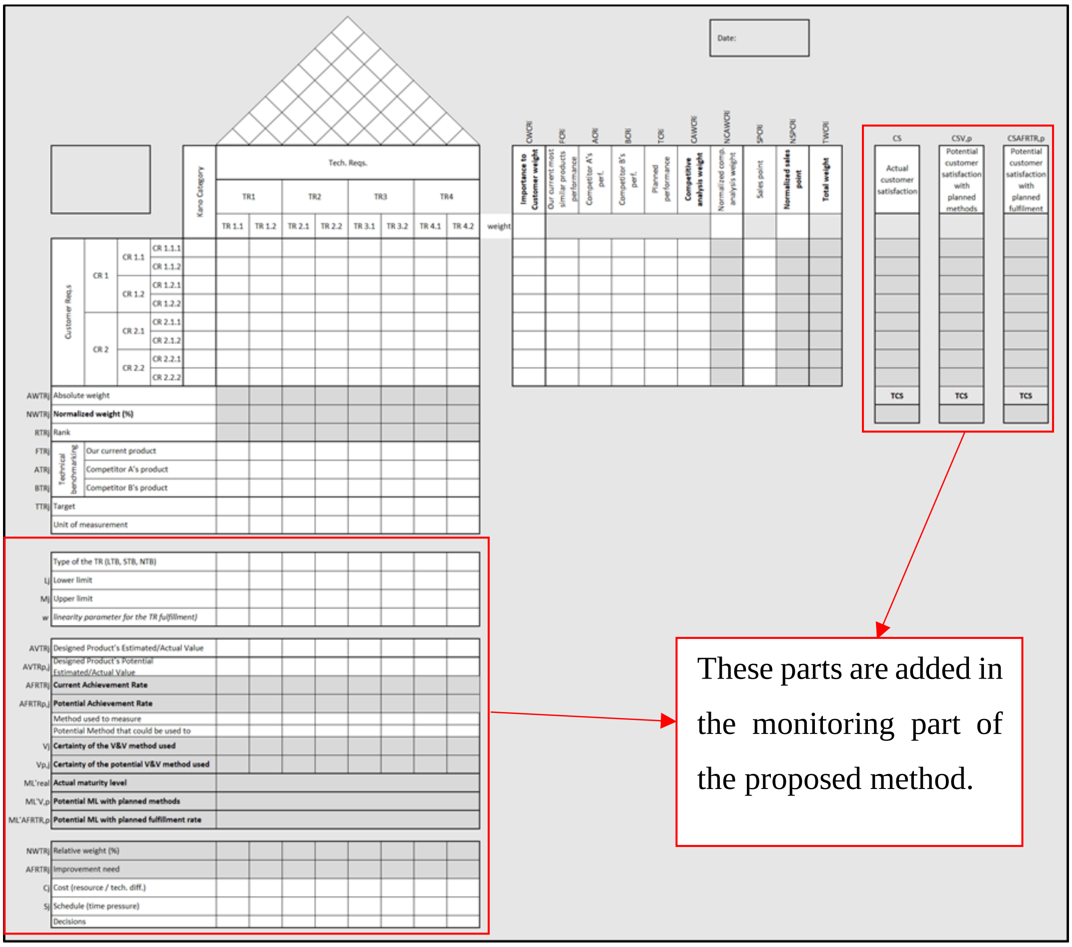


Figure 3.3. A general view of the example HoQ at the monitoring part of the proposed method

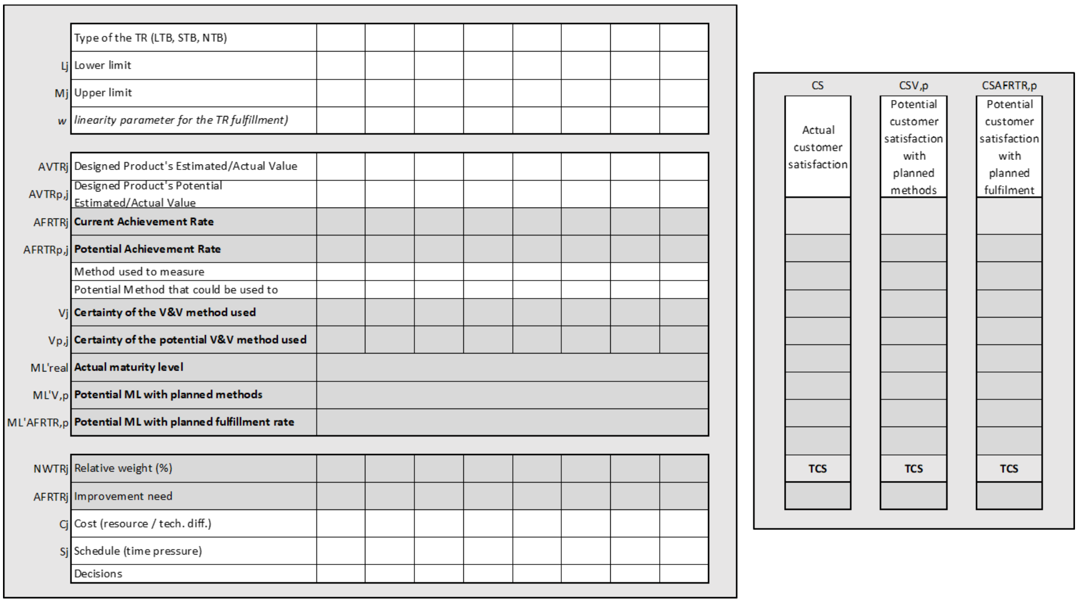


Figure 3.4. Monitoring sections added to the HoQ

Figure 3.5 shows the proposed method in a diagram.

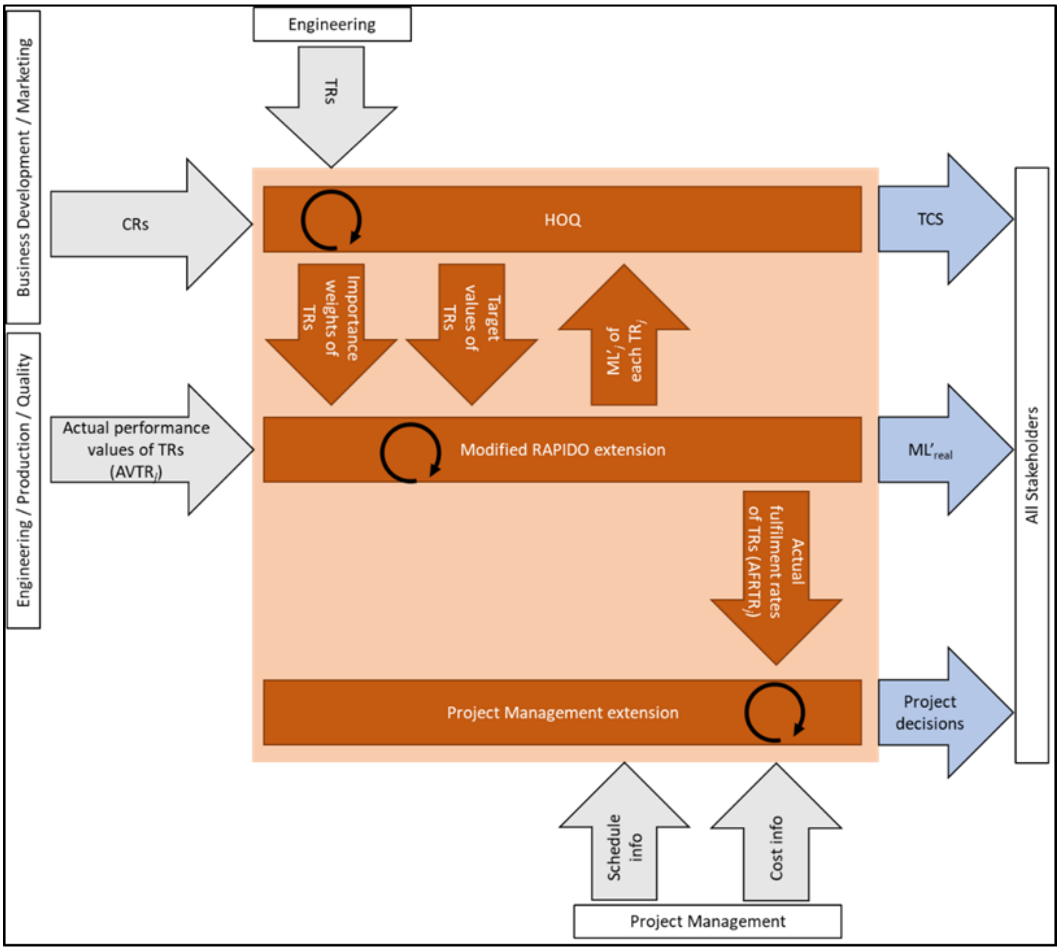


Figure 3.5. The diagram of the proposed method

The center of the diagram represents the proposed model including the construction of the HoQ and then adding the extensions proposed; maturity calculations and project management. CRs come from the customer with the help of business development departments and TRs from the engineering departments, to the HoQ. HoQ outputs the importance weights and target values of TRs to the maturity calculation part. Also, actual performance values of TRs come to this part from the operational departments such as engineering, production and quality. Then maturity levels (ML' and TCS values) are output to all stakeholders. Project management extension takes actual fulfillment rates of TRs from the maturity calculation part and combines it with schedule and cost info that come from the project management team. Then the project decisions are taken with respect to these data, informing all stakeholders.

CHAPTER 4

A HYPOTHETICAL CASE STUDY

In defense industry, it is generally a procurement authority that supplies products for the armies. Department of Defense (DoD) in USA and Presidency of Defence Industries (*Savunma Sanayi Başkanlığı* - SSB) in Turkey are examples to such authorities. SSB is an intermediary institution both fulfilling the actual needs of the army, assuring quality and also forecasting the future needs and guiding the defense industry in terms of new products and services. Hence, for a defense industry company operating in Turkey, it is essential to ensure the quality of the current products and also to support development of innovative products to be ready to supply the future needs of the army.

