# Quality Function Deployment Integration with Design Methodologies

**Mengli Shu**

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This is to certify that the thesis prepared

By: **Mengli Shu**

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complies with the regulations of this University and meets the accepted standards with respect to originality and quality.

Signed by the Final Examining Committee:

______________________________ Chair
*Dr. Arash Mohammadi*

______________________________ External Examiner
*Dr. Mingyuan Chen (MIE)*

______________________________ Examiner
*Dr. Amin Hammad*

______________________________ Supervisor
*Dr. Yong Zeng*

Approved by ______________________________
Rachida Dssouli, Chair
Department of Concordia Institute for Information Systems Engineering

____________ 2017

______________________________
Amir Asif, Dean
Faculty of Engineering and Computer Science

# Abstract

Quality Function Deployment Integration with Design Methodologies

Mengli Shu

Under the background of the economic globalization, customer requirements play an increasingly important role today in almost every industry. Achieving customer satisfaction becomes the key way for a company to win market shares in the intensive global competitions. In this thesis, a four phase QFD-oriented product design framework is proposed by integrating Quality Function Deployment (QFD) with 3 different design methodologies (Environment-Based Design, Analytic Hierarchy Process, Axiomatic Design), to systematically guide product design from the planning phase to the detail design phase, and to build the link between design variables in different phases, so that it is known how customer requirements are met during each development phase, and till the end, customer requirements and product characteristics are clearly linked together. Apart from the theoretical side, a web application design case study is presented to illustrate how this framework is applied. In the case study, customer requirements are successfully captured and mapped down to the detail design level.

# Acknowledgments

My sincere gratitude to my supervisor Dr. Yong Zeng who is always optimistic towards any problems and passionate about research. It is a great honor to study and work under his supervision. I could not make this far without his wise guidance, support and help. And I am sure I will keep benefiting from this experience even after a long time.

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# Chapter 1

# Introduction

## 1.1 Background and Motivation

Under the background of the economic globalization, customer requirements play an increasingly important role today in almost every industry. To achieve customer satisfaction becomes the key way for a company to win market shares in the intensive industrial competitions. As it is defined by Harvey et al in one paper, one of the nature of quality is that quality is often a relative concept which varies according to different people or even the same person but at different time (Harvey & Green, 1993). Two things are implied in this definition: first, seeing from the customers perspective is a fundamental step to capture the right customer requirements; second, customer requirements are essentially dynamic. Therefore, people started to realize the importance of integrating customer requirements into the product design process (Bailetti & Litva, 1995). Customer requirement identification, traceability and how the product characteristics are linked with the identified customer requirements become very active topics in marketing science, design science and many other domains (Ilieska, 2013) (Ramesh & Jarke, 2001) (Y. Wang & Tseng, 2011) (Zeithaml, Bitner, & Gremler, 2006). Especially in the domains which requires great agility in the product development process because the customer requirements change frequently, for example software development (Akman, zmut, Aydn, & Gktrk, 2016) (Al-Karaghouli, AlShawi, & Elstob, 1999). Industrial companies are also keen to find out systematic approaches that can ensure customer requirements are met throughout their product development process.

Traditionally, most of the engineering design methodologies are process oriented and perceive design problems from engineers or designers perspectives, which could lead to products that do not meet customer expectations. For instance, the Systematic Design methodology proposed by Pahl and Beitz (2013). The four-phase design process (Product Planning, Conceptual Design, Embodiment Design and Detail Design) in Systematic Design is widely accepted and practiced around the world. It captures the essential design activities and provides a general customizable design framework that can be applied to almost any projects. But how to meet customer requirements is not a central concern of this methodology. Another example is the widely applied Object-Oriented Design in software engineering. The object-oriented design methodology offers an excellent paradigm on how to model software products from a programming perspective. Moreover, it is usually easy for engineers to overlook the value of management work or design philosophies. It will not be not fatal in small projects, however, it will be when facing highly complex design problems. This is the reason why these methodologies need helps from other methodologies or techniques to shift their focus and adding values to how to meet customer requirements.

Quality Function Deployment (QFD) is a customer-oriented technique that provides guidance to product development teams through different stages of product development product planning, conceptual design, detail design, and manufacturing. Bouchereau summarized the benefits and difficulties when applying QFD as listed in the table below. QFD provides an overall concept of mapping customer requirements with engineering solutions, while due to the difficulties in its application, it also needs to be integrated with other methodologies and techniques to make it more systematic and definitive.

## 1.2 Objective

As described in the background, we can see that there is a need for a requirement-oriented product design framework. The first objective of this thesis is to propose a requirement-oriented product design framework using phase-based Quality Function Deployment (QFD). The second objective is to integrate other appropriate design methodologies and techniques with QFD to tackle the difficulties mentioned above. The proposed framework integrates Recursive Object Model (ROM) to model verbal data; Environment-Based Design (EBD) to elicit and capture customer requirements; Analytic Hierarchy Process (AHP) to prioritize customer requirements; and Axiomatic Design (AD) to provide an overall guidance on what are the input and output in each QFD phase.

## 1.3 Contribution

This thesis contains the following contributions:

1. Integrated EBD with QFD to cope with verbal data and capture customer requirements in product design.

2. Proposed a requirement-oriented product design framework by integrating QFD, EBD, AHP, and AD.

3. Conducted a case study by applying the proposed framework.

## 1.4 Thesis Outline

The rest of the thesis are organized as follows:

- Chapter 2 is the literature review of the origins, developments, applications of the related design methodologies.

- Chapter 3 provides an overview of the framework to show the big picture, then a detailed description of how the methodologies are integrated together in this framework and the detailed procedures of each methodology.

- Chapter 4 contains a web development case study from product design statement to a detailed design solution to demonstrate how to apply this framework and to illustrate the benefits of applying this framework.

- Chapter 5 contains the conclusion which summarizes the findings in this thesis; discussion that contains suggestions for the application and future development; and finally the future work.

# Chapter 2

# Literature Review

## 2.1 Quality Function Deployment(QFD)

### 2.1.1 Origin and development

QFD was originally introduced in Japan in the 1960s by Mr. Oshiumi and K. Ishihara who applied some approaches that contained QFDs main characteristics; then it was applied by Akao and proved to be powerful as a product design methodology in the early 1970s. In the 1980s, it was rapidly spreaded to the US and it has been practiced in many different industries by leading companies around world since 1966 (Akao & Mazur, 2003) (L.-K. Chan & Wu, 2002) (Prasad, 1998). According to Akao and Mazur (2003), there are two significant changes brought by QFD:

1. Quality control has been moved upstream starting from the beginning of product design, which totally changed the mode and focus of traditional product development process.

2. QFD also provided a tool to help engineers and designers better understand customer expectations and to improve the communication inside the development team as well.

The House of Quality (HOQ), as shown in the figure 2-1, is a quality chart for QFD. It

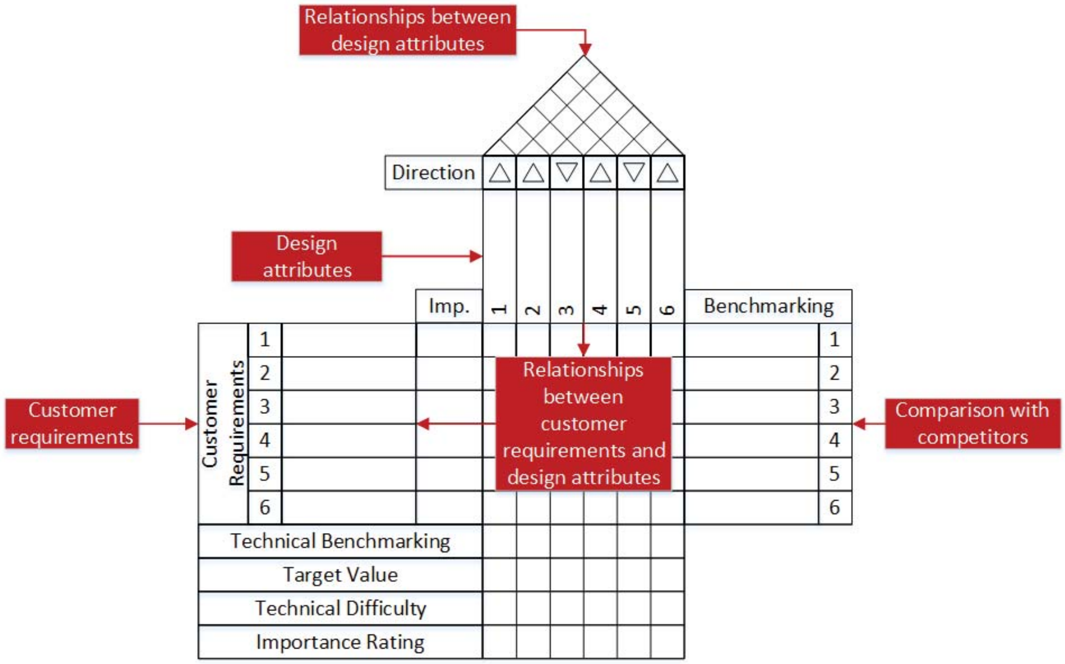



Figure 2.1: House of quality (HOQ)

was invented by Toyota Auto Body and used by Tsuneo Sawada for the Light Ace van, then later introduced to the USA by Fukuhara (Akao & Mazur, 2003). HOQ integrates customer needs, engineering attributes, engineering measures, and competitors information to help the team understand how the customer needs are met by the engineering attributes.

### 2.1.2 Phase-based QFD

Phase-based QFD is a product development approach that uses QFD throughout the product life cycle. The approach usually consists of four phases: 1) product planning, 2) product design, 3) process planning, 4) process control. Each phase takes the proposed solutions from the previous phase (Bouchereau & Rowlands, 2000). The number of phase can be customized according to different projects needs. One to two phase QFD process is usually applied to facilitate communications between customers and engineers, or for quick problem identification and potential solution identification. Three to four phase QFD approach is usually applied for more complex product design and development problems. Tidwell and Sutterfield (2012) conducted a case study using a two-phase QFD to help the communication among stakeholders during the selection of packaging suppliers. Paryani, Masoudi, and Cudney (2010) applied a three-phased QFD process in the hospitality industry to create action plans in order to improve hospitality services to better achieve customer satisfaction. Dai and Blackhurst (2012) proposed a four-phase AHP-QFD approach to assess supplier by developing supplier assessment criteria against customer requirements from a sustainable perspective.

### 2.1.3 Application

As it was summarized in Chan and Wus review, QFD has been used worldwide in plenty of different fields for product development, quality management, customer needs analysis, product design, decision making etc. (L.-K. Chan & Wu, 2002). For product design, QFD has been integrated with the Kano model to understand customer requirement and further achieve customer satisfaction by creating attractive product attributes (Chaudha, Jain, Singh, & Mishra, 2011) (Shen, Tan, & Xie, 2000), (Tontini, 2007). Sakao (2007) proposed a QFD-centred design methodology for product design with an emphasis on environmental qualities. In decision making, QFD was applied by Dikmen, Birgonul, and Kiziltas (2005) as a decision-making tool to make comparisons with competitors and select the best marketing strategy in the construction industry; QFD was applied to identify manufacturing automation alternative for selecting manufacturing automation technologies (Almannai, Greenough, & Kay, 2008).

## 2.2 Environment-Based Design (EBD)

### 2.2.1 Origin and development

Environment-Based Design (EBD) is a generic design methodology proposed by Zeng, and it contains three interdependent activities: environment analysis, conflict identification and solution generation (Zeng, 2004). EBD was built upon three foundations: 1) the recursive logic which was observed to be the nature of design: the conclusion of the reasoning is recursively dependent on the major premise of the reasoning (Zeng & Cheng, 1991); 2) the axiomatic theory, generated by observing engineers design activities and based on the two axioms about how the universe is defined, as well as the attributes of human thought (Zeng, 2002); 3) the Recursive Object Model (ROM), a tool for modelling engineering design information by modelling natural language (Zeng, 2008). ROM was derived from a previous work of Chen and Zeng where the structure of product requirement was formalized (Z. Y. Chen & Zeng, 2006). Since it was proposed, EBD has been evolving and research has been done to connect EBD with other methodologies and tools. Wang and Zeng formalized the question asking process for environment analysis which is a critical part in EBD (M. Wang & Zeng, 2009). In 2011, Zeng officially formalized EBD by summarizing its development over time including all its components, processes and definitions (Zeng, 2011).

### 2.2.2 Application

As a generic design methodology, EBD is very effective in problem understanding and analysis. This has been proven by many applications in different fields.

To help designers cope with the increasing complexity of the functional requirements of medical devices, M. Chen, Chen, Kong, and Zeng (2005) proposed a systematic approach to guide the requirement gathering process by applying EBD. Sun, Zeng, and Zhou (2011) developed a manual for quality management system using EBD where it played a critical role in understanding the current service and identifying the critical conflicts. Tan, Milhim, Chen, Schiffauerova, and Zeng (2011) applied EBD to help solve Enterprise Application Integration issue by treating it as a design problem, and EBD showed its expertise in customer requirement identification as well as its highly holistic view towards a product. Liu and Zeng (2009) proposed a hierarchical conceptual model of design chain management by applying EBD. Based on Lius work, Sun, Zeng, and Liu (2013) formalized the conceptual model for the design chain system using EBD while taking product lifecycle into consideration. M. Wang, Zeng, Chen, and Eberlein (2013) proposed an algorithm to transform ROM diagram into Function-Behaviour-State (FBS) model. Barklon, Wang, and Xu (2014) applied EBD in a preliminary study on improving the efficiency of recruiting in a staffing agency, where it was acknowledged that with the help of EBD, the author was able to find the key elements for the design problem.

### 2.2.3 Integrated EBD

EBD is a fairly new design methodology compared to other design methodologies such as Systematic Design, Decision-Based Design, Axiomatic Design, Affordance-Based Design etc. Hence, there are not many integration with other methodologies or techniques are found. Another reason may be because EBD is a generic methodology with a high level of abstraction and generalization, it is a challenge to integrate it with other methodologies. The only one found is the integration of EBD and AHP developed by Du Chen et al. as an approach to evaluate the effectiveness of engineering projects, where EBD is applied to construct evaluation criteria which will be passed to AHP. This approach was also verified through an eco-concrete project (D. Chen, Wang, Liu, Zeng, & Chen, 2015).

## 2.3 Analytic Hierarchy Process (AHP)

### 2.3.1 Origin and development

The Analytic Hierarchy Process (AHP) is a method for multi-criteria decision making, proposed by Thomas L. Saaty. According to the review from Ishizaka and Labib (2011), the oldest reference of AHP can be traced to 1972. Later in 1977, Saaty (1977) described in details about the AHP process, its mathematical foundation, and he also discussed why the ranking scale was used . T. Saaty derived many former findings to form the AHP method: the pair-wise comparison (Thurstone, 1927); the hierarchical decision problem formulation (J. R. Miller, 1969); the relative rating scale (Stevens, 1957); and 72 which is the optimal criterion number for each level (Miller, 1956). Saaty and Vargas (2001) also summarized 7 fundamental elements of the AHP method in a book chapter.

### 2.3.2 Application

Since it was proposed, AHP has been widely practiced in various domains. In education, AHP has been applied to evaluate faculty performance in terms of research, teaching and service (Badri & Abdulla, 2004); to measure performances of learning systems (Ho, Higson, Dey, Xu, & Bahsoon, 2009); to help university rank the majors provided to students (Rad, Naderi, & Soltani, 2011) etc. In industry, it has been applied to help e-business to enhance their website quality (Y. Lee & Kozar, 2006); to measure business performance (Cheng & Li, 2001); (H. Lee, Kwak, & Han, 1995); to evaluate and select suppliers (Barbarosoglu & Yazgac, 1997); (F. T. Chan & Chan, 2010); (Levary, 2007) In management, it has been applied to help negotiate and resolve conflicts (Al-Tabtabai & Thomas, 2004); to select project (Huang, Chu, & Chiang, 2008); to manage risk (Mustafa & Al-Bahar, 1991); (Wen-ying, 2009); and many other areas with specialties on the topics of selection, evaluation, benefit-cost analysis, allocations, planning and development, priority and ranking, decision making as well as forecasting (de FSM Russo & Camanho, 2015); (Vaidya & Kumar, 2006).

### 2.3.3 Integrated AHP

Due to the expertise of AHP method, it has been applied combining with many other methods. Combined AHP with mathematic programming (Bertolini & Bevilacqua, 2006) (Kearns, 2004) (C.-E. Lee & Hsu, 2004) (Malladi & Min, 2005); combined AHP with SWOT analysis (Kajanus, Kangas, & Kurttila, 2004) (Kurttila, Pesonen, Kangas, & Kajanus, 2000)(Masozera, Alavalapati, Jacobson, & Shrestha, 2006); combined AHP with Data Envelopment Analysis (DEA)(Saen, Memariani, & Lotfi, 2005) (Takamura & Tone, 2003) (Yang & Kuo, 2003); combined AHP with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Dadeviren, Yavuz, & Kln, 2009); as well as combined AHP with Quality-Function Deployment (QFD) where mostly AHP is used to prioritize customer requirements. According to the literature review conducted by William Ho, the AHP-QFD is the second popular integration among all the integrated AHP methods in the last decade (Ho, 2008). This is the combination used as a part of the method in this thesis.

### 2.3.4 AHP-QFD

Kksal and Eitman (1998) proposed an approach using AHP-QFD to improve the quality of industrial engineering education. In this approach, AHP was applied to rank stakeholder requirements while also trying to capture stakeholders group preferences by forming a focus group with five representatives. Madu, Kuei, and Madu (2002) used AHP with QFD for product design selection taking also the environment burden into consideration to develop cost-effective design plan of a paper recycling application. Here, AHP was also implemented to prioritize customer requirements. Bhattacharya, Sarkar*, and Mukherjee (2005) integrated QFD with AHP for robot selection where AHP was used to prioritize customer requirements (CR), then the identified technical requirements (TR) in the QFD were rated based on the relationships with their corresponding CRs and the importance of the related CRs. Thereafter, the pair-wise comparison and the Saatys scale were applied to obtain the weight of each alternative with respect to each TR. Finally, the overall score of each alternatives were calculated considering both the importance of the TRs and the weights of the alternatives. Tu, Zhang, He, Zhang, and Li (2011) applied the AHP-QFD method to develop new sports earphone and select the best conceptual design.

Dai and Blackhurst (2012) proposed a four-phase AHP-QFD approach for supplier selection from the perspective of sustainability. Each phase has its own HOQ and these HOQs are linked by the Hows parameters passed between phases.

## 2.4 Axiomatic Design (AD)

### 2.4.1 Origin and development

An axiom is a principle or observation that is accepted to be true but cannot be proven, and it remains true until a counterexample is validated. Based on two axioms, Axiomatic Design (AD) is a design theory developed by Nam P. Suh to establish a scientific basis to improve design activities (Suh, 1990) (Suh & Sekimoto, 1990). The two axioms: the independent axiom and the information axiom provide designers a good way to evaluate design solutions with rationality rather than relying heavily on experience. The independence axiom has been widely applied, while the information axiom gradually become popular after its combination with fuzzy logic (Kulak, 2005) (Kulak, Cebi, & Kahraman, 2010). Besides the axioms, another thing that makes the AD powerful in design is the design domains and the mapping process between them: Customer Attributes (CA) in the customer domain, Functional Requirements (FR) in the functional domain, Design Parameters (DP) in the physical domain and Process Variables (PV) in the process domain.

### 2.4.2 Application

Since its presence, AD has been broadly used in many different fields, including product design, system design, manufacturing design, software design, decision making etc.

Suh proposed a conceptual framework for the design and operation of large systems using AD, and the large systems are redefined based on the total number of the highest level FRs it must satisfy during its lifecycle (Suh, 1995). Suh developed a generic approach for software design by combining AD and the object-oriented programming method. In this approach, the customer attributes and functional requirements in AD are defined and used to construct the software hierarchy which are used to build the object-oriented model for the software product (Suh & Do, 2000). Kulak (2005) presented a cellular oriented framework based on AD for production system and it was validated. Houshmand and Jamshidnezhad (2006) proposed a generic structure for modelling the design process of a lean production system using the domain variables FR-DP-PV and their relationships in AD to clarify concepts, principles and methodologies of lean manufacturing. Durmusoglu and Kulak (2008) applied AD to design office operation to improve its efficiency and reduce customer lead time. Zein, Li, Herrmann, and Kara (2011) developed a conceptual structure to guide the implementation of energy efficiency measures for machine tools by decomposing the goal of minimizing energy demand of a machining process as the highest level FR and the machine tool as the highest level DP then mapping their sub FRs and sub DPs. Khandekar and Chakraborty (2016) applied fuzzy axiomatic design principles to form a decision-making model for selecting non-traditional machining processes.