Since there are competitors both local and abroad, a firm must excel in product development processes to do right product the right way. In that sense, we believe that this study will be useful for such organizations who wants to improve the product development process and would like to monitor it with an objective quality indicator.

The proposed method is implemented in a hypothetical defense industry project, in order to see the pros and cons of the proposed method and improve it. In this chapter, the details of the implementation are presented in a simplified form in order to ensure compliance to the information security rules of the company.

4.1. Background Information of the Pilot Company

The proposed method is applied in a private defense industry company in Turkey. The company has a multi-project environment with a product portfolio of both tracked and wheeled armored vehicles. The users of these vehicles are the armies of various countries.

This company is specialized in land vehicles and turrets. The hypothetical project that is conducted in this study is based on the development of a wheeled armored personnel carrier vehicle. The hypothetical project is assumed to have just started and has a five years project plan until building the prototype. This duration includes the customer specific design of the product, supply of materials and subsystems, prototype production and tests.

The projects' main workload is on design phase since the product has a complex nature and customer demands are challenging since the customers of this industry have to obtain the highest technology equipment in order to stay strong against any threats. Armored vehicles also have a very important mission like assuring the safety of the personnel under very harsh conditions. In addition to this very important mission, there are various expectations like mobility, maintainability, etc. which also provides competitive advantage to the armies in the field.

The projects are managed on the basis of PMI's [5] project management guidance. All project managers have PMP certification. The project management processes and design processes of the company are investigated. It is evaluated that the company's current practices are satisfying the assumptions stated in the beginning of Chapter 3.

For the projects being executed in the company, the requirements mainly come from the contract and each requirement written in the contract is broken down into details and managed altogether using DOORS software. The customer requirements are connected to technical requirements, without indicating the strength of that relationship. Systems Requirement Verification Document (SRVD) is a standard document used in the company to define which requirements relate to which subsystems, how those requirements are verified and validated and in which phase.

4.2. Problem Definition

The product or project managers have difficulties in following the quality aspect of the project in a compact manner. In project tollgates of development phases, where one sub-phase is closed and the next is started by the approval of the top management, quality aspect of the project is reported by closed work packages and completed subsystem qualifications at most. From the point of PMI project management view, this relates to scope management rather than quality management. Quality is started to be evaluated after a physical prototype is made.

Technical leader, who is a senior engineer, is responsible from the completion of the product scope in terms of the technical requirements. However, the current method used in the company is measuring this completion following the development phase, not continuously, and not starting in the very beginning of development. In addition, there is no defined method for the prioritization of the requirements, i.e. all requirements have the same priority. These may result in loss of time and money if defects are realized late in the product lifecycle or low priority requirements steal the time and effort to be spent on high priority requirements, when there are shortages for resources.

4.3. The Project

The complete details of the hypothetical project are not shared in this thesis work because of its similarity with the company's existing projects and their confidentiality. However, the application phase is described so as to share our experience with those who would like to apply this method.

4.3.1. Initiation

1) A QFD team of 8 engineers was formed and it was led by a senior systems engineer. The team included a senior systems engineer, a business excellence engineer, a configuration management engineer, a mechanical design engineer, an electronics design engineer, a quality engineer, a manufacturing engineer and an Integrated Logistics Support (ILS) engineer. The methods to be used in scope of this work is presented to the team. It is assumed that the project's kick-off was just made.

2) As a second step, customers are defined. The customers that are most critical for the business should be selected as target customers. The major customers of the hypothetical project is SSB and Turkish Army and they are both important for the success of the business of the firm. Hence, the customers of the hypothetical project are assumed to be SSB and Turkish Army.

3) A successful QFD relies on a successful Voice of Customer (VoC) study. It was assessed at the beginning that the requirements that are written in the existing contracts are not enough and additional requirements should be fed to this list by investigating the customer complaints, customer satisfaction surveys, interviews with the customer, going to gemba and observing, and expert views from the field.

   First, the contract of a project that is similar to the hypothetical project is investigated. Then, requirements that take place in that project's contract and also their breakdown to the systems and subsystems by the systems engineering department using DOORS software is investigated.

   Customer satisfaction surveys that were held with customers of similar vehicle projects are investigated. Customer complaints that were received for the previous similar projects are evaluated. Likewise, the internal nonconformity reports, verification and validation results, engineering change reasons of the previous similar projects are analyzed. Interviews with consultants who are retired military personnel that had experience with the company's products are interviewed. A short list of customer requirements is constituted. Since this case was meant to test the proposed method, the full list of requirements is not used.

   The customer requirements are grouped with an affinity diagram as in Figure 2.5 in Section 2.2. It is assured that the requirements are understood the same way by the QFD team members. The requirements are evaluated with respect to Kano Model as explained in Section 2.2. It should be assured that there is a balanced set of requirements in terms of Kano categories. In other words, if no requirement is classified as an ‘Excitement’ factor, then a few additional requirements for this class should be created by using VoC techniques. Using Kano-model, the requirements are classified as ‘Basic, ‘Performance’ and ‘Excitement’. It was found that the requirement set did not include ‘Excitement’ type of requirements. A second tour of interviews are made with the consultants and ‘Excitement’ requirements are added to the customer requirement list. This way, the requirements are somehow balanced in terms of Kano model. Overall, the vehicle level requirements are identified and listed in a three-level hierarchy in tree structure as described in Section 2.2, Figure 2.7.

For our hypothetical case, the customer requirements are defined as shown in Figure 4.1 with their Kano categories.

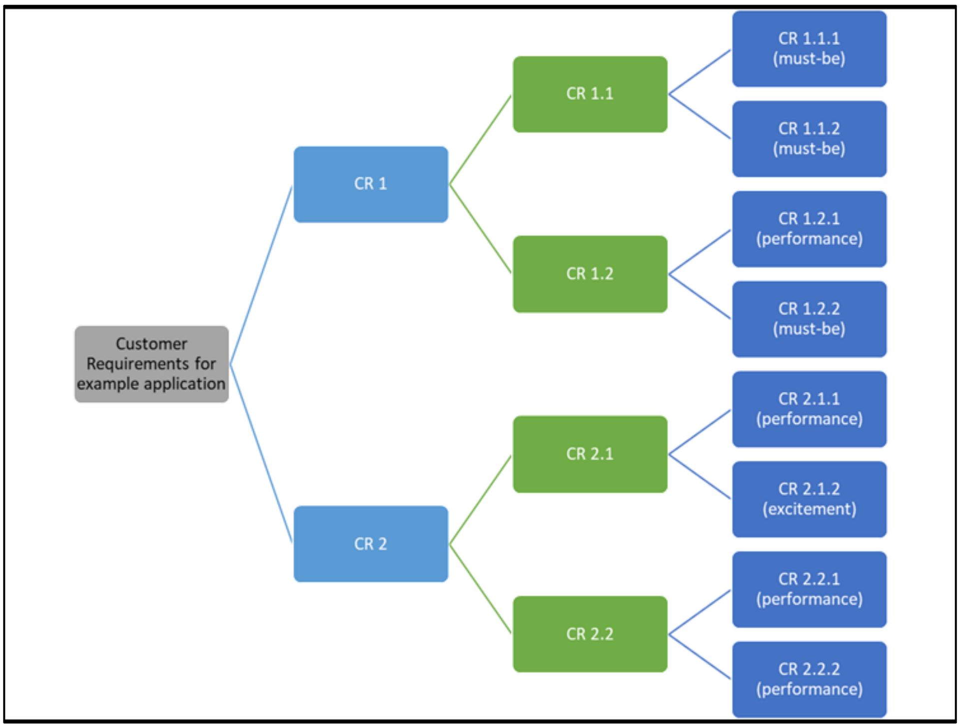


Figure 4.1. Tree structure of TRs in hypothetical case

4) Customer requirements are weighed according to their importance to the customer. For this purpose, AHP [46] is used as described in Section 2.2; Table 2.2 and Table 2.3, Equation 1 and Equation 2. Table 4.1 shows the AHP table for the importance to customer values of CRs of the hypothetical case. The question asked is: “How much the CR in the row is more important than the CR in the column?” Consistency check for all AHP applications in this study are made.

Table 4.1. *AHP for CRs' 'importance to customer' weights*

CRs	1.1.1	1.1.2	1.2.1	1.2.2	2.1.1	2.1.2	2.2.1	2.2.2	AHP rates
1.1.1	1	1	1/5	1/7	5	5	3	1/3	0.082
1.1.2	1	1	1/3	1/5	7	7	5	1	0.119
1.2.1	5	3	1	1	7	9	5	3	0.257
1.2.2	7	5	1	1	9	9	7	5	0.332
2.1.1	1/5	1/7	1/7	1/9	1	3	1	1/5	0.032
2.1.2	1/5	1/7	1/9	1/9	1/3	1	1/3	1/5	0.020
2.2.1	1/3	1/5	1/5	1/7	1	3	1	1/5	0.038
2.2.2.	3	1	1/3	1/5	5	5	5	1	0.120
sums	17.733	11.486	3.321	2.908	35.333	42.000	27.333	10.933	1.000

The CRs with Kano categories and customer importance weights are placed into HoQ as in Figure 4.2.

Figure 4.2. Hypothetical case HoQ - 1

5) A competitive analysis is conducted for the customer requirements by investigating the company's and competitors' similar products or services as explained in Section 2.2. QFD team evaluated the last similar project vehicle and two competitors' similar vehicles for the competitive analysis part of QFD. Target achievement rates are assigned. Competitive analysis weights are assigned as shown in Equation 10 and Equation 11.

The competitive analysis part of the HoQ for the hypothetical case is shown in Figure 4.3.

Example Application HoQ				Kano Category	wght	Importance to Customer weight (CWCRi)	Our current most similar products performance (FCRi)	Competitor A's perf. (ACRi)	Competitor B's perf. (BCRi)	Planned performance (TCRi)	Competitive analysis weight (CAWCRi)	Normalized comp. analysis weight (NCAWCRi)
Customer Req.s	CR 1	CR 1.1	CR 1.1.1	M		0.082	3	4	2	5	0.558	0.206
Customer Req.s	CR 1	CR 1.1	CR 1.1.2	M		0.119	3	4	3	4	0.263	0.097
Customer Req.s	CR 1	CR 1.2	CR 1.2.1	P		0.257	3	4	4	4	0.263	0.097
Customer Req.s	CR 1	CR 1.2	CR 1.2.2	M		0.332	3	4	2	3	0.122	0.045
Customer Req.s	CR 2	CR 2.1	CR 2.1.1	P		0.032	3	4	3	3	0.122	0.045
Customer Req.s	CR 2	CR 2.1	CR 2.1.2	E		0.020	3	4	4	4	0.263	0.097
Customer Req.s	CR 2	CR 2.2	CR 2.2.1	P		0.038	3	4	2	5	0.558	0.206
Customer Req.s	CR 2	CR 2.2	CR 2.2.2	P		0.120	3	4	3	5	0.558	0.206

Figure 4.3. Hypothetical case HoQ - 2

6) Since marketing is an important need, sales point weighing is also made, as shown in Equation 12 and Equation 13. For this part, support from marketing unit is requested. The sales points are assigned through the gathered market information in the previous steps and their own tacit knowledge.
7) Total weight for each customer requirement is calculated regarding all the information: Importance to customer, competitive analysis results and sales point weights. The QFD team can decide which input – customer importance weights, improvement needs for competition or sales points – has more importance over the others and assign contributors' weights, considering Equation 14 in Section 2.2. Giving customer importance grading a weight of 0.50 and competitive analysis and sales point parts 0.25 each, a weighted sum is found for weights of each customer requirement of the hypothetical case as described in Section 2.2, Equation 15.

The sales point part and the total weight calculations of CRs part of the HoQ for the hypothetical case is shown in Figure 4.4.

Example Application HoQ				Kano Category		CWCRi Importance to Customer weight	FCRi Our current most similar products performance	ACRi Competitor A's perf.	BCRi Competitor B's perf.	TCRi Planned performance	CAWCRi Competitive analysis weight	NCAWCRi Normalized comp. analysis weight	SPCRi Sales point	NSPCRi Normalized sales point	TWCRi Total weight
					wght	0.5						0.25		0.25	
Customer Req.s	CR 1	CR 1.1	CR 1.1.1	M		0.082	3	4	2	5	0.558	0.206	0.633	0.251	0.155
			CR 1.1.2	M		0.119	3	4	3	4	0.263	0.097	0.260	0.103	0.110
		CR 1.2	CR 1.2.1	P		0.257	3	4	4	4	0.263	0.097	0.260	0.103	0.179
			CR 1.2.2	M		0.332	3	4	2	3	0.122	0.045	0.633	0.251	0.240
	CR 2	CR 2.1	CR 2.1.1	P		0.032	3	4	3	3	0.122	0.045	0.106	0.042	0.038
			CR 2.1.2	E		0.020	3	4	4	4	0.263	0.097	0.260	0.103	0.060
		CR 2.2	CR 2.2.1	P		0.038	3	4	2	5	0.558	0.206	0.106	0.042	0.081
			CR 2.2.2	P		0.120	3	4	3	5	0.558	0.206	0.260	0.103	0.137

Figure 4.4. Hypothetical case HoQ - 3

8) The correlation matrix is filled by the QFD team. Negative correlations are noted and taken as action items for further studies.

9) The next step is to derive product technical characteristics. They already existed in mixture with customer requirements in the similar projects' contracts and derived requirements. A list of technical requirements (product characteristics, engineering requirements) is identified for the product and shown in a tree-structure in Figure 4.5.

   Correlation values are assigned as described in Section 2.2, Equation 17. Figure 4.6 shows the HoQ with TRs and their correlation values for the product. Starting an engineering study is noted since there are two negative correlations.

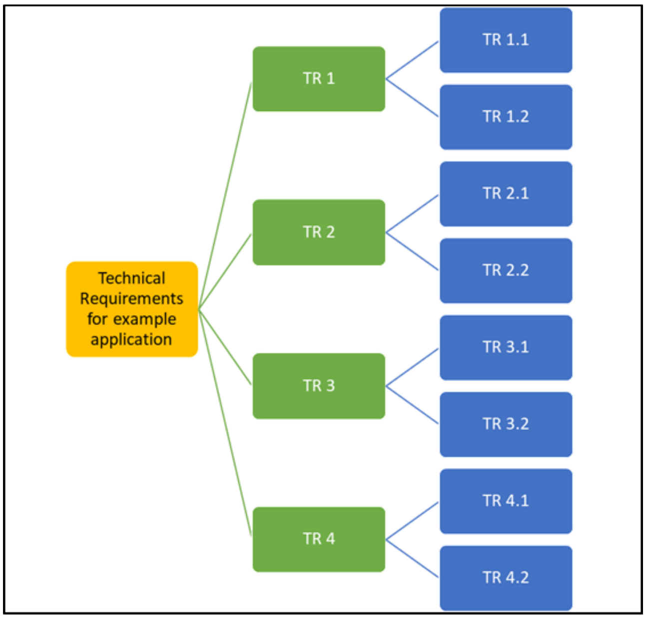


Figure 4.5. Tree-structure for TRs of the hypothetical case

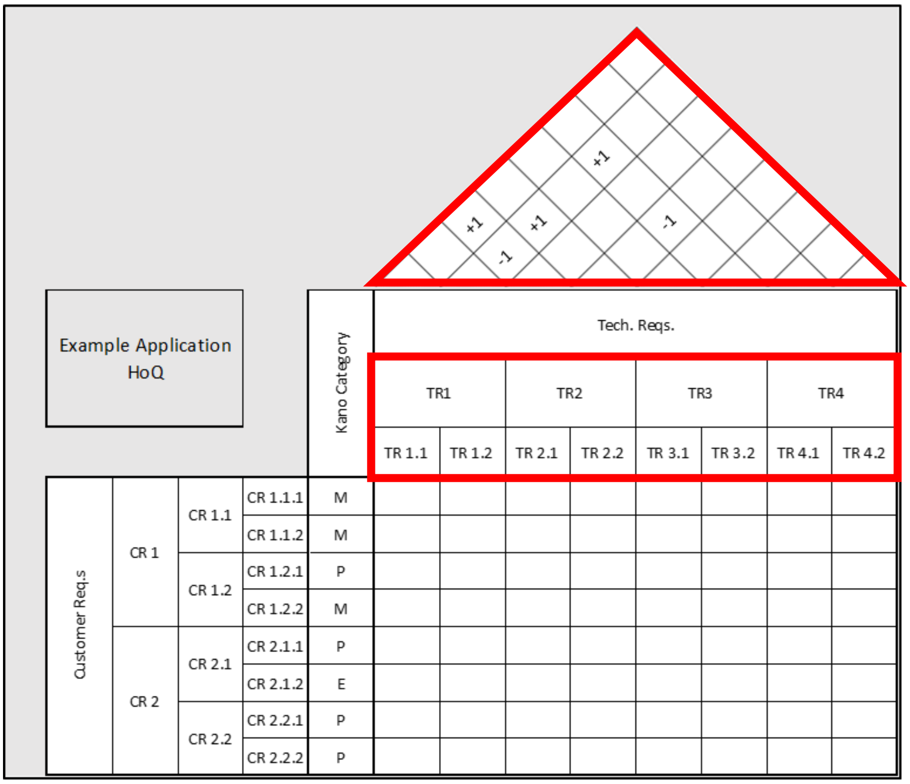
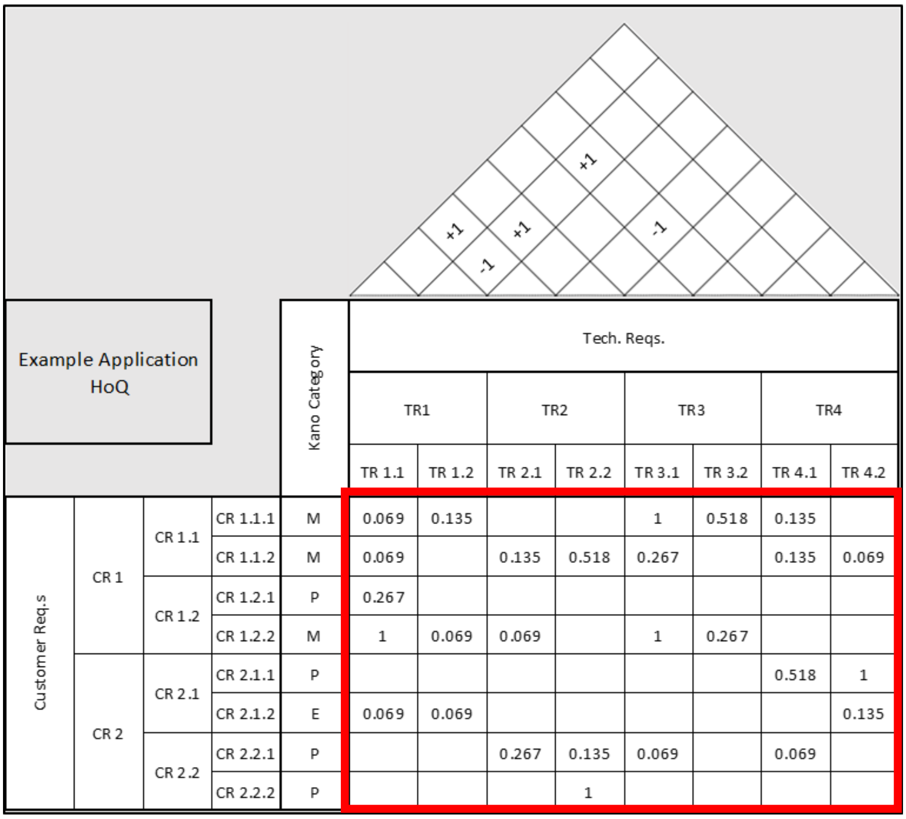


Figure 4.6. Hypothetical case HoQ - 4

10) The relationship of customer requirements with technical requirements is studied. For each CR and TR intersection, a relationship value is assigned in the relationship matrix part of HoQ. Table 2.4 or Table 2.5 in Section 2.2 can be used for the relationship values.