### 2.4.3 Axiomatic Design-QFD

Kurniawan, Zhang, and Tseng (2005) proposed systematic approach to connect customer in the product design process, where they listed QFD as one of the tools for translating the elicited needs into structured engineering-oriented needs which can be further used as customer attributes in the product design process based on AD. Gonalves-Coelho, Mourao, and Pereira (2005) found that the ADs design matrix and QFDs relationship matrix represent the same reality while in different format. They also pointed out that AD and QFD can be integrated together to avoid multilevel iterations. Celik, Cebi, Kahraman, and Er (2009) developed a Ship of Quality framework by integrating QFD with Fuzzy AHP and Fuzzy AD to perform data-oriented shipping investment decision-making. Carnevalli, Miguel, and Calarge (2010) presented a conceptual model to use QFD where AD is applied to reduce the difficulties of its usage. Gilbert III, Omar, and Farid (2014) applied QFD to assess customer needs, then identified and divided the technical requirements into constraints, non-functional requirements and functional requirements. The functional requirements were used for further development guided by the mapping process and independence axiom in AD. Similar process of combining AD and QFD were also applied by Ashtiany and Alipour (2016) to redesign an airplane tail.

# Chapter 3

# Methodologies

## 3.1 Introduction

The proposed framework is requirement-oriented, hence, it focuses on building the linkage between customer requirements, conceptual solutions and process parameters etc... By doing so a product development team can know how the customer requirements are met during each phase of the product design process, and thus to assure customer satisfaction and minimize changes and rework. This framework can be applied for product design that starts from scratch, and it can also be applied for product design that modifies an existing product. For this kind of improvement design, designers can start somewhere in the middle of the framework, and go both up and down directions using abstraction and decomposition to build traceability.

The meaning of requirement in this framework is not only defined as customer requirements. Between development phases, whenever the process proceeds to a next phase or requirements are broken down to lower levels, the results from the previous phase or level will become the requirements for the successor phase or level. In this way, a requirement-solution hierarchy is formed, which can help improving requirement traceability.

There are numbers of design methodologies dealing with design problems from different or similar perspectives. Each of them has its own strengths and weaknesses. By integrating some of them together, they can take each others advantages to complement their weaknesses accordingly. As it is shown in the literature review, there are 4 design methodologies (QFD, EBD, AHP and AD) that are adapted and configured into this framework. This chapter contains the details about the layout of each methodology in this framework and their procedures. The content is organized as follows: first, the overall product design framework will be introduced, including a brief description about the application of the proposed QFD-oriented process; second, the QFD-oriented process will be elaborated.

## 3.2 Overview of Product Design Process

Starting from some fuzzy ideas or requirements to a concrete product, the product design process can be very complex, therefore, it is very important to provide designers a framework to systematically guide the process and to ensure it is manageable, traceable, well-documented. Defined by Pahl and Beitz (2013) in Systematic Design, generally, product development process consists of four main phases: Product Planning; Conceptual Design; Embodiment Design; and Detail Design, as it is illustrated in Figure 3.1. As the process proceeds, the design of the product becomes more definitive and detailed. As we can see, the Systematic Design is a process-oriented methodology.

Another well-known methodology  Axiomatic Design (AD) perceives design problems from another perspective. It defines design process as a mapping process between four domains: the customer domain, the functional domain, the physical domain and the process domain (Figure 3.2). The definition of the variables in the four domains in AD are:

(1) Customer Attributes (CAs)

Variables that describe customer needs and wants that the completed design must

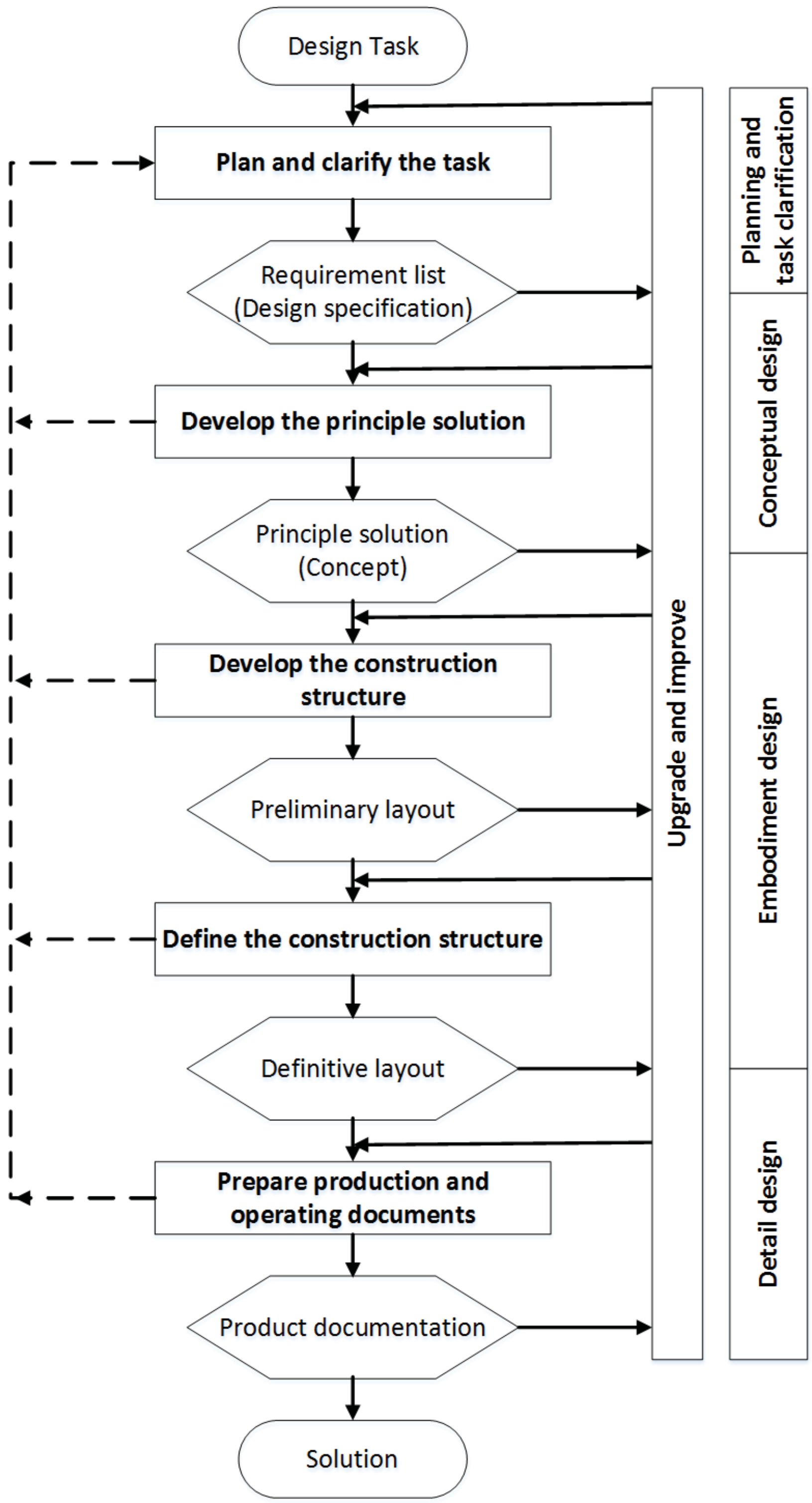



Figure 3.1: Product development process in Systematic Design(Pahl & Beitz, 2013).

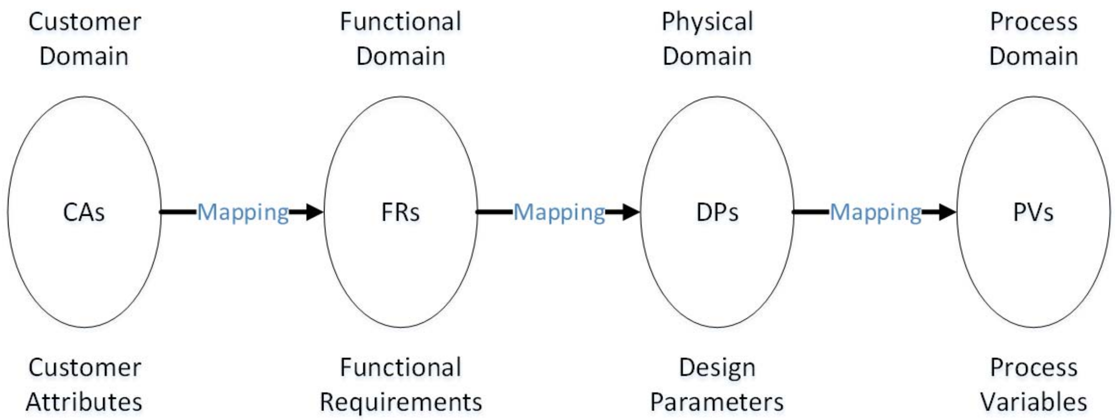



Figure 3.2: Four domains in Axiomatic Design

fulfill.

(2) Functional Requirements (FRs)

Variables that describe the intended behaviour of the product.

(3) Design Parameters (DPs)

Variables that describe the physical characteristics of a particular design.

(4) Process Variables (PVs)

Variables that characterize the design in the manufacturing process.

Although there is a customer domain in AD, it is not a requirement-oriented methodology. It believes that the design process begins with the establishment of FRs because it assumes the customer needs in the customer domain are already gathered and defined in some ways (Suh, 1990). Therefore how to deal with customer requirement is missing in AD.

Inspired by both Systematic Design and Axiomatic Design, the proposed product design framework is shown in the following Figure 3.3. The framework also contains four phases same as the Systematic Design. While the product planning phase mainly aims to elicit and capture customer requirements using Environment-Based Design (EBD). It is an interactive sub process that requires both designers and customers participation. After product planning, the customer requirements are already defined and the QFD process comes into play in the following three phases. The CR-FR QFD is to develop the FRs that will meet the defined CRs, which corresponds to the mapping process between the customer domain and the functional domain; the FR-DP QFD is to develop design parameters that will meet the FRs obtained in the conceptual design phase, which corresponds to the mapping process between the functional domain and the physical domain; similarly, the DP-VP QFD is for mapping the physical domain and the process domain. The physical domain in AD is the physical implementation of the FRs. To extend its usage to a non-concrete field, the FR-DP QFD is the process of defining the concrete deployment of the FRs. For example the software architecture using the Object-Oriented Design in the Information Technology field.

Although the process is divided into four phases, the boundary between two phases is not always definite, and designers usually need to go back and forth between them. As the process goes on, the results and information in previous phases need to be updated and refined, because design is a recursive process and it is difficult to get every step right in just one round, especially in the planning or conceptual design phases where the uncertainties are high and changes are likely to happen. Whenever change happens, the link between the four domains can help designers to trace all impacted CRs, FRs, DPs and PVs, and make corresponding adjustment to each of them.

### 3.2.1 Product planning

Product planning is usually the first phase of product design process. The purpose of the planning phase is to analyse and identify customer requirements. The input and output of the product planning phase are a design task and a requirement list respectively. A

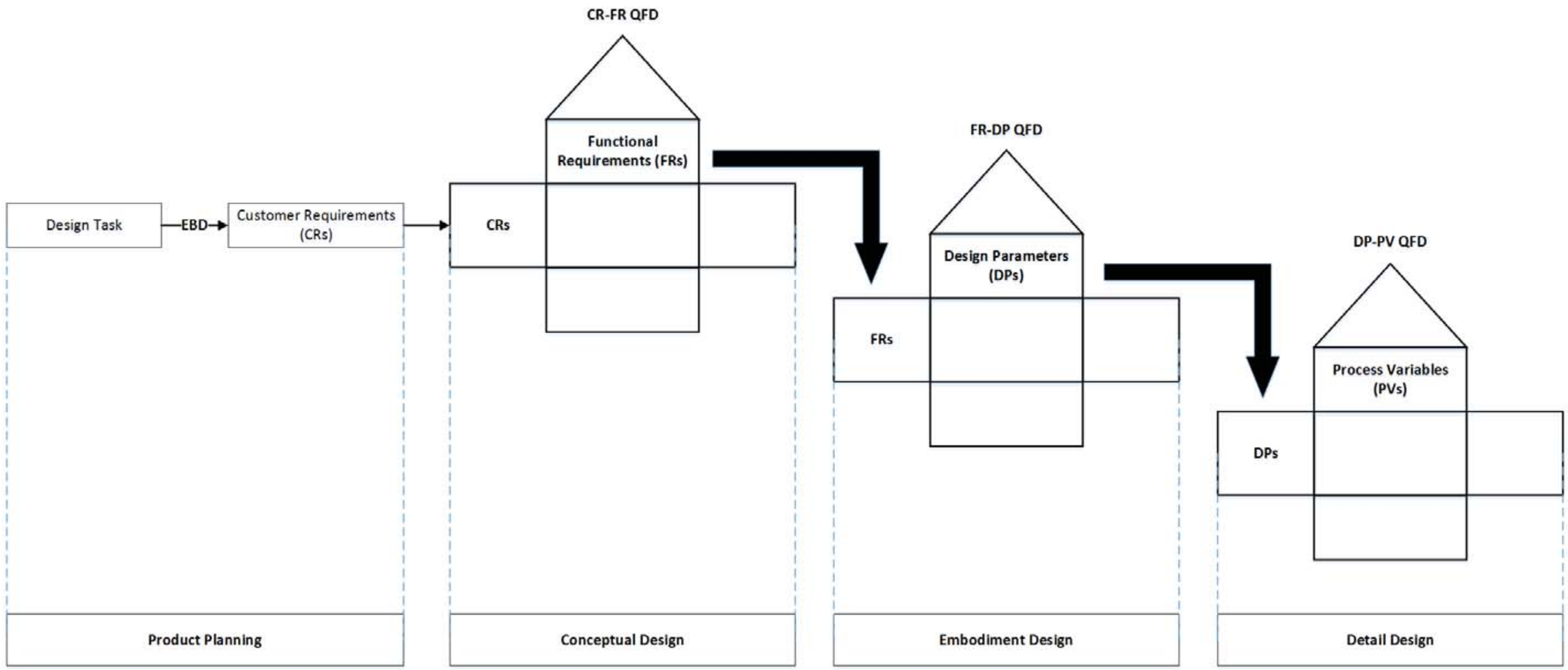



Figure 3.3: Overview of product design process

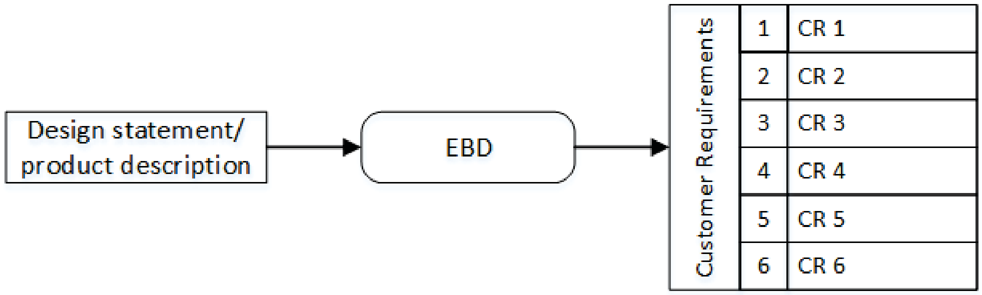



Figure 3.4: Input and output of EBD methodology in the planning phase

design task is usually given to designers as a design statement or a product description containing the design objectives as well as very limited other related information. Product planning can involve dealing with large amount of verbal data, which leads to high fuzziness and ambiguity at the beginning. Therefore, it is very important for designers to collect information to specify customer requirements as well as possible constraints.

Customer requirement can fall into three categories: obvious requirement; implied requirement; and unknown requirement. Obvious requirements may be stated by customers in the product description or any communication with the development team in a very clear way. Implied requirement means if a customer wants function A, then there is a probability that he/she also wants function B. Finally, sometimes customers themselves do not know what they want exactly. One of the eight characteristics of design summarized by N. Cross is: design is rhetorical (Cross, 1999), which also confirmed the existence of the third type requirement. In order to obtain the right customer requirements, designers need a systematic methodology to help them define customer requirement in the planning phase. Environment Based Design (EBD) is integrated in this framework to help designers identify the right customer requirement in the planning phase (Figure 3.4). EBD is based on Recursive Object Model (ROM) which is used to model verbal design data. The detail process will be elaborated in the EBD methodology section.

### 3.2.2 QFD Design Process

QFD Design Process is a sub process used in the conceptual design, embodiment design and detail design phases, to convert variables from one domain to another domain. HOQ is a good representation of the links between requirements and their corresponding solutions. There are different HOQs which are customized to serve for specific types of problems, but the overall idea does not vary much. To complete QFD, there are five kinds of information that should be gathered or generated and each kind corresponds to one section in the HOQ diagram: 1) Requirements and their weight of importance; 2) Solutions or product characteristics to meet the requirements and their internal relationships; 3) Relationships between requirements and solutions; 4) Benchmarking with competitors; 5) Target values and importance of the solutions. Having all this information means to have a clear idea of what to do in the product design process. Then, the problem lies on how to obtain the right information. According to the five kinds of information needed in the QFD process, a HOQ diagram is divided into five sections (Figure 3.5):

A. Requirement section

B. Solutions section

C. Requirement-solution matrix section

D. Benchmarking section

E. Evaluation and target section

Strictly speaking, QFD is not able to do the requirement-solution conversion on its own. It needs other methods to produce results for each of its sections.

The obtained requirement list from the planning phase will be the input for the CR-FR QFD design process in the conceptual design phase. AHP will be used to prioritize the requirements so that designers know what requirements are more important and should be of higher priority in resource allocation. Speaking to achieving customer satisfaction, it is always better to meet all the customer requirements if allowed. Therefore, requirements

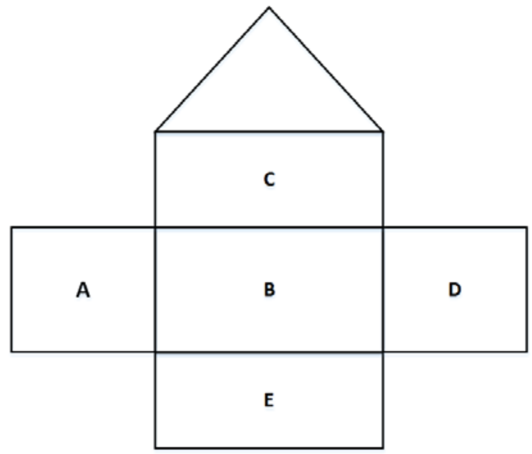



Figure 3.5: Five sections of a HOQ

with lower priorities are also important, but they are not as important as the requirements with higher priorities when resources are limited.

After the requirements are defined and prioritized, engineers or designers can work to generate solutions to meet the requirements. Solution generation requires background knowledge and experience. The solutions developed by different people may vary significantly, which can surely affect the final design of the product. On another hand, to evaluate the proposed solutions is a work relying heavily on relevant experience too. Hence, it would be of great help if there is a standard or criteria that can be used to evaluate solutions. This is where the expertise of AD lies. The two axioms in AD are two most general standard that a best design should comply. Thus, AD is also integrated into the QFD process for solution evaluation.

The overall QFD process in the proposed framework is shown in Figure 3.6.

During each QFD process, if the HOQ is highly dimensional, the requirements should be classified into different categories or sets in order to make the number of requirement as well as functions manageable. Doing so allows different teams to focus on a specific set of requirements in one HOQ rather than to consider all the requirements at the same time, which can help them avoid chaos and maintain a clean and clear solution structure.

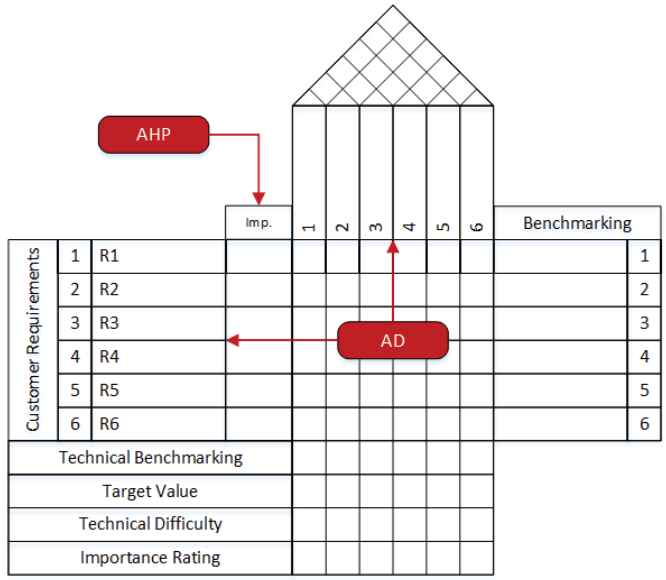



Figure 3.6: QFD integrated with AHP and AD

Moreover, it can also be helpful from two aspects in the product design process: 1) human resource allocation; 2) interface management.