The relationship matrix is filled by the QFD team. The priority values of the technical requirements are calculated by the weighted sum of the customer requirement weights and relationship values. Similarly, with the customer requirements, competitive analysis is made for the technical requirements as well. The same two vehicles that were used with customer requirements section are used in this comparison. Then the QFD team set the targets in compliance with the contract and the voice of the customer studies beforehand.

The HoQ with relationship values between CRs and TRs are shown in Figure 4.7.



			Kano	TR 1.1	TR 1.2	TR 2.1	TR 2.2	TR 3.1	TR 3.2	TR 4.1	TR 4.2
CR 1	CR 1.1	CR 1.1.1	M	0.069	0.135			1	0.518	0.135	
		CR 1.1.2	M	0.069		0.135	0.518	0.267		0.135	0.069
	CR 1.2	CR 1.2.1	P	0.267							
		CR 1.2.2	M	1	0.069	0.069		1	0.267		
CR 2	CR 2.1	CR 2.1.1	P							0.518	1
		CR 2.1.2	E	0.069	0.069						0.135
	CR 2.2	CR 2.2.1	P			0.267	0.135	0.069		0.069	
		CR 2.2.2	P				1				

Figure 4.7. Hypothetical case HoQ - 5

11) For each technical requirement TR_j, the weighted sum of the relationship values (the weights are the total weights of the customer requirements, $TWCR_i$) are found. These sums ($AWTR_j$) represent the importance weights of each TR with respect to their contribution to CRs. These weights are normalized and $NWTR_j$ values are found. The calculations are as explained in Section 2.2, Equations 19 and 20. TRs are ranked from largest to smallest, assigning (RTR_j) values.

Figure 4.8 shows the HoQ for the hypothetical case, with $AWTR_j$, $NWTR_j$ and RTR_j values. Conditional formatting in Microsoft Excel is applied for the 'normalized weight'.

Example Application HoQ				Kano Category	Tech. Reqs.							
					TR1		TR2		TR3		TR4	
					TR 1.1	TR 1.2	TR 2.1	TR 2.2	TR 3.1	TR 3.2	TR 4.1	TR 4.2
Customer Req.s	CR 1	CR 1.1	CR 1.1.1	M	0.069	0.135			1	0.518	0.135	
			CR 1.1.2	M	0.069		0.135	0.518	0.267		0.135	0.069
		CR 1.2	CR 1.2.1	P	0.267							
			CR 1.2.2	M	1	0.069	0.069		1	0.267		
	CR 2	CR 2.1	CR 2.1.1	P							0.518	1
			CR 2.1.2	E	0.069	0.069						0.135
		CR 2.2	CR 2.2.1	P			0.267	0.135	0.069		0.069	
			CR 2.2.2	P				1				
AWTRj	Absolute weight				0.310	0.042	0.053	0.205	0.430	0.145	0.061	0.054
NWTRj	**Normalized weight (%)**				24%	3%	4%	16%	33%	11%	5%	4%
RTRj	Rank				2	8	7	3	1	4	5	6

Figure 4.8. Hypothetical case HoQ - 6

12) A competitive analysis is conducted for the TRs by investigating the competitors' similar products or services, similar to the competitive analysis with the CRs.

13) Targets are set for the TRs, namely TTR_j. The importance weights and competitive analysis results are considered all together while assigning the target values to the TRs. The units of measurement for each TR_j are identified.
14) TRs are classified in terms of their types; as larger-the-better, smaller-the-better or nominal-the-best (NTB). For the LTB type TRs, the target is written also as the upper-limit value (M_j), while for STB type TRs, the target is written as the lower-limit value (L_j). For those TRs that are of type NTB, upper and lower limit values would be identified, however, there was no TR of type NTB. The linearity parameter, *w*, is identified for each TR.

Figure 4.9 shows the competitive analysis part, target values of TRs and desirability function parameters part for the hypothetical case.

	Example Application HoQ		Kano Category	Tech. Reqs.								
				TR1		TR2		TR3		TR4		
				TR 1.1	TR 1.2	TR 2.1	TR 2.2	TR 3.1	TR 3.2	TR 4.1	TR 4.2	weig
	Customer Req.s / CR 1	CR 1.1 / CR 1.1.1	M	0.069	0.135			1	0.518	0.135		
		CR 1.1.2	M	0.069		0.135	0.518	0.267		0.135	0.069	
		CR 1.2 / CR 1.2.1	P	0.267								
		CR 1.2.2	M	1	0.069	0.069		1	0.267			
	CR 2	CR 2.1 / CR 2.1.1	P							0.518	1	
		CR 2.1.2	E	0.069	0.069						0.135	
		CR 2.2 / CR 2.2.1	P			0.267	0.135	0.069		0.069		
		CR 2.2.2	P				1					
AWTRj	Absolute weight			0.310	0.042	0.053	0.205	0.430	0.145	0.061	0.054	
NWTRj	**Normalized weight (%)**			0.239	0.032	0.041	0.158	0.331	0.111	0.047	0.041	
RTRj	Rank			2	8	7	3	1	4	5	6	
FTRj	Technical benchmarking	Our current product		80	12	0.8	4	1.5	5	60	95	
ATRj		Competitor A's product		100	15	0.8	4	1.7	4	62	95	
BTRj		Competitor B's product		60	10	0.9	4	1.8	4	65	99	
TTRj	Target			100	10	0.9	5	1.5	5	65	99	
	Unit of measurement			km/h	sn	%	level	m	level	°	%	
	Type of the TR (LTB, STB, NTB)			LTB	STB	LTB	LTB	STB	LTB	LTB	LTB	
Lj	Lower limit			80	10	0.8	4	1.5	4	60	95	
Mj	Upper limit			100	12	0.9	5	1.7	5	65	99	
w	*linearity parameter for the TR fulfillment)*			1	1	1	1	1	1	1	1	

Figure 4.9. Hypothetical case HoQ - 7

By the completion of the ‘Initiation’ part, the HoQ of the hypothetical case looks like as in Figure 4.10.

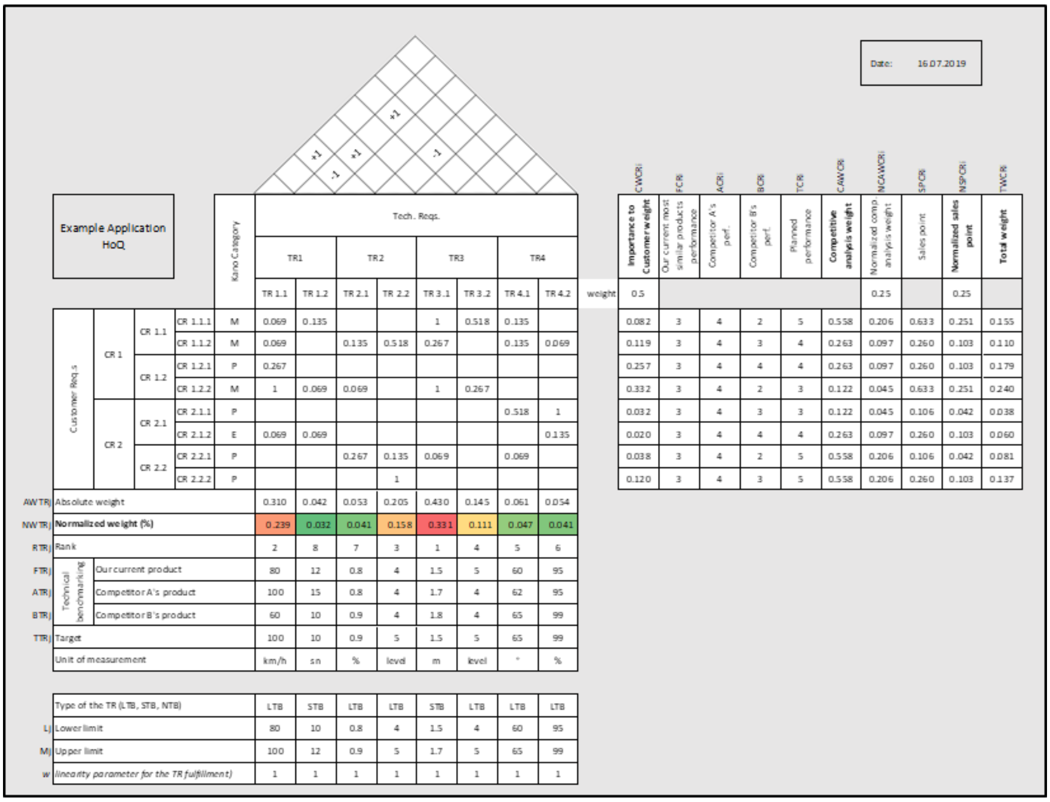


Figure 4.10. HoQ of the hypothetical case at the end of the initiation part of the proposed method

4.3.2. Monitoring

15) The current and planned fulfillment rates of the technical requirements ($AFRTR_j$) are calculated using the desirability function parameters defined in the previous step. V_j values (certainty rate of the related method used to verify/validate TR_j) based on the V&V methods used for deciding on the fulfillment rate of CRs in the hypothetical case are assigned as in Table 4.2, using AHP and the calculation method described in Chapter 3. The question asked in AHP study was “How much more certain is the method in the row than the method in the column?”