Whenever a requirement or a function crosses two areas, it creates an interface between these two areas, which tells the sub-team that is responsible for this particular requirement or function who they should talk to. Different products in different fields have different features, so the team should choose an appropriate criteria to do the classification. For example, in web-application development, the Model/View/Controller corresponds to database, user interface and workflow logic respectively on a technical level (Leff & Rayfield, 2006). By dividing the design using the Model/View/Controller (MVC) pattern, designers can set a clear boundary so that they know who should focus on which technical area in terms of meeting customer requirements. Doing so makes it easier to architect the application, and also easier to maintain and improve during its later life cycle.

With HOQ, a parent level requirements and its corresponding child level solutions are clearly linked together, so the requirement-solution hierarchy flows naturally from the very top customer requirements to the bottom specific solutions and can be clearly represented

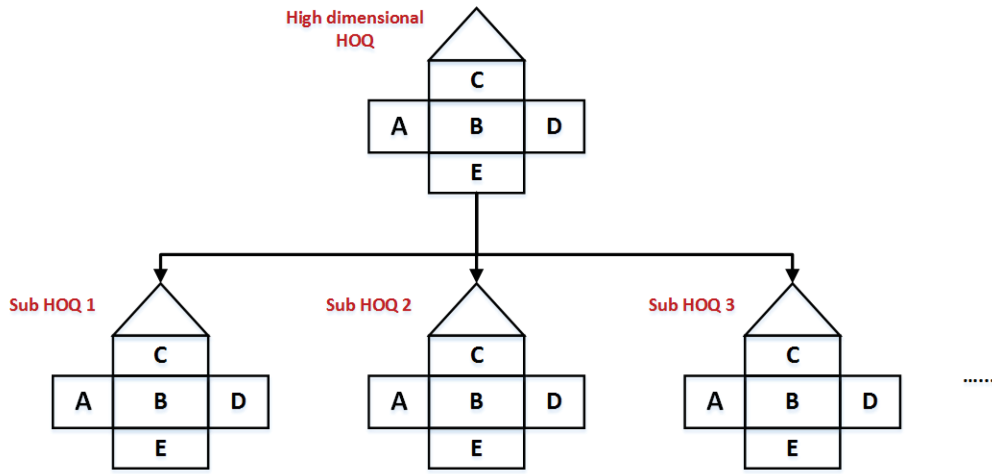



Figure 3.7: HOQ hierarchy

by the HOQ hierarchy (Figure 3.7).

## 3.3 Requirement Generation: Environment-Based Design (EBD)

Product development process usually starts from a plain text description about the desired product, for example a product proposal. How does a team understand the description by their customer, and how does the team communicate with their customer play a critical role in the product design process. Because efficient understanding about the information on what the customer really wants can help the team set a right product development direction, which will eventually help the team save resources of time, cost etc... Integrating EBD with QFD aims at helping designers cope with the ambiguity and fuzziness of verbal customer requirements, finding the right question to ask about the requirements in the product planning phase, and generating a requirement list that is able to represent customer expectations correctly, then pass it to the conceptual design phase.

EBD (Zeng, 2011) is a design methodology based on a philosophy foundation the

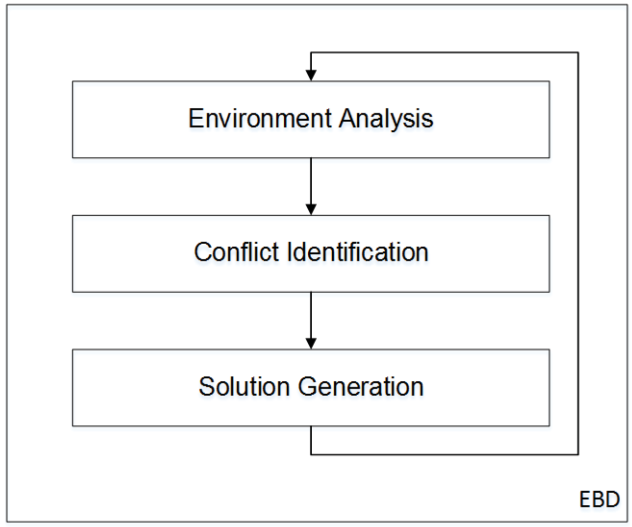



Figure 3.8: EBD process

recursive logic of design according to which design is a process that recursively iterates between design requirements and solutions until the final solution is found (Zeng & Cheng, 1991). The design process in EBD contains three main activities: Environment Analysis, Conflict Identification and Solution Generation (Figure 3.8). In each iteration, these three activities should be conducted. EBD has always been evolving, but the most recognized and proved expertise till today is that it provides designers a systematic approach to reach an excellent understanding towards a design problem even with very little experience (Tan, Zeng, Huet, & Fortin, 2013). In the proposed framework, the Environment Analysis is applied in the product planning phase to obtain customer requirements.

### 3.3.1 Recursive Object Model (ROM)

ROM was proposed as a graphical linguistic tool for design modelling in EBD using grammatical relationships in natural language. This model supports all the activities throughout EBD design process and it is based on two axioms:

**Axiom 1**: Everything in the universe is an object.

**Axiom 2**: There are relations between objects.

Figure 3.9 shows the graphical definition of different components in ROM. In a textual product description, each word is represented as an object in ROM. A compound object represents a more complex object with more than one word. In addition, there are in total three kinds of relationship between the objects. And two of them are also divided into more detailed categories.

(1) **Plain predicate relation**

The relation between a subject and its corresponding verb.

(2) **Predicate relation**

The relation between a verb and its corresponding object (from the grammatical perspective).

(3) **Plain connection relation**

The first connection relation of the connection relations among multiple objects (from the EBD perspective).

(4) **Connection relation**

The relation between two objects that are connected by conjunctions such as and, but, or etc.

(5) **Constraint relation**

The relation between an object and another object that describes and poses limitations to that object being constrained.

To analyze text documents for example a product description, building its initial ROM diagram is the first step, and then the process can proceeds to environment analysis.

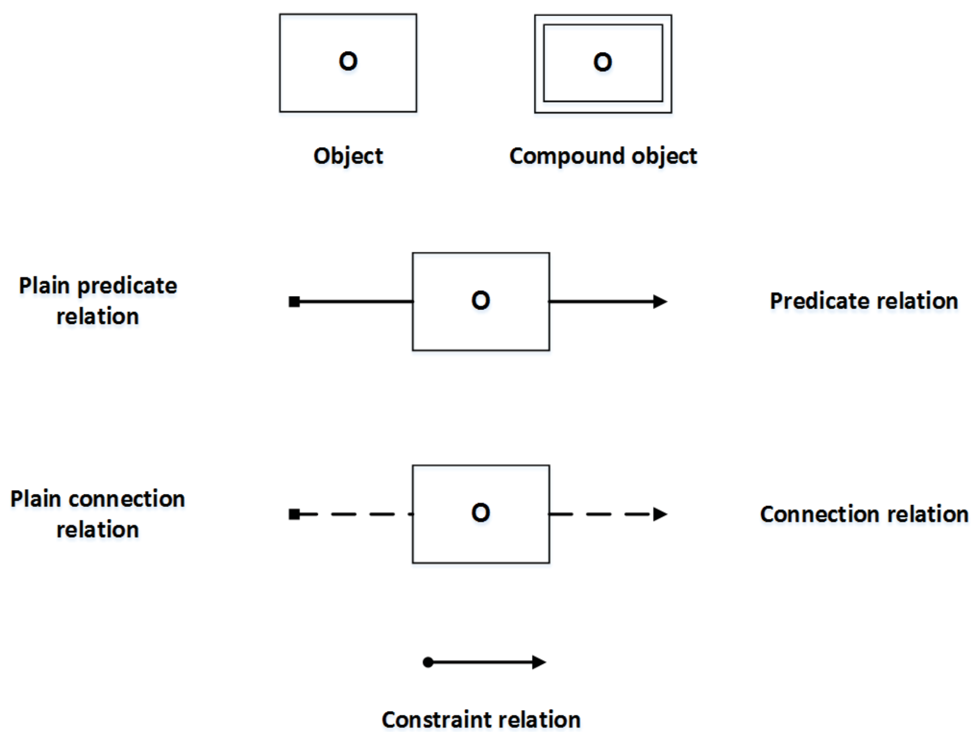



Figure 3.9: Graphical definitions of object and relations in ROM (Zeng, 2008)

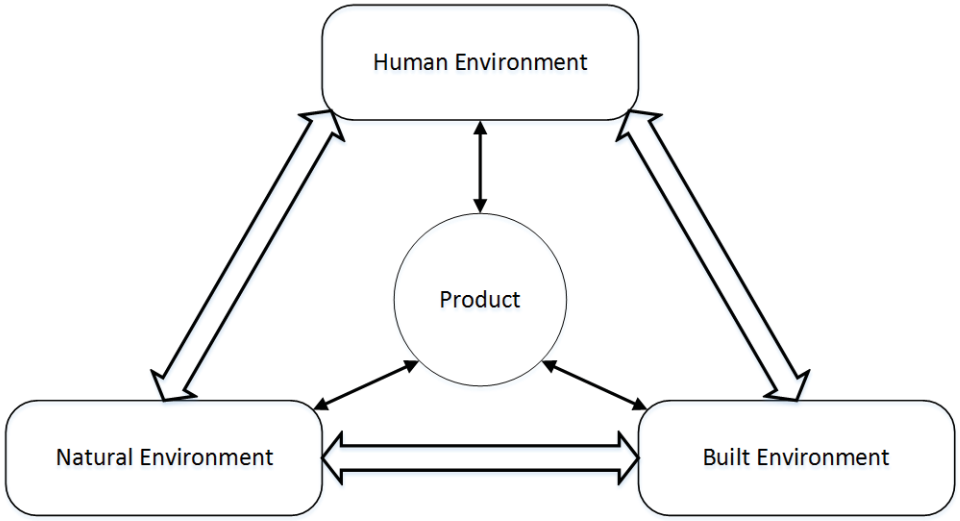



Figure 3.10: Three categories of environment for a product (Zeng, 2011)

### 3.3.2 Environment analysis

In EBD, the purpose of design is not only to generate a new artefact, from a more abstract level, it is also to change the existing environment to a desired one. Environment analysis aims at identifying what is the environment that the product will be working in and what are the relationships between each component and the product, as well as the relationships between every two components. To understand the environment of a product helps a team to understand the real needs of customers, the explicit ones, the implicit ones and even the ones the customers themselves dont know. According to Zeng, the environment can be classified into the following three categories (Figure 3.10) (Zeng, 2004).

**1. Natural Environment**

The Natural laws in the universe.

**2. Human Environment**

The human users of the artefact.

**3. Built Environment**

The artefacts designed and created by human beings.

The core component in the environment analysis process is the question asking process developed to guide designers to analyze the products environment step by step. During this process, two kinds of questions will be asked: 1) generic questions; 2) domain specific questions. Figure 3.11 illustrates the detailed environment analysis or it is also called the requirement elicitation process. Table 3.1 contains the rules for generic question asking which indicate the recommended sequence of the questions to be asked. Table 3.2 provides a template for the questions about different kinds of objects in a ROM diagram. As for domain specific question asking, the procedure is in Table 3.3. EBD doesnt offer any template but a generic roadmap for this type of questions, because it is a generic design methodology and the questions can vary significantly in different fields. The generic question asking process forces designers to give or find definitions, quantities, purposes etc... The domain specific question asking helps designers to find implicit components related to the desired product that customers are usually not aware of.

Table 3.1: Rules for generic question asking (Zeng, 2011)

| | |
|---|---|
| Rule 1 | Before an object can be further defined, the objects constraining them should be further refined |
| Rule 2 | An object with the most undefined constraints should be considered first |

Question asking is a critical part of EBD. When asking and answering questions, designers are actually defining and refining the design problem as well as the knowledge and information they have regarding to this problem, so that they can obtain a better understanding on the requirements as well as a better vision on the direction in which they should pursue. By following the question asking procedure, answers and information will be collected then transformed into ROM diagrams which will be merged with the initial ROM diagram in this iteration. When there is no more questions to be asked, the final merged ROM diagram can represent the whole picture of customers expectations on the

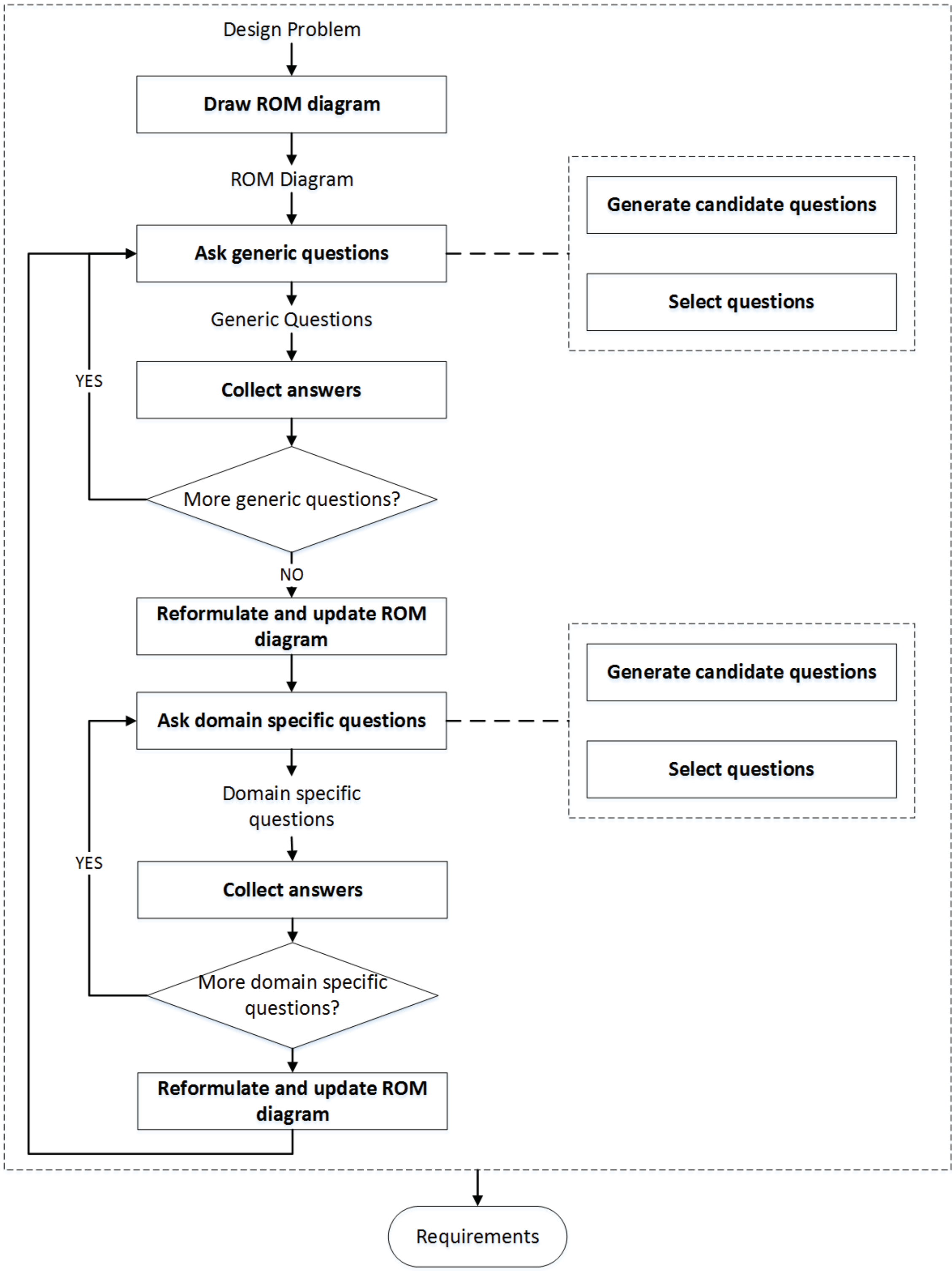



Figure 3.11: Environment analysis process (requirement elicitation process) (M. Wang & Zeng, 2009)

Table 3.2: Templates for generic question asking (Zeng, 2011)

| | Conditions | Question |
|---|---|---|
| T1 | For a concrete, proper, or abstract noun N | What is N? |
| T2 | For a noun naming a quantity Q of an object N, such as height, weidth, length, capacity, and level | How many/much/long// is the Q of N? |
| T3 | For a verb V<br>Why to V? | How to V? |
| T4 | For a modifier M of a verb V | Why V M? |
| T5 | For an adjective or an adverb A | What do you mean by A? |
| T6 | For a relation R that misses related objects | What (who) R (the given object)? (the given object) R what (whom)? |

desired product.

Table 3.3: Procedure for domain specific question asking (Zeng, 2011)

| Step | Description |
|---|---|
| 1 | Ask and answer the question: what is the lifecycle of the product to be designed? |
| 2 | For each event included in the lifecycle, ask and answer the question: what are the relevant components for natural, built and human environments for this event? |
| 3 | Generate the ROM diagram for each answer and merge them back to the original ROM diagram. |
| 4 | Apply the procedure for generic question asking. |

### 3.3.3 Example: A medical device case study

The following example is taken from a medical device case study by Tan et al. (2011). EBD has been evolving, some rules and expressions are slightly different from what is in that case study. Hence, only the content about the task is extracted and reorganized here.

The original task description:

*Design a system to read tests.*

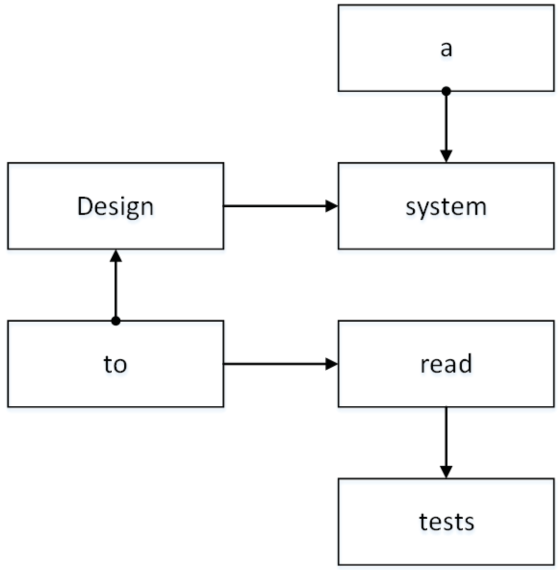



Figure 3.12: Initial ROM diagram from the task description

The original description is very unclear and fuzzy (Figure 3.12), while after one round of environment analysis, it became much richer and clearer. Depending on how big is the task, the environment analysis process can go several rounds until the team is sure that there is enough information for the current stage in the product life cycle (Figure 3.13).

The extracted interactions are listed in the following Table 3.4. Design is a human behavior which is not directly related to the desired product behaviors, so the Design an automated system is not included in the interactions associated with the desired product.