Table 4.2. *Assigning rates to V&V methods used in the hypothetical case by using AHP and linear interpolation*

V&V method	1	2	3	4	5	6	7	AHP rate	Vj value
1 Test (true environment)	1	3	5	7	7	8	9	0.399	1.000
2 Test (similar environment)	1/3	1	3	5	6	7	8	0.235	0.783
3 Test (lab)	1/5	1/3	1	3	4	7	8	0.147	0.668
4 Simulation	1/7	1/5	1/3	1	3	5	6	0.091	0.593
5 Analysis	1/7	1/6	1/4	1/3	1	5	7	0.073	0.569
6 Expert opinion with justification	1/8	1/7	1/7	1/5	1/5	1	4	0.036	0.521
7 Expert opinion	1/9	1/8	1/8	1/6	1/7	1/4	1	0.020	0.500

Current and planned methods and their relative V_j values are written in the HoQ. These parts of the HoQ for the hypothetical case can be seen together in Figure 4.11.

	HoQ	Kano Category	Tech. Reqs.							
			TR1		TR2		TR3		TR4	
			TR 1.1	TR 1.2	TR 2.1	TR 2.2	TR 3.1	TR 3.2	TR 4.1	TR 4.2
	Type of the TR (LTB, STB, NTB)		LTB	STB	LTB	LTB	STB	LTB	LTB	LTB
Lj	Lower limit		80	10	0.8	4	1.5	4	60	95
Mj	Upper limit		100	12	0.9	5	1.7	5	65	99
w	*linearity parameter for the TR fulfillment)*		1	1	1	1	1	1	1	1
AVTRj	Designed Product's Estimated/Actual Value		90	11	0.8	4	1.5	5	62	99
AVTRp,j	Designed Product's Potential Estimated/Actual Value		90	11	0.8	4	1.5	5	65	99
AFRTRj	**Current Achievement Rate**		0.500	0.500	0.000	0.000	1.000	1.000	0.400	1.000
AFRTRp,j	**Potential Achievement Rate**		0.500	0.500	0.000	0.000	1.000	1.000	1.000	1.000
	Method used to measure		Expert opinion	Expert opinion	Simulation	Expert opinion with justification	Test (similar env.)	Test (true env.)	Test (lab)	Test (true env.)
	Potential Method that could be used to measure in this phase of the project		Expert opinion	Analysis	Simulation	Expert opinion with justification	Test (similar env.)	Test (true env.)	Test (lab)	Test (true env.)
Vj	**Certainty of the V&V method used**		0.500	0.500	0.593	0.521	0.783	1.000	0.668	1.000
Vp,j	**Certainty of the potential V&V method used**		0.500	0.569	0.593	0.521	0.783	1.000	0.668	1.000

Figure 4.11. Hypothetical case HoQ - 8

16) ML'_{real} value is calculated for the hypothetical case as follows:

Consider $TR_{1.2}$.

$V_{1.2}$ = 0.500, $AFRTR_{1.2}$ = 0.500, $NWTR_{1.2}$ = 0.032

$$V_{1.2} \times AFRTR_{1.2} \times NWTR_{1.2} = 0.500 \times 0.500 \times 0.032 \cong 0.008$$

Calculating it for all TR_j and summing it up, we find 0.492 ≅ 49% for ML'_{real} at this phase of the example project.

For $TR_{1.2}$, it was planned to make an analysis but because of lack of resources, the analysis could not be done and there is expert opinion on hand. For all other TRs, assume the planned V&V methods are applied.

Then $V_{1.2}$ = 0.569, $AFRTR_1$ and $NWTR_1$ are the same.

$$V_{1.2} \times AFRTR_{1.2} \times NWTR_{1.2} = 0.500 \times 0.500 \times 0.032 \cong 0.008$$

Calculating it for all TR_j and summing it up, we find 0.493 ≅ 49% for $ML'_{V,p}$ at this phase of the example project. A difference of 0.001 comes from the method change for TR_1. Since the importance weight of this TR ($NWTR_{1.2}$) is very small relative to the other TRs, inability to apply the planned V&V method did not have a major impact on the total maturity degree.

Planned and real maturity levels in the hypothetical case can be seen in Figure 4.12. The colors in this figure are in parallel to the Figure 4.11.

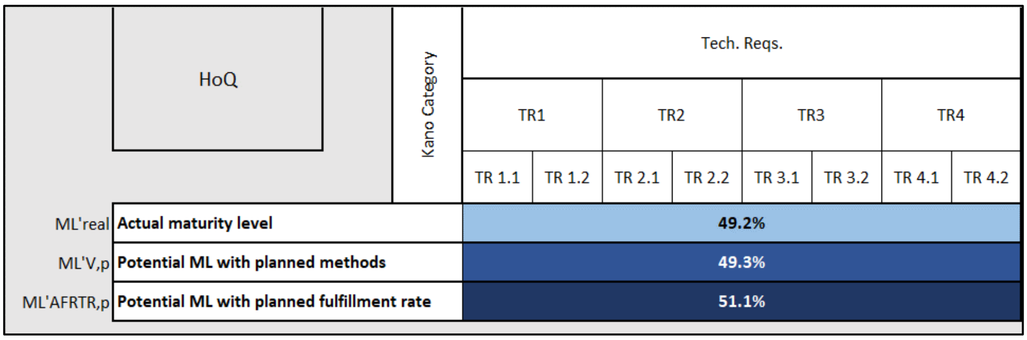


Figure 4.12. Hypothetical case HoQ - 9

17) Customer satisfaction rates are also evaluated for the hypothetical case. For instance, $CS_{1.1.1}$ is calculated as:

$$\frac{\sum_{j=1}^{m}(r_{ij} \times AFRTR_j \times V_j)}{\sum_{j=1}^{m} r_{ij}} =$$

$$= \frac{(0.069 \times 0.500 \times 0.500) + \cdots + (0.135 \times 0.400 \times 0.668)}{0.069 + \cdots + 0.135} = 0.748$$

TCS is calculated as:

$$(0.748 \times 0.155) + (0.278 \times 0.110) + \cdots + (0 \times 0.137) = 0.399$$

As in ML' indicator, assume that the method for the verification of TR_1 could not be ‘analysis’, instead, it was verified only by expert opinion. $TCS_{V,p}$ would then be 0.401, a gap of about 0.002 would exist.

The customer satisfaction calculations part added to the HoQ can be seen in Figure 4.13.

Example Application HoQ				Actual customer satisfaction	Potential customer satisfaction with planned methods	Potential customer satisfaction with planned fulfilment
Customer Req.s	CR 1	CR 1.1	CR 1.1.1	0.748	0.750	0.777
			CR 1.1.2	0.278	0.278	0.323
		CR 1.2	CR 1.2.1	0.250	0.250	0.250
			CR 1.2.2	0.548	0.549	0.548
	CR 2	CR 2.1	CR 2.1.1	0.750	0.750	0.887
			CR 2.1.2	0.621	0.630	0.621
		CR 2.2	CR 2.2.1	0.134	0.134	0.185
			CR 2.2.2	0.000	0.000	0.000
				TCS	**TCS**	**TCS**
				39.9%	**40.1%**	**41.8%**

Figure 4.13. Hypothetical case HoQ - 10

To sum up, the first indicator, which is the modified actual maturity level (ML'_{real}) value that shows the satisfaction rate of the technical requirements taking into consideration the uncertainty, is calculated. The second indicator, which is the total customer satisfaction (TCS) value is calculated. They are compared to planned levels specific to the project's current phase. The gaps are identified and possible decisions for improvement actions are noted.

18) The cost and schedule information for this hypothetical project were not prepared, hence, the project management monitoring part which uses random cost and schedule information. In the hypothetical case, TR 2.2 and TR 3.1 has the red colors in their monitoring part of the HoQ. It means that they need

attention of the project team. After an evaluation, the project team decides to increase resources for TR 2.1 and TR 2.2 and make cost improvement for TR 1.1 and TR 4.1. These decisions can be seen in the 'Decisions' row in Figure 4.14.

	HoQ	Kano Category	Tech. Reqs.							
			TR1		TR2		TR3		TR4	
			TR 1.1	TR 1.2	TR 2.1	TR 2.2	TR 3.1	TR 3.2	TR 4.1	TR 4.2
NWTRj	Relative weight (%)		0.239	0.032	0.041	0.158	0.331	0.111	0.047	0.041
AFRTRj	Current Achievement Rate		0.500	0.500	-	-	1.000	1.000	0.400	1.000
Cj	Cost (resource / tech. diff.)		0.143	0.028	0.028	0.084	0.44	0.028	0.247	0.028
Sj	Schedule (time pressure)		0.048	0.048	0.245	0.122	0.090	0.571	0.122	0.048
	Decisions		Cost improvement project (if possible)	Go as planned	Add more resources	Add more resources	Go on as planned	Go on as planned	Cost improvement project	Go on as planned

Figure 4.14. Hypothetical case HoQ - 11

The final view of the HoQ with the extensions added to it can be seen in Figure 4.15.

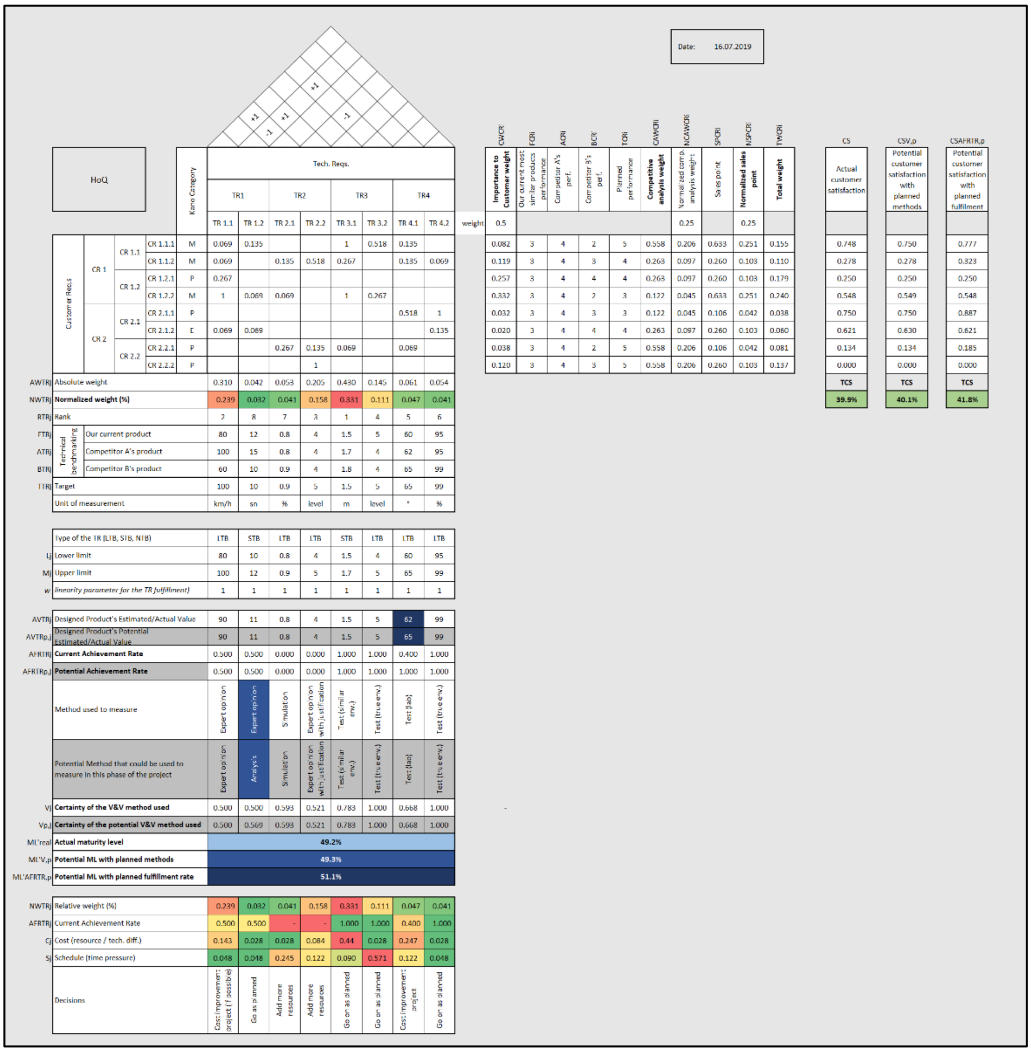


Figure 4.15. HoQ of the hypothetical case at the end of the monitoring part of the proposed method

The comments of the team who applied the proposed method to the hypothetical project, and the observed pros and cons of the proposed method are provided in Chapter 5.

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, comments about the results of the hypothetical case, the observations of the QFD team while applying the proposed method, pros and cons, and faced difficulties are discussed.

Without the prioritization approach of QFD for each TR and without incorporating the V&V method uncertainty approach of RAPIDO, a project manager would look at the technical requirement satisfaction rates in Figure 4.10 (TTR_j and $AVTR_j$ rows) and see that the average rate of fulfillment of the technical requirements is 0.930 ≅ 93% by taking the ratio of $AVTR_j$ to TTR_j for each TR and then taking the average. This value, especially in the beginning of the projects can be illusive. In addition, not having a progress margin for the upcoming phases of the project makes it an inadequate quality indicator. ML'_{real} is expected to get better as the project continues, giving a sense of improvement for all the stakeholders.

In a scenario where all TRs are validated by expert opinion and experts claim that they are all 100% achievable as shown in Figure 5.1, the ML'_{real} would still be 0.500 = 50%. This makes sense because until a requirement is verified or validated with more objective and reliable methods, a product cannot be evaluated as 'mature'.

AFRTRj	**Current Achievement Rate**	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Method used to measure	Expert opinion	Expert opinion	Expert opinion	Expert opinion	Expert opinion	Expert opinion	Expert opinion	Expert opinion
Vj	**Certainty of the V&V method used**	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
ML'real	**Actual maturity level**	**50.0%**							

Figure 5.1. A scenario where all TRs are verified by expert opinion and they are said to be 100% achievable

The limited implementation of the proposed method indicates that:

1) QFD, when used with modified RAPIDO and other extensions can be helpful for project managers to evaluate and monitor quality from the beginning of the project. All participants (QFD team, project team and other people that had contribution to or interest in the project) gave positive feedback that the method is useful.
2) The output of the application attracts attention of people involved in this pilot study.
3) This method forces to make a more detailed schedule and cost plan for the project, in order to feed this information into the method.
4) Project management needs at least one responsible person to build this system for the project, including the first set-up of the QFD and continuous update.
5) Building the QFD at first is the part that takes the longest time. This first setup activity should be calculated in the project's schedule and resources plan.
6) Sustaining this activity through the project's lifecycle requires discipline.

Based on the application of the proposed method in the pilot company, the strong and weak parts of the method are discussed as follows.

The strengths of the proposed method:

1) This method fills a void in project management practices, in terms of evaluating and monitoring quality starting from the product development phase.
2) It does not require complex mathematical operations or algorithms. It is easily applicable in a Microsoft Excel sheet.
3) It uses only the ratio scale values for the calculations, which support the objectivity of the method.
4) For those companies that are familiar with practice of QFD, this method is easy to implement. It only requires additional parts in the quality charts.

5) It is adaptable with project's schedule and cost plans, hence the decisions taken throughout the project lifecycle can be based on all three aspects.
6) Procurement authorities of defense industries may consider enforcing companies to use this or similar methods to guarantee that the projects finish with maximum customer satisfaction as well as on time and within budget.

The weaknesses of the proposed method:

1) The method needs validation by its application for different products in different industries.
2) It is not easy to persuade project managers to use this method since it changes their routine practices and brings a new way of doing their job.
3) It is challenging to relate all product development activities to technical requirements. For this purpose, the traceability of QFD matrices might be of help. For those who do not use comprehensive QFD, it becomes a difficult task to build all the relations between TRs and the project cost and project schedule plans.
4) The method is not easy to apply in companies where QFD is not already a practice. Persuading middle and top managers to allocate resources for QFD is a challenging task.

For products and services with low TRL levels (see Appendix A), it is even more challenging because the customer requirements and depending on it the technical requirements are not concise yet. Hence, applying the proposed method for those products and services may require more resources assuming that the requirements would be changing more frequently when compared to the products and services with higher TRL levels.

QFD might get exhaustive as the number of customer requirements or technical requirements increase. Due to this reason, it is not desired to have more than 20-25 requirements, in practice. When there is such a condition, it is better to proceed with separate charts for separable systems in the product. These separate charts can be assembled in order to manage the whole product. Such a study with implementation of this method can also be conducted as a future improvement to the method.

For product development projects which are relatively short-run or for businesses who work as make-to-stock such as fast-moving consumer goods sector this method would need modifications. For instance, such organizations' VoC methods, V&V methods would be different. The decision diagram in Section 3.2, Figure 3.2 might be totally different, for example any requirement that is costly may be left out at the expense of customer unsatisfaction if cost is prioritized more than the customer requirements. For fast-moving consumer goods (FMCG), this method can be used at the end of the product development just before serial production to test the maturity level of the product. However, our point of view is that the generic approach is applicable for all type of product development projects.

CHAPTER 6

CONCLUSIONS AND FUTURE STUDIES

This study is carried out in order to find a practical approach to the problem of monitoring and evaluating quality in long-run product development projects. Defining if a project is successful or not is not straightforward because it consists of objectives in terms of scope, schedule, budget and quality, as well as other stakeholder expectations such as contribution to the knowledge of the company. Merely defining a good set of objectives is not an easy task. Project managers are more comfortable with managing the scope, schedule and budget throughout the project. However, quality evaluation is left to the later phases of the project. In other words, product development phases do not include a quality measurement that is as objective as possible, showing improvement areas and helping decision making in design iterations.

The well-known method, QFD, is generally used from the beginning of the project until the end, in many industries. It assures that all activities in a project are connected to satisfaction of at least one customer requirement. On the other hand, we have observed that there is no commonly used objective measurement method that measures the fulfillment rate of customer requirements throughout the project and QFD methodology could be a good starting point for developing this methodology.

Among many quality and maturity assessment methods, RAPIDO, suggested in a recent study by Kandt et al. [2], is a promising method to integrate with QFD since its input parameters (importance, fulfillment and method uncertainty) provide an inclusive approach that can be used from the very beginning of the development phase through delivery of products.

The proposed method uses the infrastructure of QFD charts and builds on them a quality measurement system. This study's approach to quality monitoring is novel in these terms:

- This study fills a gap in terms of providing a method for quality monitoring in development phases for project management's quality management knowledge area.
- To the best of our knowledge, there is no study that uses QFD and a measurement tool together in quality evaluation and monitoring.
- The proposed method makes project workers and managers see more clearly if things are going well or not and give them a chance to improve by making necessary changes when it is cheaper and easier to make those changes.
- Also, this method makes everyone see the connections of quality characteristics to the customer requirements and prevents short-sightedness.
- As a contribution to the literature, it proposes an addition to QFD and shows that QFD with RAPIDO, after some modifications as described in Chapter 3, can provide an effective way of quality measurement for projects.