Table 3.4: Interactions from the medical device ROM diagram

| Interaction | Description |
|---|---|
| $I_1$ | System reads various commercially available lateral flow tests |
| $I_2$ | System should be effective |
| $I_3$ | System should be cost-efficient |
| $I_4$ | System should include a software kit |
| $I_5$ | A software kit is compatible with the Novatek LIMS |
| $I_6$ | System is for laboratory research |
| $I_7$ | System reads using image recognition technology |

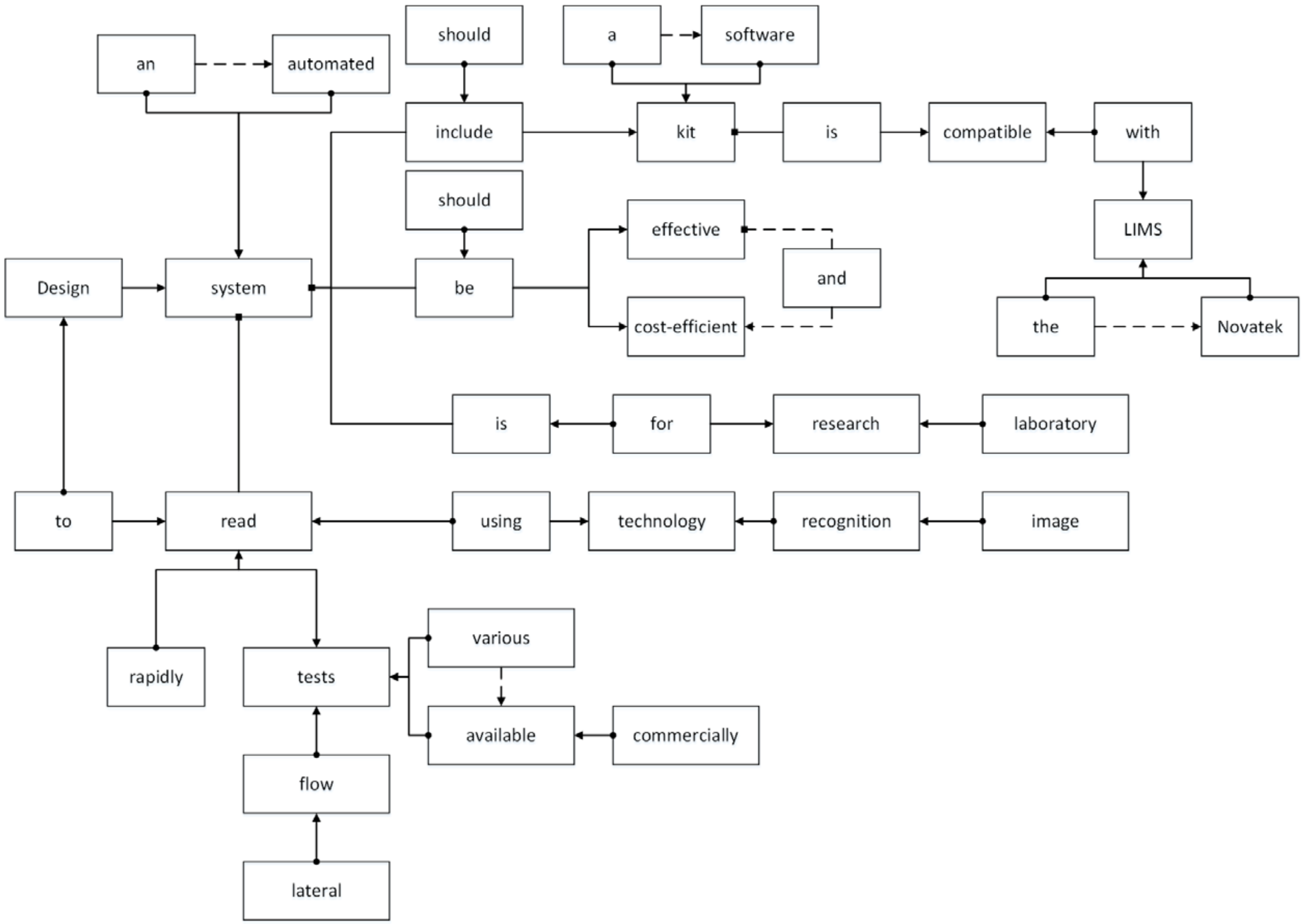



Figure 3.13: ROM diagram after one round environment analysis

| | | | Importance |
|---|---|---|---|
| Customer Requirements | 1 | System reads various commercially available lateral flow tests | |
| | 2 | System should be effective | |
| | 3 | System should be cost-efficient | |
| | 4 | System should include a software kit | |
| | 5 | A software kit is compatible with the Novatek LIMS | |
| | 6 | System is for laboratory research | |
| | 7 | System reads using image recognition technology | |

Figure 3.14: The requirement section in the initial HOQ for the medical device case study

From the interaction relation matrix, we can know:

Once all the requirements are defined and validated, they can be input to the QFD-Oriented Design Process. So if we assume there is no issue for the medical device case study, the initial requirements shall be like in the Figure 3.14.

## 3.4 Requirement Prioritization: Analytic Hierarchy Process (AHP)

In each QFD-Oriented Design Process, the first step is to gather, analyse and prioritize customer requirements. The requirement list obtained in the planning phase using EBD serves as the requirements for the CR-FR QFD phase. When it comes to next phases, the requirements should be analysed and prioritized according to the importance ratings of their corresponding requirements in the previous phase. The Analytic Hierarchy Process (AHP) method introduced below is used to prioritize the requirements.

AHP is a method for multi-criteria decision making problems. In this framework, it

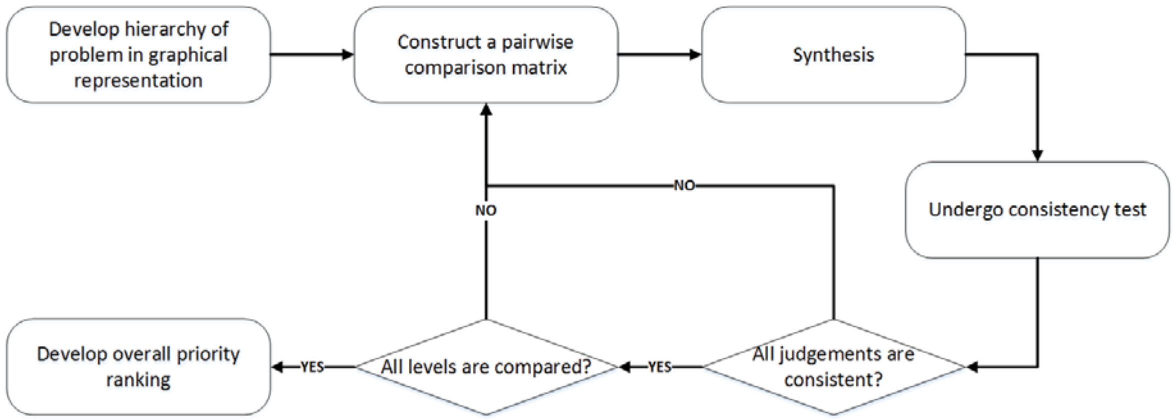



Figure 3.15: Flowchart of AHP

is applied in the requirement section of a HOQ to obtain the weight of each requirement. Generally, the AHP consists of four steps:

1. Problem definition
2. Decision hierarchy construction
3. Synthesis and pairwise comparison
4. Get the final global priority of each element

Figure 3.15 is a flowchart of AHP by Ho, Dey, and Higson (2006). The process is described as follows.

(1) First, a multi-criteria decision making problem should be defined. Then, as shown in Figure 3.16, the defined problem should be structured as a hierarchy with the overall goal on the top and decomposed criteria/sub-criteria, eventually to the final alternatives.

(2) During the pairwise comparison, for each goal, criteria and sub-criteria, every set of children criterion should be compared with respect to their parent criterion. Each comparison can be represented by an $n \times n$ comparison matrix C where n is the number of criterion on this level. And the cells $c_ij = w_i/w_j(0 < i, jn)$ are given by practitioners using the relative weight according to the following scale by Saaty

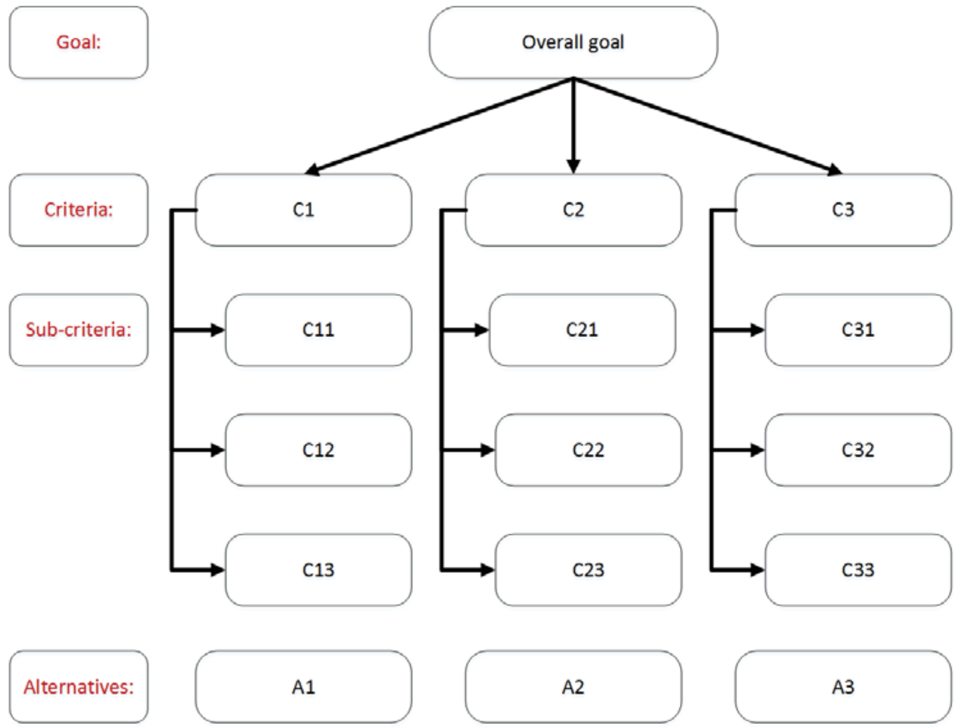



Figure 3.16: Decision hierarchy in AHP

(2004). Meanwhile, the weights of criterion i and criterion j against each other have a reciprocal relation $c_ij \times c_ji = 1$.

$$c = \begin{bmatrix} w_1/w_1 & \dots & w_1/w_n \\ \vdots & \ddots & \vdots \\ w_n/w_1 & \dots & w_n/w_n \end{bmatrix}$$

(3) Proposed by Saaty, the priority of the comparison matrix C can be estimated using its principal eigenvector.

$$c = \begin{bmatrix} w_1/w_1 & \dots & w_1/w_n \\ \vdots & \ddots & \vdots \\ w_n/w_1 & \dots & w_n/w_n \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} nw_1 \\ \vdots \\ nw_n \end{bmatrix} = nw$$

From the above equation, $w$ is the principal eigenvector C, therefore each value $v_i(1in)$ in $w$ corresponds to the estimated weight of criterion $i$.

(4) After getting the priority vector, a test needs to be conducted to ensure the consistency of all judgments, meaning the transitiveness. The degree of consistency can be represented using the Consistency Index (CI) in Eq.1., where  is the principal eigenvalue of the comparison matrix C.

$$CI = \frac{(\lambda - n)}{n - 1} \tag{1}$$

(5) Random Consistency Index (RI) is generated randomly using the scale $[1/9, 1/8, \ldots, 8, 9]$ according the following Eq.2. Then by comparing the CI and RI, we can get the Consistency Ratio (CR) of this comparison. And if the $CR \leq 10\%$, we can conclude that the degree of inconsistency is acceptable. Otherwise, the practitioners should reconsider and revise some of the weights given in step 2.

$$RI = \frac{1.98(n - 2)}{n} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

(6) Finally, the overall priority of each alternative can be calculated based on the priority value of its parent criterion all the way to the root goal.

As in the previous medical device example, if we assume that the weight for requirement $R_i$ is $w_i$, after the prioritization, the QFD will become like in the following Figure 3.17.

AHP can help the team to make logical and consistent decision when it comes to prioritizing requirements which may be a complex problem depending on how big is the project. However, it is pointed out that this method is not very efficient when dealing with large number of criterions during the pairwise comparison because of the redundancy.

| Requirements (R) | | | Importance |
|---|---|---|---|
| | 1 | System reads various commercially available lateral flow tests | $w_1$ |
| | 2 | System should be effective | $w_2$ |
| | 3 | System should be cost-efficient | $w_3$ |
| | 4 | System should include a software kit | $w_4$ |
| | 5 | A software kit is compatible with the Novatek LIMS | $w_5$ |
| | 6 | System is for laboratory research | $w_6$ |
| | 7 | System reads using image recognition technology | $w_7$ |

Figure 3.17: Prioritized requirements for the medical device example

## 3.5 Solution Evaluation: Axiomatic Design

The section B in a HOQ is actually a matrix representing how the proposed solution can meet the requirements. In traditional QFD, designers only link them together to show the interactions between them, for instance, whether it is strong positive, mild positive, mild negative or strong negative. This gives the designers a qualitative impression on meeting the requirements by the proposed solutions. AD contains two general criteria that can be used to evaluate design solutions for engineering product. The following section introduces the how the AD can be used in this framework.

Axiomatic Design is a general design methodology providing designers with a scientific approach based on theoretical foundations. Although it can go through the whole product development process, the main focus or power of this methodology lies on how it can help evaluating design solutions against the requirements by breaking down and mapping the four domains together.

The core of Axiomatic Design is the two axioms: 1. the independence axiom; 2. the information axiom. These two axioms act as the rules for selecting the most optimal design solutions to a design problem.

**Axiom 1: the independence axiom**

An optimal design always maintains the independence of its functional requirements.

**Axiom 2: the information axiom**

The best design is a functionally uncoupled design that has the minimum the information content.

As introduced before, in Axiomatic Design, the product development process is divided into the customer domain, the functional domain, the physical domain and the process domain (see figure 3-2). Different variables are used to describe the design characteristics in these four domains. And variables between two domains are mapped to see how the former domain can be satisfied by the later one.

Axiomatic Design defines the mapping process and all the variables using mathematical representations in linear algebra. Taking the mapping process between customer domain and functional requirement domain as an example, the flowing equation shows how a set of FRs meet a set of CAs. And A is called the design matrix.

$$\{CA\} = \begin{bmatrix} ca_1 \\ \vdots \\ ca_n \end{bmatrix} = [A]\{FR\} = \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{bmatrix} \begin{bmatrix} fr_1 \\ \vdots \\ fr_n \end{bmatrix}$$

Defined by how the set of CAs is met by FRs, or in other words, the types of the design matrix A, there are three types of designs in Axiomatic Design. And based on the independence axiom, the uncoupled design is the most optimal and desired one. Designers should try to solve the design problem by at least with a decoupled design.

**1. Uncoupled design**

Each customer attribute is directly met by one functional requirement, so that changing one variable does not affect others.

$$\{CA\} = [A]\{FR\} = \begin{bmatrix} a_{11} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & a_{nn} \end{bmatrix} \begin{bmatrix} fr_1 \\ \vdots \\ fr_n \end{bmatrix}$$

**2. Decoupled design**

The variables are not completely independent, while it is still possible to keep its predictability and maintainability by setting their values following a certain order. But it will affect the whole design if the value of one variable changes.

$$\{CA\} = [A]\{FR\} = \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ 0 & \dots & a_{nn} \end{bmatrix} \begin{bmatrix} fr_1 \\ \vdots \\ fr_n \end{bmatrix}$$

**3. Coupled design**

The performance of the design is hard to predict and maintain because a change in any of the variables will affect the whole design, and there is no pattern that one can follow to avoid it.

$$\{CA\} = [A]\{FR\} = \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{bmatrix} \begin{bmatrix} fr_1 \\ \vdots \\ fr_n \end{bmatrix}$$

Inspired by the Shannon Entropy theory, Nam Suh defined the information content in a very similar way. Let $p_i$ be the probability of satisfying $cr_i$ with $fr_i$, and the information content $I_i$ can be calculated according to Eq.4. While proved by Frey, Jahangir, and Engelhardt (2000) summation of information requires probabilistic independence of the relevant variables. Therefore, the calculation for information content of an uncoupled design is shown as Eq.5. And according to the Information Axiom, among multiple designs that meet the axiom 1, the one with the minimum information content is the best one.

**Information Content**

$$I_i = \log_2 \frac{1}{p_i} \tag{4}$$

**Information Content of Uncoupled Design**

$$I_i = \sum \log_2 \frac{1}{p_i} = -\sum \log_2 p_i \tag{5}$$

Therefore, after obtaining the solutions for their corresponding requirements, these two axioms can help the team determine if the proposed solution is good and optimal.

# Chapter 4

# Case Study

## 4.1 Introduction

The journal of Integrated Design and Process Science (JIDPS) is the official journal of the Society for Design and Process Science (SDPS). The JIDPS editorial system is a non-profit web service developed by students to support the editorial process of the journal. Different roles and documents are managed through the editorial workflow. There are already three versions of the system that has been developed. The first version of the system was developed and released in 2013, the second one in 2015 redesigned and developed by Y J Zeng (Zeng, 2015), and the third one in 2016 by Suo et al. Each version was developed according to the requirements from Dr. Yong Zeng who is one of the Editors in Chief of JIDPS. According to Dr. Yong Zeng, before the web service was developed, the editorial process was managed only by email, so there was no traceability of paper or user management function, which led to significant workload for each editor in the journal. And due to the great demand of attention from editors to assure the editorial process, there was a period of three years during which this journal had no one single paper that got published. The journal was almost about to disappear. This is the main reason why the editorial system was developed.

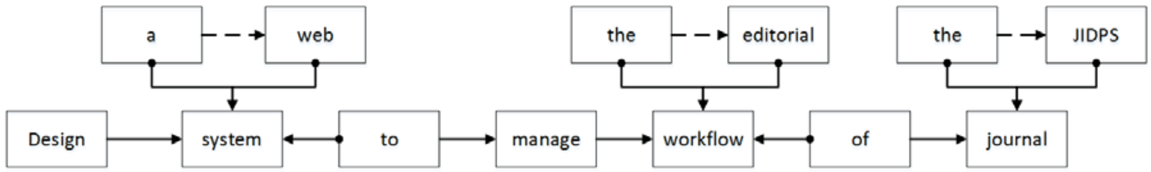



Figure 4.1: Initial ROM diagram for the problem statement

A case study was conducted to illustrate how the proposed framework can be applied in product design process and to explore other possibilities and potentials. The case study starts with a design problem statement, then goes through the four design phases: product planning, conceptual design, embodiment design and detail design. Detail design is elaborated briefly to avoid going into too much technical details. In the planning phase: EBD was applied to help elicit and understand the customer requirements gathered from customers description, then the AHP was applied to prioritize these requirements; in later phases, the importance rate are divided equally because the these phases of the case do not involve high analytical multi-criteria decision making. For each phase, the links between every requirement and its corresponding solutions are clearly recorded in the HOQ.

## 4.2 Case Study Procedure

### 4.2.1 Product planning

**Requirement identification**

As it is indicated in the case study introduction, the design problem statement is defined as:

*Design a web system to manage the editorial workflow of the JIDPS journal.*

Requirement identification shall start with this statement and expand using EBD. The ROM diagram for the statement is shown in Figure 4.1.

According to the rules for question asking, the following questions were asked and the results are shown in Table 4.1. The answers to the questions about definitions of terminologies were found on the Internet. While the answers to the questions that are related to the intent of the customer, were gathered directly from the communication with the customer, Dr. Yong Zeng. Some questions that yield similar answers were omitted, and some similar answers are merged together to simplify the ROM diagram. By using the collected answers, the initial ROM diagram was updated as it is shown in Figure 4.2. Figure 4.3 was collected in order to answer the question What is the editorial workflow of the JIDPS journal.

Table 4.1: Round 1 generic questions and answers

| | Question | Answer |
|---|---|---|
| 1 | What is the JIDPS journal? | The JIDPS journal is a seasonal publication. |
| 2 | What is the editorial workflow of the JIDPS journal? | The editorial workflow of the JIDPS journal is a series of process that a manuscript undergoes to get published. |
| 3 | What do you mean by manage the editorial workflow of the JIDPS journal? | The system manages the editorial process to let every user know his/her tasks and link them together to form the entire workflow. |
| 4 | How to manage the editorial workflow of the JIDPS journal? | By managing users and roles, papers and related files, user tasks and user actions, notifications. |
| 5 | Who to manage the editorial workflow of the JIDPS journal? | The web system. |
| 6 | Why to manage the editorial workflow of the JIDPS journal? | To reduce the workload of users and to track status of papers.The JIDPS journal is a seasonal publication. |

By analysing environment components in different stages of the products lifecycle in Table 4.2, can implied requirements be identified. Because this case study focuses on meeting customer requirements about the expected behaviours of the system, environment components in design, implement and test events, mostly relate to project resources schedule, cost and scope as well as human resource will not be elaborated in details.

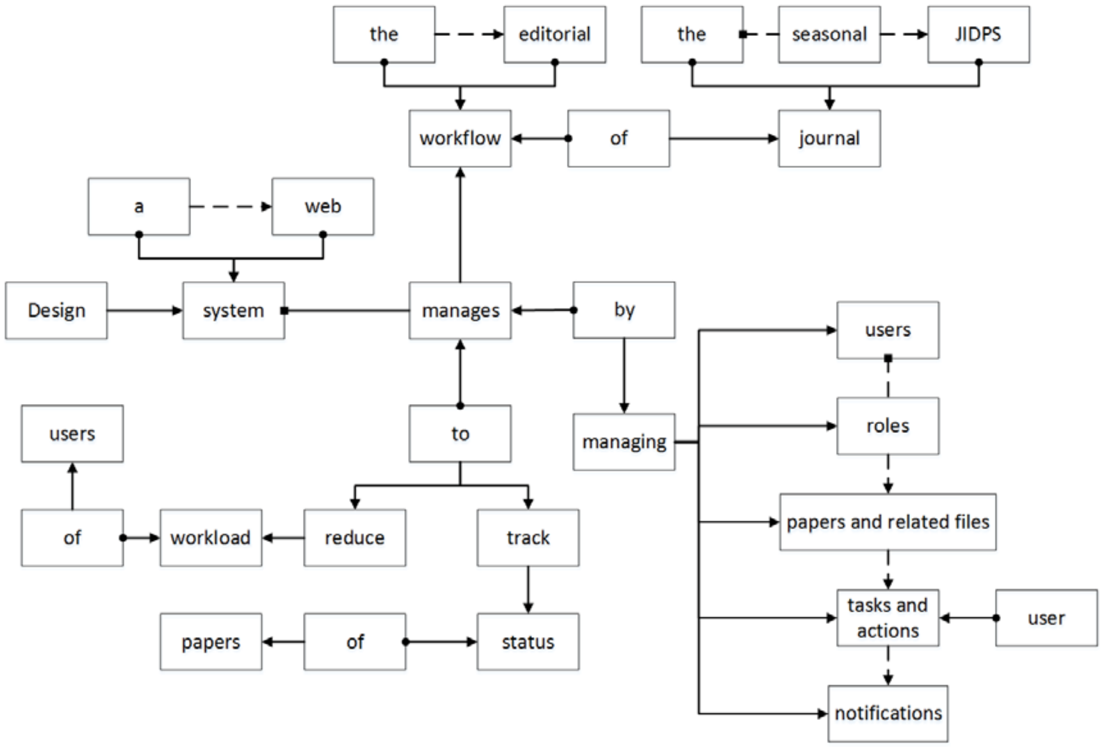



Figure 4.2: Updated ROM diagram after the first round of generic QA

Table 4.2: Round 1 generic questions and answers

| | Event | Natural | Built | Human |
|---|---|---|---|---|
| 1 | Design | | | |
| 2 | Implement | | Development stack, Server | |
| 3 | Test | | | Developers, Users |
| 4 | Use | Time | Users personal information, Papers and related files, Comments on papers, Decisions, Notifications, Invitations, User feedback to the website | Users, Users to be invited, Hackers |
| 5 | Maintain | | New data | Developers, Users |

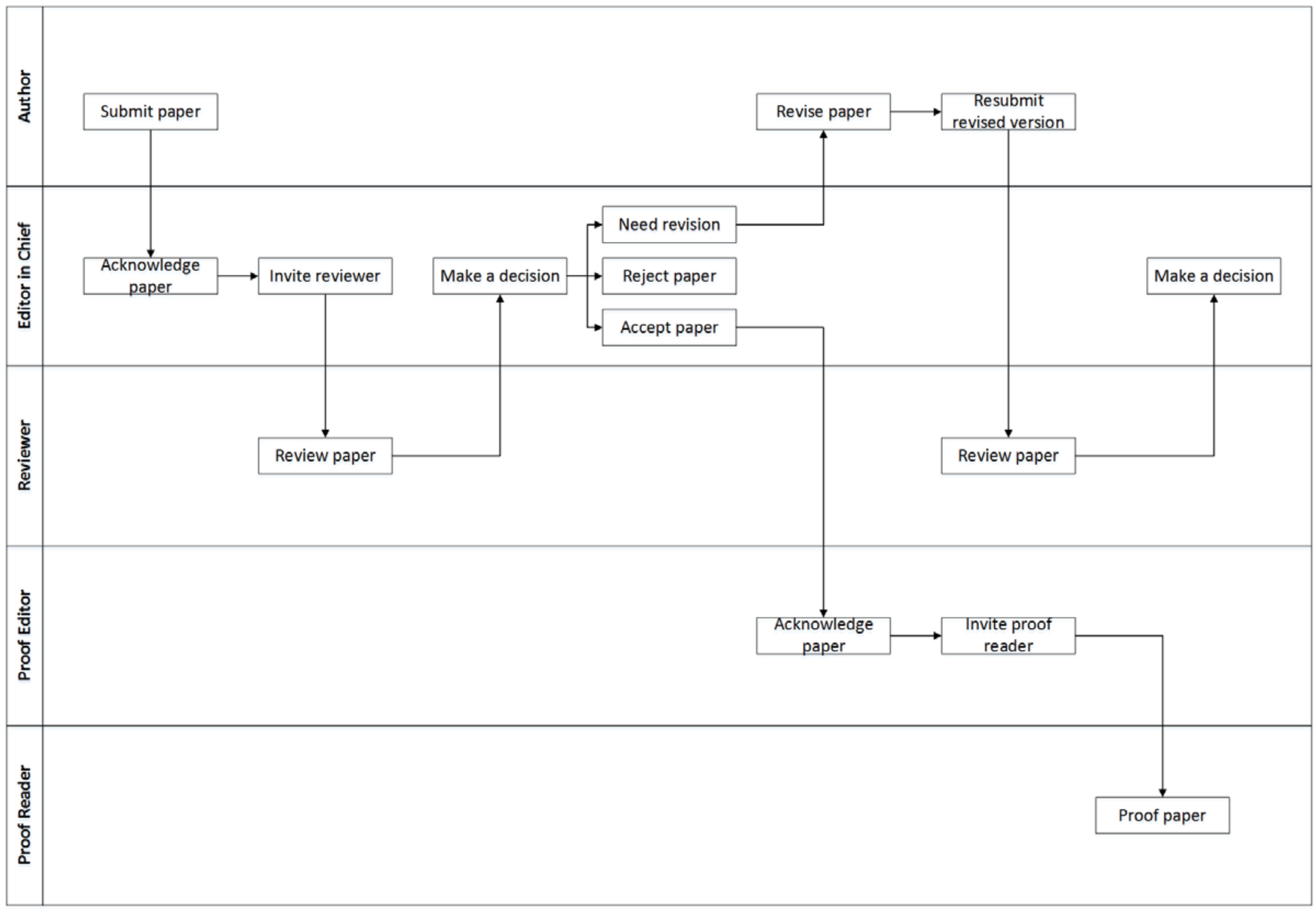



Figure 4.3: Overview of the workflow of the JIDPS

During the use event, the system should manage and protect users personal information, papers and related files such as a papers pdf version, source file and reference library etc... Certain users like reviewers and editors can comment on related papers; editors can make decisions whether to accept or reject a paper; the system should send internal user messages and external notifications to users when there is any news for them, like new task invitations, decision about related papers etc... Users can also send task invitations and invitations to people that are not yet registered in the system. Moreover, users may encounter problems or have suggestions regarding to the system, so the system should also be able to collect user feedback. During the maintain event in the products lifecycle, the system should be improved regarding to the feedback collected in the use event, meanwhile, all the new data should be backed up regularly to avoid losing data due to unexpected issues. As for natural laws, service software is not like concrete products such as motorcycle and aircraft. It does not involve many components that can pose constraints on it, but there is still one, that is time. So the system should record timestamps of related actions and status changes.

After the analysis of web development lifecycle, the ROM diagram can be updated by merging all the new information collected (Figure 4.4).

All the boxes in red contain all the verbs. In order to find what are the desired product behaviors, the all the subject-verb-object (SVO) patterns should be extracted from the ROM diagram. While an SVO with prepositions indicating the means should not be included because it is a higher level summary of behaviors that are specified by the indicated means. For instance: the system manages the editorial workflow by managing users, user roles After defining the product behaviors, the requirements can be defined by reformulating those behaviors, then recorded formally by putting them into the requirement section in a HOQ (Table 4.3).

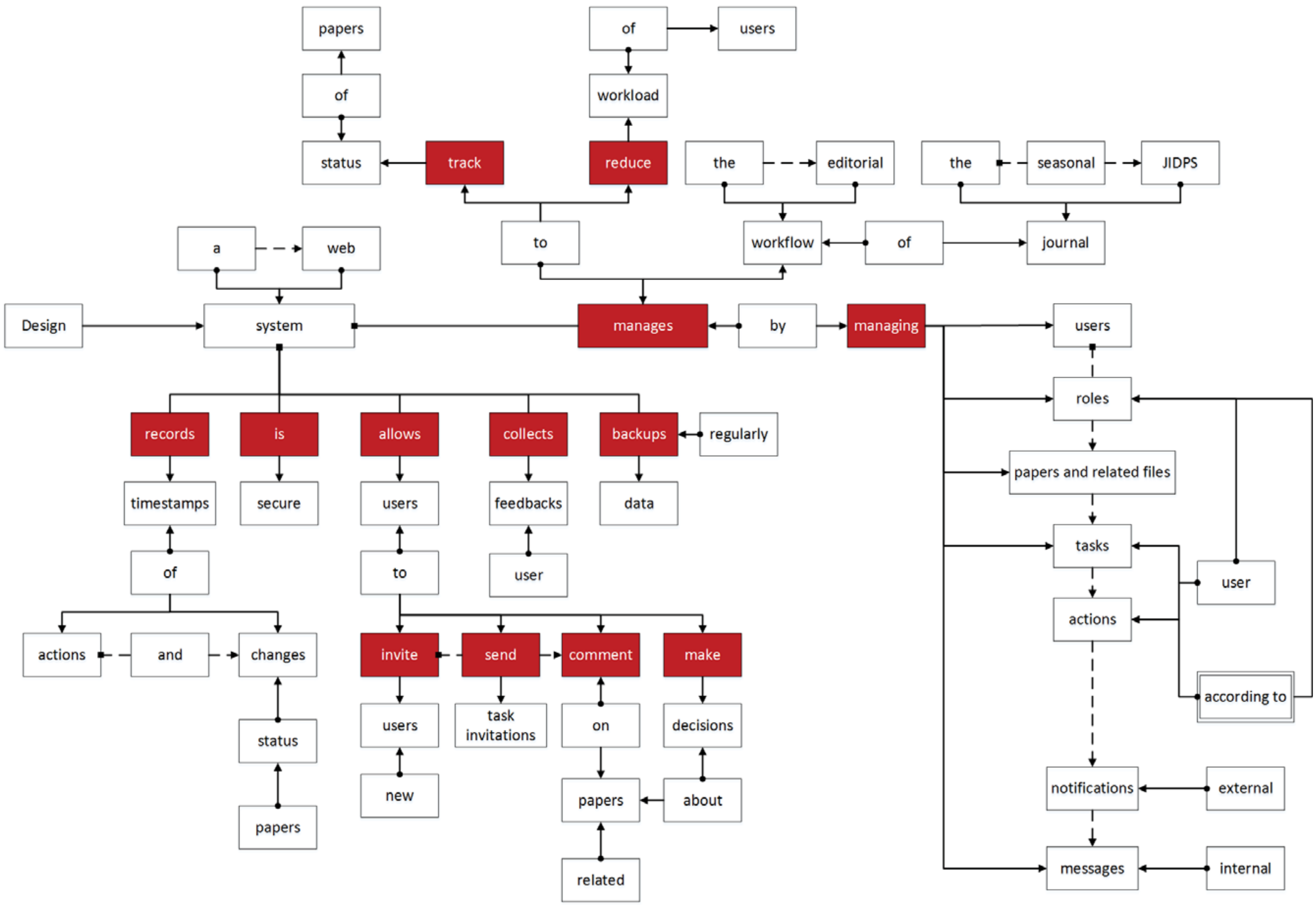



Figure 4.4: Updated ROM diagram after domain-specific question asking

Table 4.3: Customer requirements

| | CR | Importance |
|---|---|---|
| 1 | The system shall manage users | |
| 2 | The system shall manage user roles | |
| 3 | The system shall manage papers and related files | |
| 4 | The system shall manage user tasks | |
| 5 | The system shall manage user actions according to user roles | |
| 6 | The system shall manage internal notifications | |
| 7 | The system shall manage external notifications | |
| 8 | The system shall reduce user workload | |
| 9 | The system shall be secure | |
| 10 | The system shall collect user feedbacks | |
| 11 | The system shall backup data regularly | |
| 12 | The system shall record timestamps of actions and paper status changes | |

**Requirement prioritization**

Applying AHP to prioritize customer requirements requires to construct the problem hierarchy first. Because this is a non-profit web service with very limited human resource (mainly the students), cost and human resource are usually two great constraints in its development. While it is not a very big project, the problem hierarchy and the pairwise comparison tables are shown below. Due to the limited space here, all the normalized comparison matrixes for the final alternatives are recorded in the appendix A. According to the rules described in the methodology chapter, the ideal mode should be applied when choosing a best alternative among a set of similar options, while the distributive mode should be used when the uniqueness of an alternative needs to be considered. For this project, the different requirements need to be prioritized considering the limited resources, hence, the distributive mode of synthesis is chosen to synthesis the results.

The problem hierarchy for this web system is shown below. The tree main concerns: time, cost and quality are listed as the three criteria considered on the first level, with the

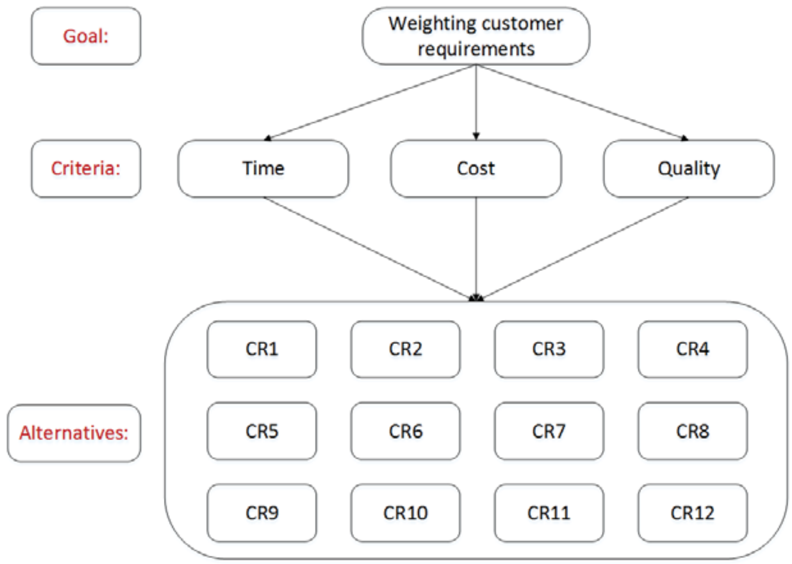



Figure 4.5: Hierarchy for weighting customer requirements

CRs listed as alternatives to be weighted and ranked with regard to these criteria. The first pairwise comparison is conducted for the criteria with regard to the main goal: weighting customer requirements, see the pairwise comparison in Table 4.4 and the normalized one in Table 4.5 with the final importance calculated. The rest comparisons for the CRs are done in the same manner, each followed by a consistency test for judgement verification.

Table 4.4: Pairwise comparison matrix of criteria with respect to the goal

| Goal | Time | Cost | Quality |
|---|---|---|---|
| Time | 1 | 1/7 | 1/9 |
| Cost | 7 | 1 | 1/3 |
| Quality | 9 | 3 | 1 |

Although the weight of each criteria has already been calculated at this step, a consistency test has to be conducted as it is described in the methodology chapter, to ensure the transitiveness of the judgement. Hence, by using the Eq.3, the Consistency Ratio of this pairwise comparison is

$ConsictencyRatio = 7.01\%$

Table 4.5: Normalized pairwise comparison matrix of criteria with respect to the goal

| Goal | Time | Cost | Quality | Criteria Weight | Rank |
|---|---|---|---|---|---|
| Time | 0.058824 | 0.034483 | 0.076923 | 0.056743 | 3 |
| Cost | 0.411765 | 0.241379 | 0.230769 | 0.294638 | 2 |
| Quality | 0.529412 | 0.724138 | 0.692308 | 0.648619 | 1 |
| Sum | 1 | 1 | 1 | 1 | |

The ratio is lower than 10%, which is to say that the rank is a consistent reflection of the importance of this set of criteria. Therefore, we can say for sure that the quality of the product is the most important criteria, cost is the second, and time is the least important criteria for this particularly project.

After comparing these three criteria, a pairwise comparison for the alternatives with respect to each criteria should also be conducted. First, pairwise comparison among all the specified requirements with respect to the time criteria was conducted. The pairwise comparison matrix with respect to the time criteria is in Table 4.6, and the importance rate of the CRs regarding to time are shown in Table 4.7.

Similarly, to determine if the comparison is based on transitive judgements, the consistency test was carried out. And the calculated consistency ratio is

$ConsistencyRatio = 7.57\%$

That is to say, the importance rank of the requirements with respect to the time criteria is acceptable. So from the result we know that security is the most important requirement because the system will collects researchers personal information and their paper manuscripts, which makes the importance of security quite obvious. And the second important CRs are CR1 and CR2, managing users and their roles, which are two very fundamental requirements for the editorial workflow to be able to proceed.

Same to the above process, the pairwise comparison with respect to the cost criteria was conducted. The following Table 4.8 is the comparison matrix. The calculated weight

Table 4.6: Pairwise comparison with respect to time

| Time | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 | CR8 | CR9 | CR10 | CR11 | CR12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CR1 | 1 | 1 | 1 | 1 | 3 | 5 | 7 | 1/3 | 7 | 7 | 1 | 3 |
| CR2 | 1 | 1 | 1 | 1 | 3 | 5 | 7 | 1/3 | 7 | 7 | 1 | 3 |
| CR3 | 1 | 1 | 1 | 1 | 1 | 5 | 7 | 1/3 | 7 | 7 | 1 | 3 |
| CR4 | 1 | 1 | 1 | 1 | 1 | 5 | 7 | 1/3 | 5 | 5 | 1 | 3 |
| CR5 | 1/3 | 1/3 | 1 | 1 | 1 | 5 | 7 | 1/3 | 5 | 5 | 1 | 3 |
| CR6 | 1/5 | 1/5 | 1/5 | 1/5 | 1/5 | 1 | 1/2 | 1/8 | 3 | 4 | 1/3 | 3 |
| CR7 | 1/5 | 1/5 | 1/5 | 1/5 | 1/5 | 1 | 1/2 | 1/8 | 3 | 4 | 1/3 | 3 |
| CR8 | 1/7 | 1/7 | 1/7 | 1/7 | 1/7 | 2 | 1 | 1/9 | 4 | 6 | 1/5 | 3 |
| CR9 | 3 | 3 | 3 | 3 | 3 | 8 | 9 | 1 | 9 | 4 | 3 | 7 |
| CR10 | 1/7 | 1/7 | 1/7 | 1/5 | 1/5 | 1/3 | 1/4 | 1/9 | 1 | 2 | 1/4 | 2 |
| CR11 | 1/7 | 1/7 | 1/7 | 1/5 | 1/5 | 1/4 | 1/6 | 1/4 | 1/2 | 1 | 1/4 | 2 |
| CR12 | 1 | 1 | 1 | 1 | 1 | 3 | 5 | 1/3 | 4 | 4 | 1 | 3 |
| Sum | 9.161905 | 9.161905 | 9.828571 | 9.94286 | 13.9429 | 40.58333 | 51.4167 | 3.72222 | 55.5 | 56 | 10.366 | 38 |

Table 4.7: Importance rate of CRs from pairwise comparison with respect to time

| Time | Weight | Rank |
|---|---|---|
| CR1 | 0.121289053 | 2 |
| CR2 | 0.121289053 | 2 |
| CR3 | 0.109335501 | 4 |
| CR4 | 0.103356308 | 5 |
| CR5 | 0.091228795 | 6 |
| CR6 | 0.029057661 | 9 |
| CR7 | 0.029057661 | 9 |
| CR8 | 0.034725291 | 8 |
| CR9 | 0.236494486 | 1 |
| CR10 | 0.017430606 | 12 |
| CR11 | 0.017823919 | 11 |
| CR12 | 0.088911667 | 7 |

for each requirements are shown in Table 4.9. The most important requirement is still the security of the system and the second is the system shall reduce user workload. To determine if the judgement needs to be readjusted, the consistency ratio of this comparison is:

$ConsistencyRatio = 6.39\%$

The consistency ration is less than 10%, which is to say that the comparison is acceptable, and the result obtained can be used to calculate the final importance rate.

Finally, the pairwise comparison of requirements with respect to the quality criteria was conducted (Table 4.10), and the calculated weights and ranks are listed in Table 4.11. The consistency ratio of this comparison is

$ConsistencyRatio = 5.57\%$

The ratio is lower than 10%, which means the result is acceptable.