The proposed method is expected to be useful mostly in product development projects, especially those that have long durations for development. Also, it can be useful to test the maturity level of the products before they meet the consumers, for products with short product development durations.

This method aims to:

- Increase the customer satisfaction rate by
  - Making all the development process status visible
  - Prioritizing the most important requirements
- Decrease product development duration and cost by
  - Decreasing number of design iterations
  - Assuring resources are assigned in the best way
  - Decreasing reworks and retrofits

It is easy to implement this method if QFD is already used by the project team. Furthermore, this work is expected to increase the use of QFD by project teams, since it proposes ease of measuring the quality performance of the project as a whole.

As in all new methods, this method should be validated by other examples from different sectors. Sector-based differences in terms of project management and design processes may require modifications to the proposed steps of the method.

Another improvement area would be to make the sensitivity analysis of this method to understand how the changes in data affect the output of the model. Since the product evaluations, importance values, weights are mostly assigned by the QFD or project team, hence most of them depending on human judgement, seeing the effect of errors would be beneficial to improve the model.

In this study, only the integration of the first quality chart (Product planning or HoQ) with modified RAPIDO is presented. In fact, the same measurement systematic can be applied to the other quality charts. Integration of the other quality charts used in QFD would be an improvement to this method. Also, integrating Kano Model also in the proposed quality indicators would be another improvement area to this study.

In addition, the uncertainty of the used method (used in maturity level assessment) needs standardization at least within the company in order to compare different projects. Otherwise, the differing rates given in different projects may lead to wrong decisions at the level of portfolio management.

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APPENDICES

A. Other Product Maturity Assessment Methodologies

A.1. TRL

A group of Product Maturity Indicators which is widely accepted and used worldwide is Technology Readiness Level (TRL) and other metrics related to it, such as Manufacturing Readiness Level (MRL), Integration Readiness Level (IRL), System Readiness Level (SRL).

TRL can be said to be the first measurement method to have a sense of the readiness of a potential technology or item to be used in a product. TRL is an indicator to assess if a new technology is ready to be used or included in a product/service. It was found in 1980s by NASA. Since then its use is expanded in defense industries and other sectors where new technology inclusion is essential. TRL can be applied either to all elements of the product or just to the selected critical elements. The former has the advantage of assuring all components are under control, whereas the latter has cost advantage.

TRL provides a common understanding on maturity where different components can be compared in design and acquisition decisions. It brings a systematic approach to track system development and eases the monitoring of quality for project managers. The TRL rates and their explanations can be seen in Table A.1.

Table A.1. *TRL levels and their descriptions, as used by DoD [7]*

TRL	Description
9	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation.
8	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development.
7	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space.
6	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.
5	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
4	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
3	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology.
2	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions.
1	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.

In one approach, the critical technology elements (CTEs) of the system is identified. In general, the new systems or systems that are used in a new way are chosen as CTE. TRL of each CTE is estimated by experts. In another approach, all systems are evaluated in terms of TRL. The choice is up to the time and/or resource limitations. In the end, an overall view of the whole system is at hand, identifying the systems with low TRLs.

The increasing complexity of the systems especially in defense, and the objectivity questions about TRL limited its use [7]. Users seek for more robust methods, which also provide information about the risks and help decision making more than the way TRL metric does.

After all, the weaknesses of TRL are:

- Lack of objectivity, since the experts decide on the level of TRL with the information at hand, or by their projections since there is not any set of criteria other than the conventional rating scale of the TRL.
- Lack of a commonly accepted method; different institutes use different definitions of the levels and different calculation methods, making it difficult to compare systems.
- Evaluation of only the technology or system in itself, not the interactions with other systems.
- Difficulty of use with complex systems since there is no one metric that can be deducted from the TRLs of the subsystems that make up the overall system.

To overcome some of the weaknesses of TRL, some other indexes are developed, similar to the logic of TRL in general structures. They are Integration Readiness Level (IRL), Manufacturing Readiness Level (MRL) and System Readiness Level (SRL) [7], [94].

IRL is also a 9-level scale, just like TRL, and helps identifying the maturity level of the interfaces (integrations) between technologies. The IRL rates and their explanations can be seen in Table A.2.

Table A.2. *IRL levels, definitions and descriptions [94]*

IRL	Definition	Description
9	Integration is Mission Proven through successful mission operations.	IRL 9 represents the integrated technologies being used in the system environment successfully. In order for a technology to move to TRL 9 it must first be integrated into the system, and then proven in the relevant environment, so attempting to move to IRL 9 also implies maturing the component technology to TRL 9.
8	Actual integration completed and Mission Qualified through test and demonstration, in the system environment.	IRL 8 represents not only the integration meeting requirements, but also a system-level demonstration in the relevant environment. This will reveal any unknown bugs/defect that could not be discovered until the interaction of the two integrating technologies was observed in the system environment.
7	The integration of technologies has been Verified and Validated with sufficient detail to be actionable.	IRL 7 represents a significant step beyond IRL 6; the integration has to work from a technical perspective, but also from a requirements perspective. IRL 7 represents the integration meeting requirements such as performance, throughput and reliability.
6	The integrating technologies can Accept, Translate and Structure Information for its intended application.	IRL 6 is the highest technical level to be achieved, it includes the ability to not only control integration, but specify what information to exchange, unit labels to specify what the information is, and the ability to translate from a foreign data structure to a local one.
5	There is sufficient Control between technologies necessary to establish, manage and terminate the integration.	IRL 5 simply denotes the ability of one or more of the integrating technologies to control the integration itself; this includes establishing, maintaining and terminating.
4	There is sufficient detail in the Quality and Assurance of the integration between technologies.	Many technology integration failures never progress past IRL 3, due to the assumption that if two technologies can exchange information successfully, then they are fully integrated. IRL 4 goes beyond simple data exchange and requires that the data sent is the data received and there exists a mechanism for checking it.
3	There is Compatibility (i.e. common language)	IRL 3 represents the minimum required level to provide successful integration. This means that

	between technologies to orderly and efficiently integrate and interact.	the two technologies are able to not only influence each other, but also communicate interpretable data. IRL 3 represents the first tangible step in the maturity process.
2	There is some level of specificity to characterize the Interaction (i.e. ability to influence) between technologies through their interface.	Once a medium has been defined, a 'signalling' method must be selected such that two integrating technologies are able to influence each other over that medium. Since IRL 2 represents the ability of two technologies to influence each other over a given medium, this represents integration proof-of-concept.
1	An Interface between technologies has been identified with sufficient detail to allow characterization of the relationship.	This is the lowest level of integration readiness and describes the selection of a medium for integration.

SRL is somehow different than the previous three readiness level scales. It considers the TRL of a number of systems and IRL of their integrations, and deduces a system readiness level metric for the overall system [94]. In this way, it provides a better information for complex system. The visual representation of the approach as shown in Sauser's work [94] can be seen in Figure A.1.

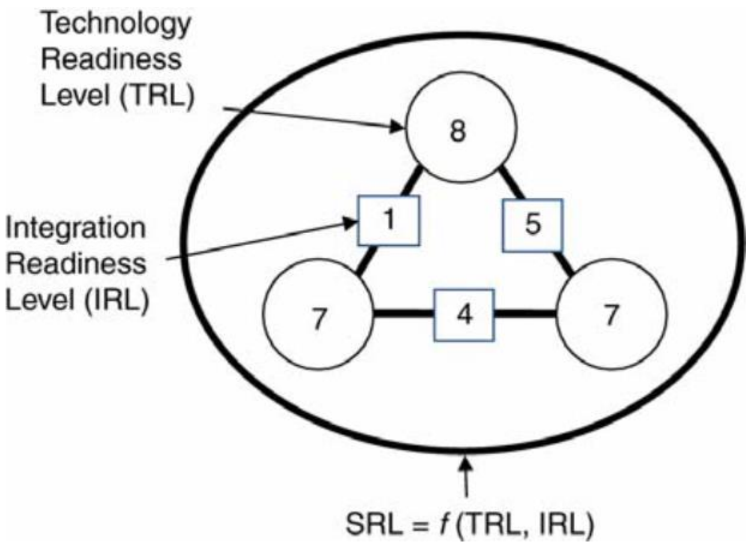

Figure A.1. Visual representation of the SRL approach

Let, *n* subsystems that are subject to TRL evaluation be chosen and their TRLs are set in a vector [TRL]:

$$[\mathrm{TRL}]_{n\times 1} = \begin{bmatrix} \mathrm{TRL}_1 \\ \mathrm{TRL}_2 \\ \dots \\ \mathrm{TRL}_n \end{bmatrix} \tag{43}$$

The pairwise IRLs of these *n* subsystems has to be a *n* x *n* matrix:

$$[\mathrm{IRL}]_{n\times n} = \begin{bmatrix} \mathrm{IRL}_{11} & \mathrm{IRL}_{12} & \dots & \mathrm{IRL}_{1n} \\ \mathrm{IRL}_{21} & \mathrm{IRL}_{22} & \dots & \mathrm{IRL}_{2n} \\ \dots & \dots & \dots & \dots \\ \mathrm{IRL}_{n1} & \mathrm{IRL}_{n2} & \dots & \mathrm{IRL}_{nn} \end{bmatrix} \tag{44}$$

Then, the SRL vector is calculated as TRL x IRL:

$$[\mathrm{SRL}]_{n\times 1} = [\mathrm{IRL}]_{n\times n} \times [\mathrm{TRL}]_{n\times 1} \tag{45}$$