The final importance rates and ranks can be calculated by synthesis all the weights of the alternatives under each parent criteria. The final overall requirement priority ranks are calculated and listed in Table 4.12. From the table we can know that compared to other requirements, the security of the system is the most important requirement with a

Table 4.8: Pairwise comparison with respect to cost

| Cost | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 | CR8 | CR9 | CR10 | CR11 | CR12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CR1 | 1 | 1 | 1/2 | 1 | 1 | 1/3 | 1/3 | 1/4 | 1/7 | 5 | 5 | 1 |
| CR2 | 1 | 1 | 1/2 | 1 | 1 | 1/3 | 1/3 | 1/4 | 1/7 | 5 | 5 | 1 |
| CR3 | 2 | 2 | 1 | 2 | 2 | 1/2 | 1/2 | 1/3 | 1/5 | 7 | 7 | 2 |
| CR4 | 1 | 1 | 1/2 | 1 | 1 | 1/3 | 1/3 | 1/4 | 1/7 | 5 | 5 | 1 |
| CR5 | 1 | 1 | 1/2 | 1 | 1 | 1/3 | 1/3 | 1/4 | 1/7 | 5 | 5 | 1 |
| CR6 | 3 | 3 | 2 | 3 | 3 | 1 | 1 | 1/3 | 1/6 | 3 | 3 | 3 |
| CR7 | 3 | 3 | 2 | 3 | 3 | 1 | 1 | 1/3 | 1/6 | 3 | 3 | 3 |
| CR8 | 4 | 4 | 3 | 4 | 4 | 3 | 3 | 1 | 1/7 | 7 | 7 | 4 |
| CR9 | 7 | 7 | 5 | 7 | 7 | 6 | 6 | 7 | 1 | 9 | 9 | 5 |
| CR10 | 1/5 | 1/5 | 1/7 | 1/5 | 1/5 | 1/3 | 1/3 | 1/7 | 1/9 | 1 | 1 | 1/5 |
| CR11 | 1/5 | 1/5 | 1/7 | 1/5 | 1/5 | 1/3 | 1/3 | 1/7 | 1/9 | 1 | 1 | 1/5 |
| CR12 | 1 | 1 | 1/2 | 1 | 1 | 1/3 | 1/3 | 1/4 | 1/5 | 5 | 5 | 1 |
| Sum | 24.4 | 24.4 | 15.78571 | 24.4 | 24.4 | 13.83333 | 13.83333 | 10.53571 | 2.669841 | 56 | 56 | 22.4 |

Table 4.9: Importance rate of CRs from pairwise comparison with respect to cost

| Cost | Weight | Rank |
|---|---|---|
| CR1 | 0.045354353 | 7 |
| CR2 | 0.045354353 | 7 |
| CR3 | 0.075778448 | 5 |
| CR4 | 0.045354353 | 7 |
| CR5 | 0.045354353 | 7 |
| CR6 | 0.09151783 | 3 |
| CR7 | 0.09151783 | 3 |
| CR8 | 0.154709359 | 2 |
| CR9 | 0.326279724 | 1 |
| CR10 | 0.015820728 | 11 |
| CR11 | 0.015820728 | 11 |
| CR12 | 0.047137944 | 6 |

significantly high weight; reducing user workload is the second important and managing user action according to user roles is the third. While collecting user feedback, backing up data and exception control are the least important ones.

However, the result does not mean that the requirements with lower ranks are not important. It means with all considerations and limitations posed by the criteria, the requirements with higher ranks are relatively more important. Of course, all the requirements should be met at 100% in order to achieve the maximum customer satisfaction or even to exceed customer expectations. After prioritizing the requirements, the requirement section in HOQ is completed, as it is illustrated in Figure 4.6. And the QFD-oriented product development process can proceed to the next step.

### 4.2.2 Conceptual design

Customer requirements can be of variety for numerous reasons. What they require can be very general like the product should be easy to use, reliable, secure etc., or very specific such as: the product should be 10 meters long, 5 meters high with a tolerance of $\pm 0.05$

Table 4.10: Pairwise comparison with respect to quality

| Quality | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 | CR8 | CR9 | CR10 | CR11 | CR12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CR1 | 1 | 1 | 1 | 1 | 1/3 | 3 | 3 | 1/5 | 1/9 | 3 | 3 | 1 |
| CR2 | 1 | 1 | 1 | 1 | 1/3 | 3 | 3 | 1/5 | 1/9 | 3 | 3 | 1 |
| CR3 | 1 | 1 | 1 | 1 | 1/3 | 3 | 3 | 1/5 | 1/9 | 3 | 3 | 1 |
| CR4 | 1 | 1 | 1 | 1 | 1/3 | 3 | 3 | 1/5 | 1/9 | 3 | 3 | 1 |
| CR5 | 3 | 3 | 3 | 3 | 1 | 5 | 5 | 1 | 1/9 | 5 | 5 | 3 |
| CR6 | 1/3 | 1/3 | 1/3 | 1/3 | 1/5 | 1 | 1 | 1/3 | 1/9 | 1 | 3 | 1/3 |
| CR7 | 1/3 | 1/3 | 1/3 | 1/3 | 1/5 | 1 | 1 | 1/3 | 1/9 | 1 | 3 | 1/3 |
| CR8 | 5 | 5 | 5 | 5 | 1 | 3 | 3 | 1 | 1/9 | 9 | 9 | 3 |
| CR9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 1 | 9 | 9 | 9 |
| CR10 | 1/3 | 1/3 | 1/3 | 1/3 | 1/5 | 1 | 1 | 1/9 | 1/9 | 1 | 2 | 1/3 |
| CR11 | 1/3 | 1/3 | 1/3 | 1/3 | 1/5 | 1/3 | 1/3 | 1/9 | 1/9 | 1/2 | 1 | 1/3 |
| CR12 | 1 | 1 | 1 | 1 | 1/3 | 3 | 3 | 1/3 | 1/9 | 3 | 3 | 1 |
| Sum | 23.33333 | 23.33333 | 23.33333 | 23.33333 | 13.46667 | 35.33333 | 35.33333 | 13.02222 | 2.222222 | 41.5 | 47 | 21.33333 |

Table 4.11: Importance rate of CRs from pairwise comparison with respect to quality

| Quality | Weight | Rank |
|---|---|---|
| CR1 | 0.051195389 | 5 |
| CR2 | 0.051195389 | 5 |
| CR3 | 0.051195389 | 5 |
| CR4 | 0.051195389 | 5 |
| CR5 | 0.11382031 | 3 |
| CR6 | 0.025645547 | 9 |
| CR7 | 0.025645547 | 9 |
| CR8 | 0.148082104 | 2 |
| CR9 | 0.390997171 | 1 |
| CR10 | 0.022450426 | 11 |
| CR11 | 0.016528707 | 12 |
| CR12 | 0.052048632 | 4 |

Table 4.12: Overall requirement priorities

| Alternatives | Time | Cost | Quality | Total | Rank |
|---|---|---|---|---|---|
| | 0.056743 | 0.294638 | 0.648619 | | |
| CR1 | 0.121289 | 0.045354 | 0.051195 | 0.053452 | 5 |
| CR2 | 0.121289 | 0.045354 | 0.051195 | 0.053452 | 5 |
| CR3 | 0.109336 | 0.075778 | 0.051195 | 0.061738 | 4 |
| CR4 | 0.103356 | 0.045354 | 0.051195 | 0.052434 | 8 |
| CR5 | 0.091229 | 0.045354 | 0.11382 | 0.092366 | 3 |
| CR6 | 0.029058 | 0.091518 | 0.025646 | 0.045248 | 9 |
| CR7 | 0.029058 | 0.091518 | 0.025646 | 0.045248 | 9 |
| CR8 | 0.034725 | 0.154709 | 0.148082 | 0.143603 | 2 |
| CR9 | 0.236494 | 0.32628 | 0.390997 | 0.363162 | 1 |
| CR10 | 0.017431 | 0.015821 | 0.02245 | 0.020212 | 11 |
| CR11 | 0.017824 | 0.015821 | 0.016529 | 0.016394 | 12 |
| CR12 | 0.088912 | 0.047138 | 0.052049 | 0.052693 | 7 |
| Sum | 1 | 1 | 1 | 1 | |

| | | | Imp. | Rank |
|---|---|---|---|---|
| Customer Requirements | CR1 | The system shall manage users | 5.35% | 5 |
| | CR2 | The system shall manage user roles | 5.35% | 5 |
| | CR3 | The system shall manage papers and related files | 6.17% | 4 |
| | CR4 | The system shall manage user tasks | 5.24% | 8 |
| | CR5 | The system shall manage user actions according to user roles | 9.24% | 3 |
| | CR6 | The system shall manage internal messages | 4.53% | 9 |
| | CR7 | The system shall manage external notifications | 4.53% | 9 |
| | CR8 | The system shall reduce user workload | 14.36% | 2 |
| | CR9 | The system shall be secure | 36.32% | 1 |
| | CR10 | The system shall collect user feedbacks | 2.02% | 11 |
| | CR11 | The system shall backup data regularly | 1.64% | 12 |
| | CR12 | The system shall record timestamps of actions and paper status changes | 5.27% | 7 |

Figure 4.6: Requirement section in HOQ for JIDPS web development

cm. To cope with the CR variety to understand the overlaps and relationships among the CRs, it is very important to build up the CR hierarchy and further decompose them onto a functional level, which is the mapping process between the CR domain and FR domain in Axiomatic Design.

Some of the CRs gathered above using EBD are already on the functional level, while some are not. CR8 and CR9 are more general which require more levels of decomposition. While others can already be seen as the highest level FR that can be further decomposed onto sub FR levels. Due to the limited space, the sub requirements of CR5 are merged into subcategories according to different user roles, and only the important role: user/author, editor in chief, reviewer, proof editor, proof reader and web administrator in the workflow are analysed here. Functional requirements for other roles such as: handling editor, associate editor and guest editor that are similar to editor in chief, can be easily identified once the FRs for editor in chief are clarified. And there is a similar relation between regular papers and papers for the special issue.

In the HOQ of this phase, we can see that the conceptual design of this case is a decoupled design. The FRs at the end level are the input for the embodiment design phase.

### 4.2.3 Embodiment design

In embodiment design, design has been to a more technical level. For a web development problem, it means the process starts to involve the programming knowledge and concepts. There are numbers of web development framework, for instance: Python Django using Python; Ruby on Rails using Ruby; .Net using C#; Spring, Spark, Play etc. all using Java. While in terms of the software architectural pattern, they are all using the Model-View-Controller pattern no matter how it is defined exactly in the frameworks. Model is the central component that expresses the systems behaviour in terms of the problem domain. View is the representation of the information, such as a web page. And controller defines the logic of when and how to render the models to be presented in the views. Hence, in this design problem, we are only considering the models. Views and controllers that are needed can be easily identified once the models are defined.

As we can see that the implementation of FRs for the security criteria are not directly related to the design and architecture of this web application and they can be achieved completely independently. Hence the following analysis focuses only on how to realize the proposed functionality of this system from an object-oriented programming perspective.

We already obtained CRs and FRs from the previous section, the importance rate of the FRs can be calculated according to the importance rate of their corresponding parent CRs. And it is assumed that all FRs of a CR are equally important, therefore the importance rate of a FR is

$$IR_{FR_i} = \sum \frac{IR_{CR}}{n}$$

Where the $IR_{CR}$ is the importance rate of CR (the parent of $FR_i$); and n is the number

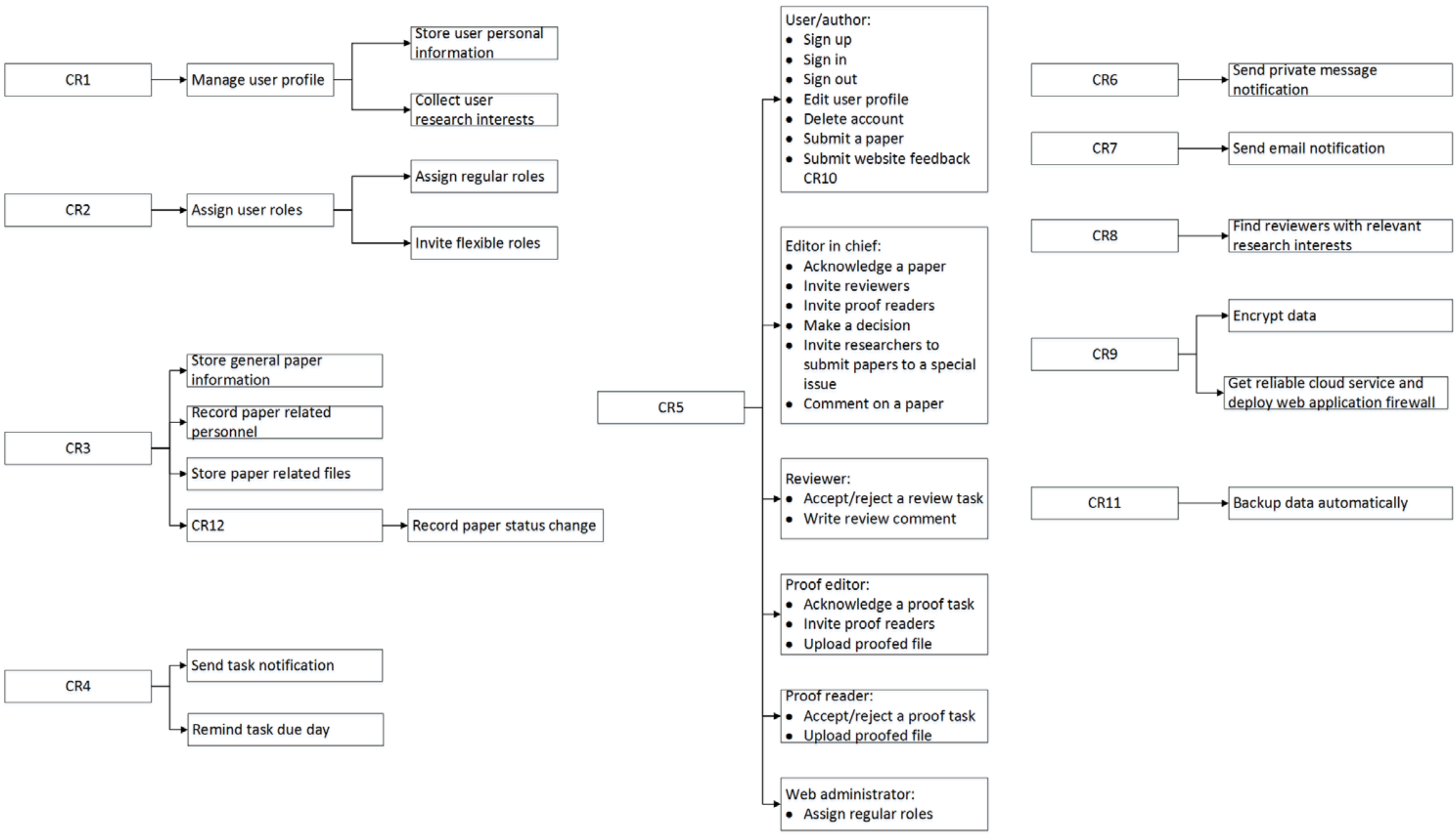
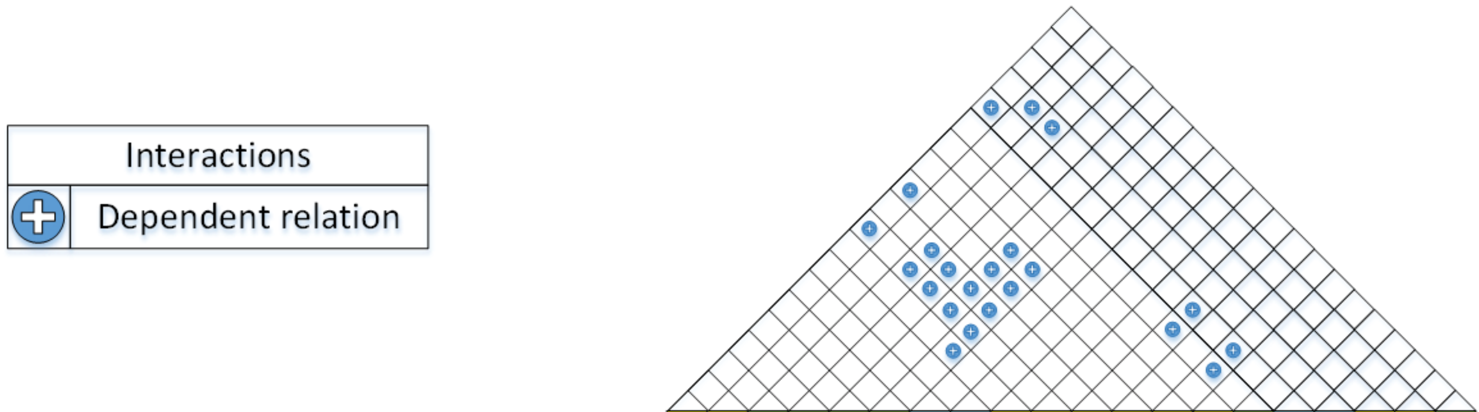



Figure 4.7: Functional requirement for JIDPS




| | | | Imp. | Rank | Store personal information | Collect research interests | Store general paper information | Record related personnel | Store related files | Record status change | Send task notification | Remind task due day | User/author actions | Editor in chief actions | Reviewer actions | Proof editor actions | Proof reader actions | Web administrator action | Send private message notification | Send email notification | Find reviewers with relevant research interests | Encrypt data | Get reliable cloud service and deploy WAF | Backup data automatically |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Customer Requirements | CR1 | The system shall manage users | 5.35% | 5 | X | X | | | | | | | | | | | | | | | | | | |
| | CR2 | The system shall manage user roles | 5.35% | 5 | | | | | | | | | | X | | X | | X | | | | | | |
| | CR3 | The system shall manage papers and related files | 6.17% | 4 | | | X | X | X | X | | | | | | | | | | | | | | |
| | CR4 | The system shall manage user tasks | 5.24% | 8 | | | | | | | X | X | | | | | | | | | | | | |
| | CR5 | The system shall manage user actions according to user roles | 9.24% | 3 | | | | | | | | | X | X | X | X | X | X | | | | | | |
| | CR6 | The system shall manage internal messages | 4.53% | 9 | | | | | | | | | | | | | | | X | | | | | |
| | CR7 | The system shall manage external notifications | 4.53% | 9 | | | | | | | | | | | | | | | | X | | | | |
| | CR8 | The system shall reduce user workload | 14.36% | 2 | | | | | | | | | | | | | | | | | X | | | |
| | CR9 | The system shall be secure | 36.32% | 1 | | | | | | | | | | | | | | | | | | X | X | |
| | CR10 | The system shall collect user feedbacks | 2.02% | 11 | | | | | | | | | X | | | | | | | | | | | |
| | CR11 | The system shall backup data regularly | 1.64% | 12 | | | | | | | | | | | | | | | | | | | | X |
| | CR12 | The system shall record timestamps of actions and paper status changes | 5.27% | 7 | | | | | | X | | | | | | | | | | | | | | |

Figure 4.8: Mapping between CRs and FRs in HOQ

of child FRs of that CR. Therefore, each FR is assigned an equal portion of the importance of its parent CR (Table 4.13).

Table 4.13: CRs and corresponding FRs

| | | | |
|---|---|---|---|
| CR1 (5.35%) | FR1<br>FR2 | CR6 (4.53%) | FR15 |
| CR2 (5.35%) | FR10<br>FR12<br>FR14 | CR7 (4.53%) | FR16 |
| CR3 (6.17%) | FR3<br>FR4<br>FR5<br>FR6 | CR8 (14.36%) | FR17 |
| CR4 (5.24%) | FR7<br>FR8 | CR12 (5.27%) | FR6 |
| CR5 (9.24%) | FR9<br>FR10<br>FR11<br>FR12<br>FR13<br>FR14 | | |

The DPs in this phase is the preliminary function to meet the FRs defined in the previous phase. In order to define the DPs for this web system, the classes needed in the system are identified first, like in Table 4.14. The five roles are defined as class separately to distinguish different actions each role can perform. The user class should be the base class of others and the default role of a user is the author role because every user can submit a paper. Each task invitation is associated with a task and a task performer will be assigned to it after he/she accepts the invitation. Only after identifying the classes can we further layout the functions that can meet the FRs.

Figure 4.9 is the HOQ for the embodiment design phase. Each function under a certain class is meant to fulfil a specific FR in the requirement section of the HOQ. For instance, a user can submit a paper using the system, and the function submitPaper under the user

Table 4.14: Identified classes and their descriptions

| Class | Description |
|---|---|
| User/Author | User class containing user attributes and behaviours. Author is the default role for every user |
| Paper | Paper class that containing paper attributes and functions |
| EditorInChief | Editor in chief class containing the functions for actions of editors in chief |
| Reviewer | Reviewer class containing the functions for actions of reviewers |
| ProofEditor | Proof editor class containing the functions for actions of proof editors |
| ProofReader | Proof reader class containing the functions for actions of proof readers |
| Administrator | Administrator class containing the functions for actions of administrator who has the top priority in the system accessing to sitefeedback, users and papers |
| Task | Task class containing information for review and proof tasks |
| Message | Message class containing message text, attributes and functions |
| Invitation | Invitation class containing invitation attributes and functions |
| Notifier | Notifier class containing the functions for sending messages and invitations |
| Comment | Comment class containing comment attributes and functions |
| SiteFeedback | Site feedback class containing site feedback attributes and functions |

class is to meet this particular FR. The attributes are not listed in full due to the space limitation. Some classes are not in the HOQ because in this phase, only the main functions are specified to show that the requirements from the conceptual design phase are met successfully. From the figure, the links between the conceptual phase and the embodiment phase are clearly showed. We can see in the HOQ, according to the independence axiom, this is a decoupled design.

With Figure 4.9, the architecture of the model has already been laid out preliminarily. In order to illustrate the classes and their relationships, a corresponding class diagram, see Figure 4.10, is created using the Unified Modeling Language (UML) according to the above HOQ. In a class diagram, there are several basic relationships between two classes: dependency, association, aggregation, composition, inheritance. A brief introduction to UML is provided in Appendix B. In this class diagram, only aggregation relationship is shown because the diagram would be a mess with all the relationships included.

In this preliminary class diagram, all the attributes and functions listed in the HOQ are covered and put in the right class with necessary input parameters. With this preliminary layout, the architecture of the model of the system has become more definitive. Therefore, the framework can now proceed to the next detail design phase.

### 4.2.4 Detail design

With the layout from the embodiment design and the functions that have to be delivered to meet the FRs obtained in the conceptual design as well as the CRs defined in the planning phase, in detail design, all the necessary supporting definitions, functions, input parameters and outputs have to be defined. After finishing the detail design, the design has been narrowed down so that only minor changes may occur in the implementation process, or in software industry the coding and configuration stage.

To provide a brief illustration while avoiding going into too much programming detail,

| Functional Requirements | | | Imp. | Attribute.: User.FirstName, LastName etc... | Attribute: User.ResearchInterests | Attribute: Paper.Title, Abstract, Keywords etc... | Attribute: Paper.EditorInChief, Reviewers etc... | Attribute: Paper.UserSubmissionFile, RevisedFile, ProofedFile etc... | Attribute: Paper.Status | Fun.: Invitation.Invitation() | Fun.: Notifier.remindTaskDue() | Fun.: User.User() | Fun.: User.authenticate() | Fun.: User.signOut() | Fun.: User.editProfile() | Fun.: User.deleteAccount() | Fun.: User.submitPaper() | Fun.: User.submitFeedback() | Fun.: EditorInChief.acknowledgePaper() | Fun.: EditorInChief.inviteReviewers() | Fun.: EditorInChief.inviteProofReaders() | Fun.: EditorInChief.makeDecision() | Fun.: EditorInChief.invitePaperSubmission() | Fun.: EditorInChief.commentOnPaper() | Fun.: User.acceptReviewInvitation() | Fun.: User.declineReviewInvitation() | Fun.: Reviewer.commentOnPaper() | Fun.: ProofEditor.acknowledgeProofTask() | Fun.: ProofEditor.inviteProofReaders() | Fun.: ProofEditor.commentOnPaper() | Fun.: User.uploadFile() | Fun.: User.acceptProofInvitation() | Fun.: User.declineProofInvitation() | Fun.: Administrator.assignUserRole() | Fun.: Notifier.sendPrivateMessage() | Fun.: Notifier.sendEmail & Message () | Fun.: Reviewer.findReviewers() |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FR1 | | Store user personal information | 2.68 % |X| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| FR2 | | Collect user research interests | 2.68 % | |X| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| FR3 | | Store general paper information | 0.67 % | | |X| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| FR4 | | Record paper related personnel | 0.67 % | | | |X| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| FR5 | | Store paper related files | 0.67 % | | | | |X| | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| FR6 | | Record paper status change | 5.94 % | | | | | |X| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| FR7 | | Send task invitation | 2.62 % | | | | | | |X| | | | | | | | | | | | | | | | | | | | | | | | |X|X| |
| FR8 | | Remind task due day | 2.62 % | | | | | | | |X| | | | | | | | | | | | | | | | | | | | | | | | | | |
| FR9 | User/author actions | Sign up | 1.54 % | | | | | | | | |X| | | | | | | | | | | | | | | | | | | | | | | | | |
| | | Sign in | | | | | | | | | | |X| | | | | | | | | | | | | | | | | | | | | | | | |
| | | Sign out | | | | | | | | | | | |X| | | | | | | | | | | | | | | | | | | | | | | |
| | | Edit profile | | | | | | | | | | | | |X| | | | | | | | | | | | | | | | | | | | | | |
| | | Delete account | | | | | | | | | | | | | |X| | | | | | | | | | | | | | | | | | | | | |
| | | Submit a paper | | | | | | | | | | | | | | |X| | | | | | | | | | | | | | | | | | | | |
| | | Submit website feedback | | | | | | | | | | | | | | | |X| | | | | | | | | | | | | | | | | | | |
| FR10 | Editor in chief actions | Acknowledge a paper | 3.32 % | | | | | | | | | | | | | | | |X| | | | | | | | | | | | | | | | | | |
| | | Invite reviewers | | | | | | | | | | | | | | | | | |X| | | | | | | | | | | | | | | | | |
| | | Invite proof readers | | | | | | | | | | | | | | | | | | |X| | | | | | | | | | | | | | | | |
| | | Make a decision | | | | | | | | | | | | | | | | | | | |X| | | | | | | | | | | | | | | |
| | | Invite researchers to submit papers | | | | | | | | | | | | | | | | | | | | |X| | | | | | | | | | | | | | |
| | | Comment on a paper | | | | | | | | | | | | | | | | | | | | | |X| | | | | | | | | | | | | |
| FR11 | Reviewer actions | Accept a review task | 1.54 % | | | | | | | | | | | | | | | | | | | | | |X| | | | | | | | | | | | |
| | | Decline a review task | | | | | | | | | | | | | | | | | | | | | | | |X| | | | | | | | | | | |
| | | Write review comment | | | | | | | | | | | | | | | | | | | | | | | | |X| | | | | | | | | | |
| FR12 | Proof editor actions | Acknowledge a proof task | 3.32 % | | | | | | | | | | | | | | | | | | | | | | | | |X| | | | | | | | | |
| | | Invite proof readers | | | | | | | | | | | | | | | | | | | | | | | | | | |X| | | | | | | | |
| | | Write proof comment to a paper | | | | | | | | | | | | | | | | | | | | | | | | | | | |X| | | | | | | |
| | | Upload proofed file | | | | | | | | | | | | | | | | | | | | | | | | | | | | |X| | | | | | |
| FR13 | Proof reader actions | Accept/reject a proof invitation | 1.54 % | | | | | | | | | | | | | | | | | | | | | | | | | | | |X| | | | | |
| | | Write proof comment to a paper | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |X| | | | |
| | | Upload proofed file | | | | | | | | | | | | | | | | | | | | | | | | | | | | |X| | | | | | |
| FR14 | Web administrator actions | Assign user roles | 3.32 % | | | | | | | | | | | | | | | | | | | | | | | | | | | | |X| | | |
| FR15 | | Send private message notification | 4.53 % | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |X| | |
| FR16 | | Send email notification | 4.53 % | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |X| |
| FR17 | | Find reviewers with relevant research interests | 14.36 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |X|

Figure 4.9: Functional requirements and their corresponding function in the system

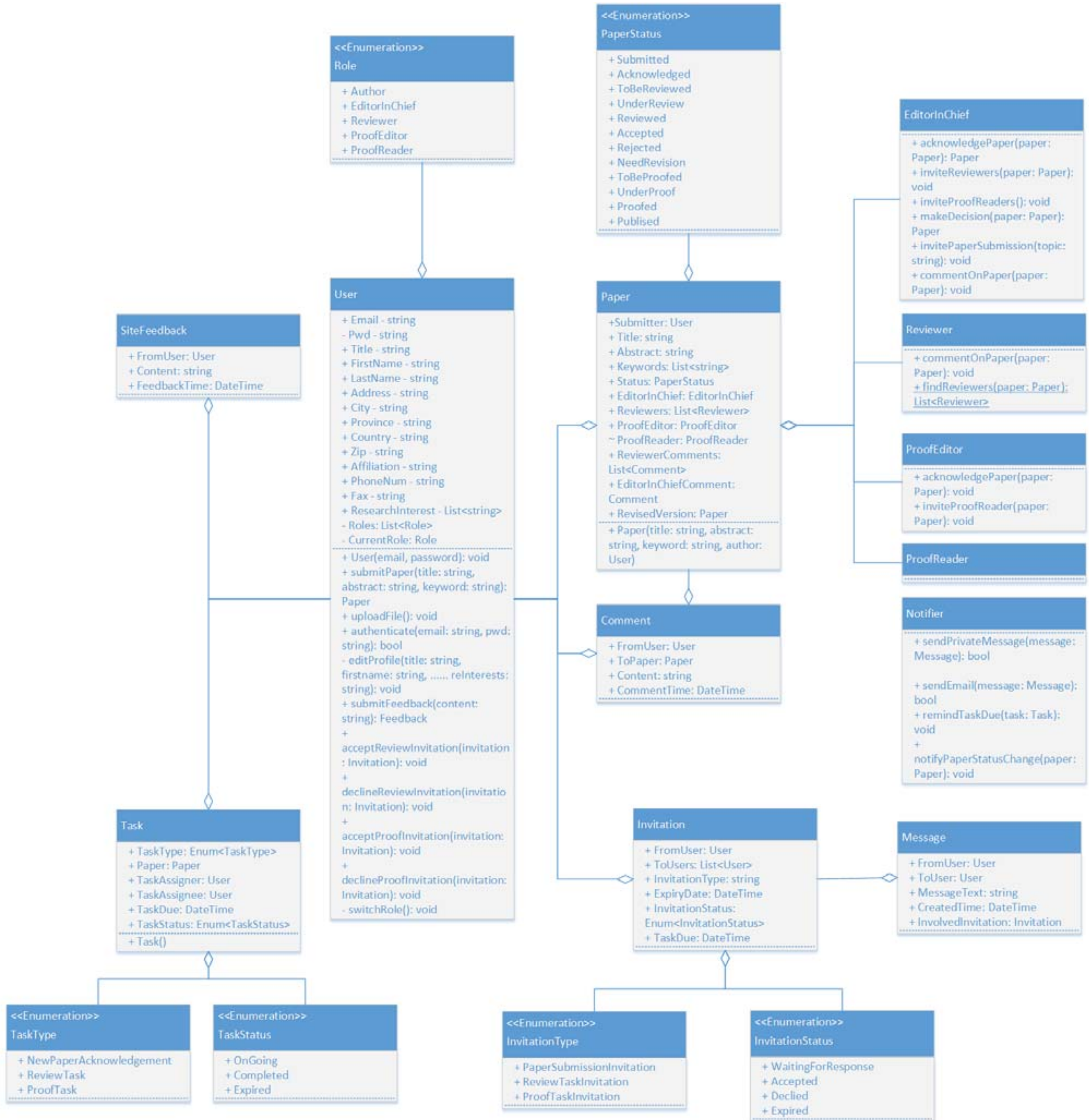



Figure 4.10: Preliminary class diagram

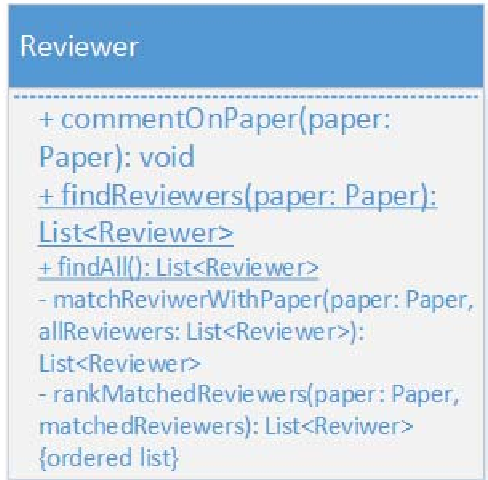



Figure 4.11: Reviewer class after adding supporting functions for invite reviewer function

take the use case where the editor in chief need to invite reviewers for a paper as an example. In order to be able to carry out this function, there are another 3 supporting functions needed.

1. Retrieve all reviewers:

+ Reviewer.findAll (): List<Reviewer>

2. Match paper keywords with reviewers according to research interests:

Reviewer.matchReviewerWithPaper (paper: Paper, allReviewers: List< Reviewer>): List<Reviewer>

3. Rank the matched reviewers from most relevant to least relevant:

Reviewer.rankMatchedReviewer (paper: Paper, matchedReviewers: List<Reviewer>): List<Reviewer> {ordered list}

Hence, the reviewer class should be like in Figure 4.11.

# Chapter 5

# Conclusion and Future Work

## 5.1 Conclusion

This thesis proposed a requirement-oriented product design framework based on QFD, EBD, AHP and AD. By applying the framework, Customer requirements are analysed and captured using EBD in an interactive manner involving both customers and designers or engineers; different variables in different design phases are defined and linked together using the definition in AD to improve design traceability, which is of great help when change happens during any phase of the product design process; the AHP is integrated in the framework to prioritize requirements; and the AD provides an overall process to map design variables in different design domains.

Throughout the case study, a web system design has been carried out to the detail design phase and the links between different domains in terms of software engineering are established. The design in different phases were evaluated according to the independence axiom, so the framework procedure and its potential were illustrated.

## 5.2 Discussion

The proposed framework provides a general product design process. Therefore customization is important when dealing with different problems in different fields and industries. As per the case study, for software design, the detail design phase is not about shapes, materials etc. Because software does not have all these attributes. Hence, detail software design is to determine all the parameters and supporting functions for the main functions defined in the embodiment phase. But for any product design, the core idea is the same to keep track of how the customer requirements are met throughout the product design process.

Solution generation for each design phase requires knowledge from the specific field. Depending on the problem complexity and the characteristics of the field, the knowledge demand can vary significantly. Thus, how to acquire the right knowledge for the design problem at the right time is very important. The special characteristics of EBD make it a promising methodology to tackle this problem, which has been validated by Suo Tan et al. While EBD is a methodology that has its own ecosystem, so how it can be applied to guide information and knowledge acquisition not just in the planning phase can be an interesting topic. Apart from knowledge acquisition, the conflict identification can also be applied to help product development identify resource competition and missing resource in the design space. This is very similar to the contradiction identification in TRIZ, but more abstract and generic.

For AD, it is sometimes challenging to apply its two axioms especially in product design when there is no concrete parameter to meet the requirements, which means the requirements and solutions are qualitative rather than quantitative. In this case, the abstraction level of how they are defined and described can affect how they are meeting the independent axiom. Fuzzy set theory can be integrated to help to deal with the vagueness and imprecision. Lots of research has been done for multi-attribute selection, decision making and performance evaluation (Celik et al., 2009) (Kahraman & eb, 2009) (Kannan, Govindan, & Rajendran, 2015). Solution evaluation is actually a selection problem, fuzzy set theory can be combined with the information axiom to cope with the imprecise description of requirements and design, for instance applying the fuzzy information axiom to evaluate conceptual design (Akay, Kulak, & Henson, 2011).

To keep the process manageable, it is important to decompose a design problem to different sub areas which different sub teams are in charge of. Besides, software tools are surely needed, otherwise the process can be extremely time-consuming.

## 5.3 Future Work

The proposed framework only combines two methodologies for two HOQ sections in the QFD process. So in the future, other potential methodologies can be evaluated then integrated in this framework to help generating the information for other sections of an HOQ. For example: the TRIZ (theory of inventive problem solving) by S. D. Savransky (Savransky, 2000) to help in the solution generation process; the Decision-Based Design (W. Chen & Wassenaar, 2003) (Hazelrigg, 1998) for setting up target value for each solution.

In this particular case study, due to the special characteristics of software design that meeting one requirement is not probabilistic, the information axiom cannot be reflected in the case study. Therefore, a more complex case study for a more concrete design problem, for instance mechanical design, should be conducted to verify the capability of this framework, and with the information axiom applied to show how they are used in other product design problems.

Besides, algorithms for determining the importance of a set of solutions considering benchmarking information and target values can be developed. In this way, the framework will become more integrated and comprehensive.

# Appendix A

# Normalized Pairwise Comparisons for Customer Requirements

**Normalized pairwise comparison with respect to time**

| | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 | CR8 | CR9 | CR10 | CR11 | CR12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CR1 | 0.10915 | 0.10915 | 0.10174 | 0.10057 | 0.21516 | 0.1232 | 0.1232 | 0.13614 | 0.08955 | 0.12613 | 0.125 | 0.09646 |
| CR2 | 0.10915 | 0.10915 | 0.10174 | 0.10057 | 0.21516 | 0.1232 | 0.1232 | 0.13614 | 0.08955 | 0.12613 | 0.125 | 0.09646 |
| CR3 | 0.10915 | 0.10915 | 0.10174 | 0.10057 | 0.07172 | 0.1232 | 0.1232 | 0.13614 | 0.08955 | 0.12613 | 0.125 | 0.09646 |
| CR4 | 0.10915 | 0.10915 | 0.10174 | 0.10057 | 0.07172 | 0.1232 | 0.1232 | 0.13614 | 0.08955 | 0.09009 | 0.08929 | 0.09646 |
| CR5 | 0.03638 | 0.03638 | 0.10174 | 0.10057 | 0.07172 | 0.1232 | 0.1232 | 0.13614 | 0.08955 | 0.09009 | 0.08929 | 0.09646 |
| CR6 | 0.02183 | 0.02183 | 0.02035 | 0.02011 | 0.01434 | 0.02464 | 0.02464 | 0.00972 | 0.03358 | 0.05405 | 0.07143 | 0.03215 |
| CR7 | 0.02183 | 0.02183 | 0.02035 | 0.02011 | 0.01434 | 0.02464 | 0.02464 | 0.00972 | 0.03358 | 0.05405 | 0.07143 | 0.03215 |
| CR8 | 0.01559 | 0.01559 | 0.01453 | 0.01437 | 0.01025 | 0.04928 | 0.04928 | 0.01945 | 0.02985 | 0.07207 | 0.10714 | 0.01929 |
| CR9 | 0.32744 | 0.32744 | 0.30523 | 0.30172 | 0.21516 | 0.19713 | 0.19713 | 0.17504 | 0.26866 | 0.16216 | 0.07143 | 0.28939 |
| CR10 | 0.01559 | 0.01559 | 0.01453 | 0.02011 | 0.01434 | 0.00821 | 0.00821 | 0.00486 | 0.02985 | 0.01802 | 0.03571 | 0.02412 |
| CR11 | 0.01559 | 0.01559 | 0.01453 | 0.02011 | 0.01434 | 0.00616 | 0.00616 | 0.00324 | 0.06716 | 0.00901 | 0.01786 | 0.02412 |
| CR12 | 0.10915 | 0.10915 | 0.10174 | 0.10057 | 0.07172 | 0.07392 | 0.07392 | 0.09724 | 0.08955 | 0.07207 | 0.07143 | 0.09646 |
| Sum | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

**Pairwise comparison with respect to cost**

| | CR1 | CR2 | CR3 | CR4 | CR5 | CR6 | CR7 | CR8 | CR9 | CR10 | CR11 | CR12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CR1 | 0.040984 | 0.040984 | 0.031674 | 0.040984 | 0.040984 | 0.024096 | 0.024096 | 0.023729 | 0.053508 | 0.089286 | 0.089286 | 0.044643 |
| CR2 | 0.040984 | 0.040984 | 0.031674 | 0.040984 | 0.040984 | 0.024096 | 0.024096 | 0.023729 | 0.053508 | 0.089286 | 0.089286 | 0.044643 |
| CR3 | 0.081967 | 0.081967 | 0.063348 | 0.081967 | 0.081967 | 0.036145 | 0.036145 | 0.031638 | 0.074911 | 0.125 | 0.125 | 0.089286 |
| CR4 | 0.040984 | 0.040984 | 0.031674 | 0.040984 | 0.040984 | 0.024096 | 0.024096 | 0.023729 | 0.053508 | 0.089286 | 0.089286 | 0.044643 |
| CR5 | 0.040984 | 0.040984 | 0.031674 | 0.040984 | 0.040984 | 0.024096 | 0.024096 | 0.023729 | 0.053508 | 0.089286 | 0.089286 | 0.044643 |
| CR6 | 0.122951 | 0.122951 | 0.126697 | 0.122951 | 0.122951 | 0.072289 | 0.072289 | 0.031638 | 0.062426 | 0.053571 | 0.053571 | 0.133929 |
| CR7 | 0.122951 | 0.122951 | 0.126697 | 0.122951 | 0.122951 | 0.072289 | 0.072289 | 0.031638 | 0.062426 | 0.053571 | 0.053571 | 0.133929 |
| CR8 | 0.163934 | 0.163934 | 0.190045 | 0.163934 | 0.163934 | 0.216867 | 0.216867 | 0.094915 | 0.053508 | 0.125 | 0.125 | 0.178571 |
| CR9 | 0.286885 | 0.286885 | 0.316742 | 0.286885 | 0.286885 | 0.433735 | 0.433735 | 0.664407 | 0.374554 | 0.160714 | 0.160714 | 0.223214 |
| CR10 | 0.008197 | 0.008197 | 0.00905 | 0.008197 | 0.008197 | 0.024096 | 0.024096 | 0.013559 | 0.041617 | 0.017857 | 0.017857 | 0.008929 |
| CR11 | 0.008197 | 0.008197 | 0.00905 | 0.008197 | 0.008197 | 0.024096 | 0.024096 | 0.013559 | 0.041617 | 0.017857 | 0.017857 | 0.008929 |
| CR12 | 0.040984 | 0.040984 | 0.031674 | 0.040984 | 0.040984 | 0.024096 | 0.024096 | 0.023729 | 0.074911 | 0.089286 | 0.089286 | 0.044643 |
| Sum | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| Pairwise comparision with respect to quality | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **CR1** | **CR2** | **CR3** | **CR4** | **CR5** | **CR6** | **CR7** | **CR8** | **CR9** | **CR10** | **CR11** | **CR12** |
| **CR1** | 0.042857 | 0.042857 | 0.042857 | 0.042857 | 0.024752 | 0.084906 | 0.084906 | 0.015358 | 0.05 | 0.072289 | 0.06383 | 0.046875 |
| **CR2** | 0.042857 | 0.042857 | 0.042857 | 0.042857 | 0.024752 | 0.084906 | 0.084906 | 0.015358 | 0.05 | 0.072289 | 0.06383 | 0.046875 |
| **CR3** | 0.042857 | 0.042857 | 0.042857 | 0.042857 | 0.024752 | 0.084906 | 0.084906 | 0.015358 | 0.05 | 0.072289 | 0.06383 | 0.046875 |
| **CR4** | 0.042857 | 0.042857 | 0.042857 | 0.042857 | 0.024752 | 0.084906 | 0.084906 | 0.015358 | 0.05 | 0.072289 | 0.06383 | 0.046875 |
| **CR5** | 0.128571 | 0.128571 | 0.128571 | 0.128571 | 0.074257 | 0.141509 | 0.141509 | 0.076792 | 0.05 | 0.120482 | 0.106383 | 0.140625 |
| **CR6** | 0.014286 | 0.014286 | 0.014286 | 0.014286 | 0.014851 | 0.028302 | 0.028302 | 0.025597 | 0.05 | 0.024096 | 0.06383 | 0.015625 |
| **CR7** | 0.014286 | 0.014286 | 0.014286 | 0.014286 | 0.014851 | 0.028302 | 0.028302 | 0.025597 | 0.05 | 0.024096 | 0.06383 | 0.015625 |
| **CR8** | 0.214286 | 0.214286 | 0.214286 | 0.214286 | 0.074257 | 0.084906 | 0.084906 | 0.076792 | 0.05 | 0.216867 | 0.191489 | 0.140625 |
| **CR9** | 0.385714 | 0.385714 | 0.385714 | 0.385714 | 0.668317 | 0.254717 | 0.254717 | 0.691126 | 0.45 | 0.216867 | 0.191489 | 0.421875 |
| **CR10** | 0.014286 | 0.014286 | 0.014286 | 0.014286 | 0.014851 | 0.028302 | 0.028302 | 0.008532 | 0.05 | 0.024096 | 0.042553 | 0.015625 |
| **CR11** | 0.014286 | 0.014286 | 0.014286 | 0.014286 | 0.014851 | 0.009434 | 0.009434 | 0.008532 | 0.05 | 0.012048 | 0.021277 | 0.015625 |
| **CR12** | 0.042857 | 0.042857 | 0.042857 | 0.042857 | 0.024752 | 0.084906 | 0.084906 | 0.025597 | 0.05 | 0.072289 | 0.06383 | 0.046875 |
| **Sum** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

# Appendix B

# Unified Modeling Language (UML)

Table B.1 shows the visibility symbols and their descriptions.