It can be re-written as:

$$[\mathrm{SRL}] = \begin{bmatrix} \mathrm{SRL}_1 \\ \mathrm{SRL}_2 \\ \dots \\ \mathrm{SRL}_n \end{bmatrix} = \begin{bmatrix} \mathrm{IRL}_{11}\mathrm{TRL}_1 & \mathrm{IRL}_{12}\mathrm{TRL}_2 & \dots & \mathrm{IIRL}_{1n}\mathrm{TRL}_n \\ \mathrm{IRL}_{21}\mathrm{TRL}_1 & \mathrm{IRL}_{22}\mathrm{TRL}_2 & \dots & \mathrm{IRL}_{2n}\mathrm{TRL}_n \\ \dots & \dots & \dots & \dots \\ \mathrm{IRL}_{\mathrm{n}1}\mathrm{TRL}_1 & \mathrm{IRL}_{n2}\mathrm{TRL}_2 & \dots & \mathrm{IRL}_{nn}\mathrm{TRL}_n \end{bmatrix} \tag{46}$$

The SRL value of the overall system is found by:

$$\mathrm{SRL} = \frac{\left(\frac{\mathrm{SRL}_1}{n}\right)+\left(\frac{\mathrm{SRL}_2}{n}\right)+\dots+\left(\frac{\mathrm{SRL}_n}{n}\right)}{n} \tag{47}$$

Sauser and his colleagues [94] also proposes to calculate a System Readiness Potential (SRP) value in order to compare it with SRL. To calculate SRP, potential values for TRLs and IRLs should be used in calculation. It is going to be seen in the upcoming sections of the literature review, that, maturity assessment methods in general have the similar logic, comparing current and potential maturity levels.

Lastly, MRL is a 10-level scale which is developed to assess manufacturing maturity associated with the system, similar to TRL and IRL metrics. To the best of our knowledge, there is not a work on the integration of MRL to SRL or other readiness level metrics, yet.

Because of the subjectivity inherent in these methods and the complexity of the target products, these methods are not preferred to be used in our proposed model.

A.2. TRIZ

The evolution trends offered by TRIZ methodology can be used as maturity assessment method for the products [101]. TRIZ is the result of more than 2 million patents, consolidating the best practices of the world and guides users on possible solutions to their problems because maybe in some other sector or with some other product, a similar problem had been solved.

In addition to its solution principle proposals to different type of problems, Altshuller, in his book [65] explains “Ideal Final Result (IFR)”. IFR does not have to be a realistic state, it is the utopia. However, it helps thinking of the solution. The more realistic foreseen limit can be thought as “evolutionary potential. To reach to the evolutionary potential, TRIZ proposes the notion of “evolution trends for technology”. The notion of “evolutionary potential” with evolution trends, help people determining opportunities for their systems. Figure A.2 shows the concept of evolutionary potential.

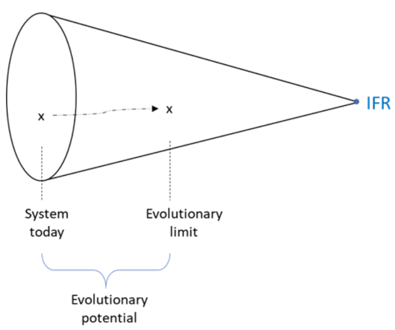

Figure A.2. The concept of evolutionary potential [101]

S-curves are used in TRIZ methodology to assess product maturity [102]. S-curve is a visualization tool that show the expected lifecycle of a product or system. The lifecycle stages are defined differently by different specialists; however, the most common use is like: infancy, growth, maturity, decline. Figure A.3 shows an S-curve [103].

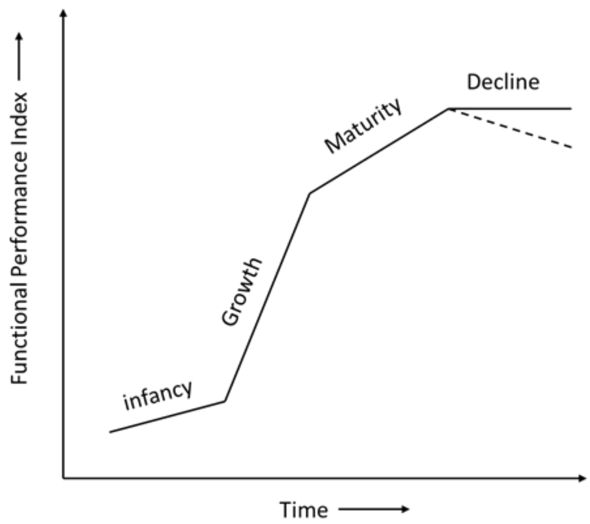

Figure A.3. System evolution graph [93]

Slocum [103] states that there are two more descriptors that helps to evaluate where a product is on its S-curve are, in addition to technical performance level:

1) Number of patents per time period
2) Level of innovation per time period

These descriptors have an expected trend in a product lifecycle. They are shown in Figure A.4.

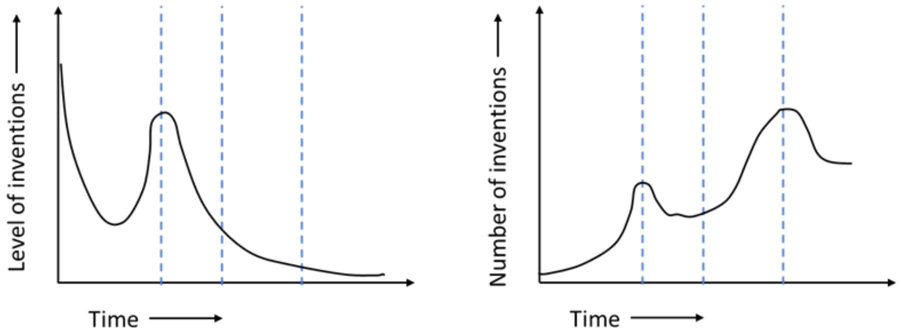

Figure A.4. S-curve descriptors

These curves are characteristic curves. Looking at the past and current situation of these metrics, one can make a prediction on where the product is in its lifecycle.

Besides evaluating the maturity of a product, this method helps design decisions. For example, whether or not to work on optimization is sometimes subject to decision and spending resources on improvement of an already mature system would be a waste.

Use of TRIZ with other design and problem solving tools are well described in Mann's study [104]. In our study, TRIZ is suggested to be used for tradeoff obligations between contradicting technical requirements and/or unachieved targets when the technical difficulty is evaluated as high.

A.3. Property-Based Product Development

Luft, Krehmer and Wartzack [8] summarizes existing approaches to the product development. They find out that the existing procedural models do not support maturity assessment of a product itself. They develop an "advanced procedural model", that consists of 33 steps that are distributed in the classical V-model which is used frequently especially in defense industry. Figure A.5 shows the general view of a modified V-model which is parted in four sections which are B-behavior, P-property, S-structure, and F-function.

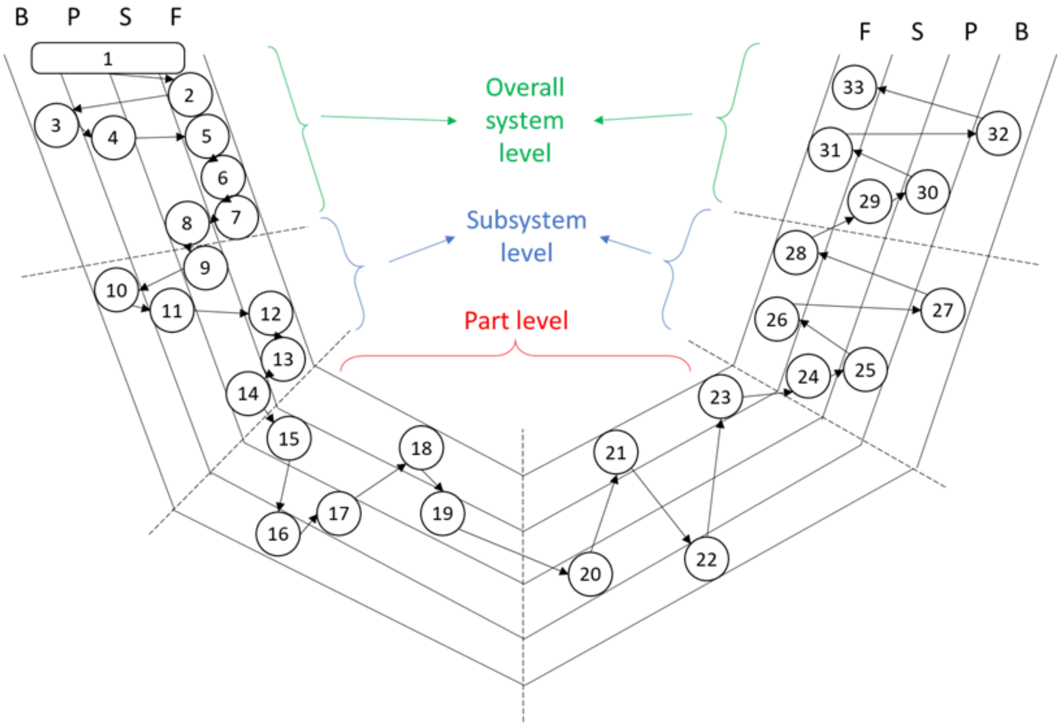

Figure A.5. Advanced procedure model of PPD on modified V-model [8]

These 33 steps start with requirement definition and weighting of requirements; and continues with detailing, definition of overall system behavior, definition of overall system properties, functions, structures, and then doing it for the subsystems and then for the parts, and then doing the checks with opposite sequence.

Although the suggested advanced procedural model is more like a procedure, Luft and his colleagues suggest that comparing planned requirements with the actualizations would give a measure of maturity. In other words, maturity can be the rate of fulfilling the requirements. A similar logic is used by the RAPIDO method as explained in the previous section. Since the logic of this method is covered in RAPIDO, it is also covered in our proposed method.