Table B.1: Visibility symbols

| Symbol | Visibility | Description |
|---|---|---|
| $+$ | Public | Accessible to all |
| $-$ | Private | Can be called only in the class where defined |
| # | Protected | Class and subclasses can all access |
| $\sim$ | Package | Can be called within this project package |

Figure Appendix B.1 shows what are the components needed to define a method in a class diagram.

Figure Appendix B.2 shows the UML notations for relations between classes.

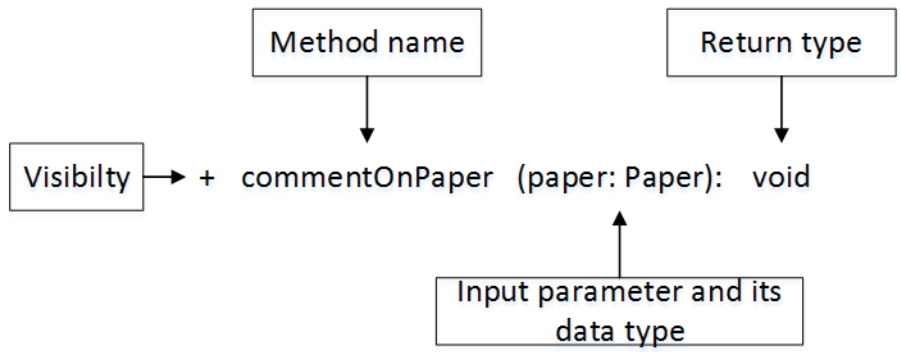



Figure B.1: Method representation in class diagram

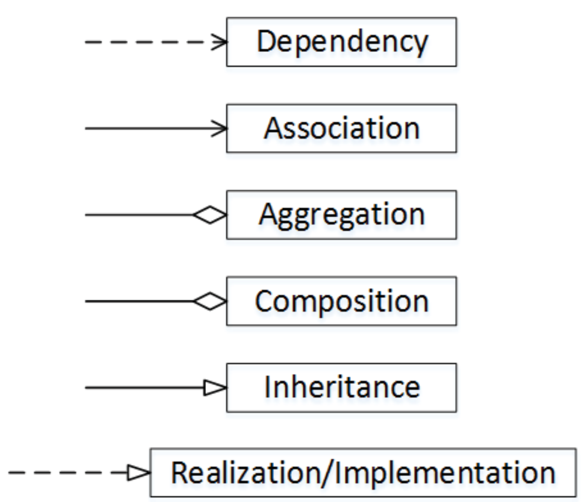



Figure B.2: UML relation notation

# References


Akao, Y., & Mazur, G. H. (2003). The leading edge in qfd: past, present and future. *International Journal of Quality & Reliability Management*, *20*(1), 20-35.

Akay, D., Kulak, O., & Henson, B. (2011). Conceptual design evaluation using interval type-2 fuzzy information axiom. *Computers in Industry*, *62*(2), 138-146.

Akman, S., zmut, M., Aydn, B., & Gktrk, S. (2016). Experience report: implementing requirement traceability throughout the software development life cycle. *Journal of Software: Evolution and Process*, *28*(11), 950-954.

Al-Karaghouli, W., AlShawi, S., & Elstob, M. (1999). Enhancing the understanding of customer requirements in business software engineering. *University of Westminster, Brunel University*.

Almannai, B., Greenough, R., & Kay, J. (2008). A decision support tool based on qfd and fmea for the selection of manufacturing automation technologies. *Robotics and Computer-Integrated Manufacturing*, *24*(4), 501-507.

Al-Tabtabai, H. M., & Thomas, V. P. (2004). Negotiation and resolution of conflict using ahp: an application to project management. *Engineering, Construction and Architectural Management*, *11*(2), 90-100.

Ashtiany, M. S., & Alipour, A. (2016). Integration axiomatic design with quality function deployment and sustainable design for the satisfaction of an airplane tail stakeholders. *Procedia CIRP*, *53*, 142-150.

Badri, M. A., & Abdulla, M. H. (2004). Awards of excellence in institutions of higher education: an ahp approach. *International Journal of Educational Management*, *18*(4), 224-242.

Bailetti, A. J., & Litva, P. F. (1995). Integrating customer requirements into product designs. *Journal of Product Innovation Management*, *12*(1), 3-15.

Barbarosoglu, G., & Yazgac, T. (1997). An application of the analytic hierarchy process to the supplier selection problem. *Production and inventory management journal*, *38*(1), 14.

Barklon, D., Wang, H., & Xu, X. (2014). Preliminary study on improving the efficiency of recruiting in a staffing agency using environment-based design methodology: Environment analysis. In *Innovative design and manufacturing (icidm), proceedings of the 2014 international conference on* (p. 276-281). IEEE.

Bertolini, M., & Bevilacqua, M. (2006). A combined goal programmingahp approach to maintenance selection problem. *Reliability Engineering & System Safety*, *91*(7), 839-848.

Bhattacharya, A., Sarkar*, B., & Mukherjee, S. K. (2005). Integrating ahp with qfd for robot selection under requirement perspective. *International journal of production research*, *43*(17), 3671-3685.

Bouchereau, V., & Rowlands, H. (2000). Methods and techniques to help quality function deployment (qfd). *Benchmarking: An International Journal*, *7*(1), 8-20.

Carnevalli, J. A., Miguel, P. A. C., & Calarge, F. A. (2010). Axiomatic design application for minimising the difficulties of qfd usage. *International Journal of Production Economics*, *125*(1), 1-12.

Celik, M., Cebi, S., Kahraman, C., & Er, I. D. (2009). An integrated fuzzy qfd model proposal on routing of shipping investment decisions in crude oil tanker market. *Expert Systems with Applications*, *36*(3), 6227-6235.

Chan, F. T., & Chan, H. K. (2010). An ahp model for selection of suppliers in the fast changing fashion market. *The International Journal of Advanced Manufacturing Technology*, *51*(9), 1195-1207.

Chan, L.-K., & Wu, M.-L. (2002). Quality function deployment: A literature review. *European journal of operational research*, *143*(3), 463-497.

Chaudha, A., Jain, R., Singh, A., & Mishra, P. (2011). Integration of kanos model into quality function deployment (qfd). *The International Journal of Advanced Manufacturing Technology*, *53*(5), 689-698.

Chen, D., Wang, X., Liu, W., Zeng, Y., & Chen, Z. (2015). Ebd extended analytic hierarchy process (ahp) approach to evaluating the effectiveness of engineering projects. *Journal of Integrated Design and Process Science*, *19*(2), 49-70.

Chen, M., Chen, Z., Kong, L., & Zeng, Y. (2005). Analysis of medical devices design requirements. *Journal of Integrated Design and Process Science*, *9*(4), 61-70.

Chen, W., & Wassenaar, H. (2003). An approach to decision-based design with discrete choice analysis for demand modeling. *Journal of Mechanical Design*, *125*, 490-497.

Chen, Z. Y., & Zeng, Y. (2006). Classification of product requirements based on product environment. *Concurrent Engineering*, *14*(3), 219-230.

Cheng, E. W., & Li, H. (2001). Analytic hierarchy process: an approach to determine measures for business performance. *Measuring Business Excellence*, *5*(3), 30-37.

Cross, N. (1999). Natural intelligence in design. *Design studies*, *20*(1), 25-39.

Dadeviren, M., Yavuz, S., & Kln, N. (2009). Weapon selection using the ahp and topsis methods under fuzzy environment. *Expert Systems with Applications*, *36*(4), 8143-8151.

Dai, J., & Blackhurst, J. (2012). A four-phase ahpqfd approach for supplier assessment: a sustainability perspective. *International Journal of Production Research*, *50*(19), 5474-5490.

de FSM Russo, R., & Camanho, R. (2015). Criteria in ahp: a systematic review of literature.

*Procedia Computer Science*, *55*, 1123-1132.

Dikmen, I., Birgonul, M. T., & Kiziltas, S. (2005). Strategic use of quality function deployment (qfd) in the construction industry. *Building and environment*, *40*(2), 245-255.

Durmusoglu, M. B., & Kulak, O. (2008). A methodology for the design of office cells using axiomatic design principles. *Omega*, *36*(4), 633-652.

Frey, D. D., Jahangir, E., & Engelhardt, F. (2000). Computing the information content of decoupled designs. *Research in Engineering Design*, *12*(2), 90-102.

Gilbert III, L. R., Omar, M., & Farid, A. M. (2014). An integrated qfd and axiomatic design methodology for the satisfaction of temporary housing stakeholders.

Gonalves-Coelho, A. M., Mourao, A. J., & Pereira, Z. L. (2005). Improving the use of qfd with axiomatic design. *Concurrent Engineering*, *13*(3), 233-239.

Harvey, L., & Green, D. (1993). Defining quality. *Assessment & evaluation in higher education*, *18*(1), 9-34.

Hazelrigg, G. A. (1998). A framework for decision-based engineering design. *Transactions-American Society of Mechanical Engineers Journal of Mechanical Design*, *120*, 653-658.

Ho, W. (2008). Integrated analytic hierarchy process and its applicationsa literature review. *European Journal of operational research*, *186*(1), 211-228.

Ho, W., Dey, P. K., & Higson, H. E. (2006). Multiple criteria decision-making techniques in higher education. *International journal of educational management*, *20*(5), 319-337.

Ho, W., Higson, H. E., Dey, P. K., Xu, X., & Bahsoon, R. (2009). Measuring performance of virtual learning environment system in higher education. *Quality Assurance in Education*, *17*(1), 6-29.

Houshmand, M., & Jamshidnezhad, B. (2006). An extended model of design process of lean production systems by means of process variables. *Robotics and Computer-Integrated Manufacturing*, *22*(1), 1-16.

Huang, C.-C., Chu, P.-Y., & Chiang, Y.-H. (2008). A fuzzy ahp application in government-sponsored r&d project selection. *Omega*, *36*(6), 1038-1052.

Ilieska, K. (2013). Customer satisfaction indexas a base for strategic marketing management. *TEM JOURNAL*, *1*(2), 327-331.

Ishizaka, A., & Labib, A. (2011). Review of the main developments in the analytic hierarchy process. *Expert systems with applications*, *38*(11), 14336-14345.

Kahraman, C., & eb, S. (2009). A new multi-attribute decision making method: Hierarchical fuzzy axiomatic design. *Expert Systems with Applications*, *36*(3), 4848-4861.

Kajanus, M., Kangas, J., & Kurttila, M. (2004). The use of value focused thinking and the awot hybrid method in tourism management. *Tourism management*, *25*(4), 499-506.

Kannan, D., Govindan, K., & Rajendran, S. (2015). Fuzzy axiomatic design approach based green supplier selection: a case study from singapore. *Journal of Cleaner Production*, *96*, 194-208.

Kearns, G. S. (2004). A multi-objective, multi-criteria approach for evaluating it investments: Results from two case studies. *Information Resources Management Journal*, *17*(1), 37.

Khandekar, A. V., & Chakraborty, S. (2016). Application of fuzzy axiomatic design principles for selection of non-traditional machining processes. *The International Journal of Advanced Manufacturing Technology*, *83*(1-4), 529-543.

Kksal, G., & Eitman, A. (1998). Planning and design of industrial engineering education quality. *Computers & industrial engineering*, *35*(3-4), 639-642.

Kulak, O. (2005). A decision support system for fuzzy multi-attribute selection of material handling equipments. *Expert systems with applications*, *29*(2), 310-319.

Kulak, O., Cebi, S., & Kahraman, C. (2010). Applications of axiomatic design principles:

A literature review. *Expert Systems with Applications*, *37*(9), 6705-6717.

Kurniawan, S. H., Zhang, M., & Tseng, M. M. (2005). Connecting customers in axiomatic design. In *Proceedings of icad2004, the third international conference on axiomatic design, seoul.*

Kurttila, M., Pesonen, M., Kangas, J., & Kajanus, M. (2000). Utilizing the analytic hierarchy process (ahp) in swot analysisa hybrid method and its application to a forest-certification case. *Forest policy and economics*, *1*(1), 41-52.

Lee, C.-E., & Hsu, S.-C. (2004). Outsourcing capacity planning for an an ic design house. *The International Journal of Advanced Manufacturing Technology*, *24*(3-4), 306-320.

Lee, H., Kwak, W., & Han, I. (1995). Developing a business performance evaluation system: An analytic hierarchical model. *The Engineering Economist*, *40*(4), 343-357.

Lee, Y., & Kozar, K. A. (2006). Investigating the effect of website quality on e-business success: An analytic hierarchy process (ahp) approach. *Decision support systems*, *42*(3), 1383-1401.

Leff, A., & Rayfield, J. T. (2006). Web-application development using the model/view/controller design pattern. In *Enterprise distributed object computing conference, 2001. edoc'01. proceedings. fifth ieee international* (p. 118-127). IEEE.

Levary, R. R. (2007). Ranking foreign suppliers based on supply risk. *Supply Chain Management: An International Journal*, *12*(6), 392-394.

Liu, W., & Zeng, Y. (2009). Conceptual modeling of design chain management towards product lifecycle management. In S.-Y. Chou, A. Trappey, J. Pokojski, & S. Smith (Eds.), *Global perspective for competitive enterprise, economy and ecology: Proceedings of the 16th ispe international conference on concurrent engineering* (p. 137-148). London: Springer London.

Madu, C. N., Kuei, C., & Madu, I. E. (2002). A hierarchic metric approach for integration of green issues in manufacturing: a paper recycling application. *Journal of environmental management*, *64*(3), 261-272.

Malladi, S., & Min, K. J. (2005). Decision support models for the selection of internet access technologies in rural communities. *Telematics and Informatics*, *22*(3), 201-219.

Masozera, M. K., Alavalapati, J. R., Jacobson, S. K., & Shrestha, R. K. (2006). Assessing the suitability of community-based management for the nyungwe forest reserve, rwanda. *Forest Policy and Economics*, *8*(2), 206-216.

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological review*, *63*(2), 81.

Mustafa, M. A., & Al-Bahar, J. F. (1991). Project risk assessment using the analytic hierarchy process. *IEEE transactions on engineering management*, *38*(1), 46-52.

Pahl, G., & Beitz, W. (2013). *Engineering design: a systematic approach*. Springer Science & Business Media.

Paryani, K., Masoudi, A., & Cudney, E. A. (2010). Qfd application in the hospitality industry: A hotel case study. *The Quality Management Journal*, *17*(1), 7.

Prasad, B. (1998). Review of qfd and related deployment techniques. *Journal of manufacturing Systems*, *17*(3), 221.

Rad, A., Naderi, B., & Soltani, M. (2011). Clustering and ranking university majors using data mining and ahp algorithms: A case study in iran. *Expert Systems with Applications*, *38*(1), 755-763.

Ramesh, B., & Jarke, M. (2001). Toward reference models for requirements traceability. *IEEE transactions on software engineering*, *27*(1), 58-93.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of mathematical psychology*, *15*(3), 234-281.

Saaty, T. L. (2004). Decision makingthe analytic hierarchy and network processes (ahp/anp). *Journal of systems science and systems engineering*, *13*(1), 1-35.

Saaty, T. L., & Vargas, L. G. (2001). The seven pillars of the analytic hierarchy process. In *Models, methods, concepts & applications of the analytic hierarchy process* (p. 27-46). Springer.

Saen, R. F., Memariani, A., & Lotfi, F. H. (2005). Determining relative efficiency of slightly non-homogeneous decision making units by data envelopment analysis: a case study in irost. *Applied Mathematics and Computation*, *165*(2), 313-328.

Sakao, T. (2007). A qfd-centred design methodology for environmentally conscious product design. *International journal of production research*, *45*(18-19), 4143-4162.

Savransky, S. D. (2000). *Engineering of creativity: Introduction to triz methodology of inventive problem solving*. CRC Press.

Shen, X.-X., Tan, K. C., & Xie, M. (2000). An integrated approach to innovative product development using kanos model and qfd. *European journal of innovation management*, *3*(2), 91-99.

Suh, N. P. (1990). The principles of design (oxford series on advanced manufacturing).

Suh, N. P. (1995). Design and operation of large systems. *Journal of Manufacturing Systems*, *14*(3), 203.

Suh, N. P., & Do, S.-H. (2000). Axiomatic design of software systems. *CIRP Annals-Manufacturing Technology*, *49*(1), 95-100.

Suh, N. P., & Sekimoto, S. (1990). Design of thinking design machine. *CIRP Annals-Manufacturing Technology*, *39*(1), 145-148.

Sun, X., Zeng, Y., & Liu, W. (2013). Formalization of design chain management using environment-based design (ebd) theory. *Journal of Intelligent manufacturing*, 1-16.

Sun, X., Zeng, Y., & Zhou, F. (2011). Environment-based design (ebd) approach to developing quality management systems: a case study. *Journal of Integrated Design and*

*Process Science*, *15*(2), 53-70.

Takamura, Y., & Tone, K. (2003). A comparative site evaluation study for relocating japanese government agencies out of tokyo. *Socio-Economic Planning Sciences*, *37*(2), 85-102.

Tan, S., Milhim, H. K. B., Chen, B., Schiffauerova, A., & Zeng, Y. (2011). Enterprise applications integration using environment based design (ebd). In *Asme 2011 international design engineering technical conferences and computers and information in engineering conference* (p. 1245-1255). American Society of Mechanical Engineers.

Tan, S., Zeng, Y., Huet, G., & Fortin, C. (2013). Effective reverse engineering of qualitative design knowledge: A case study of aerospace pylon design. In *Asme 2013 international design engineering technical conferences and computers and information in engineering conference* (p. V004T05A026-V004T05A026). American Society of Mechanical Engineers.

Thurstone, L. L. (1927). A law of comparative judgment. *Psychological review*, *34*(4), 273.

Tidwell, A., & Sutterfield, J. S. (2012). Supplier selection using qfd: a consumer products case study. *International Journal of Quality & Reliability Management*, *29*(3), 284-294.

Tontini, G. (2007). Integrating the kano model and qfd for designing new products. *Total Quality Management*, *18*(6), 599-612.

Tu, N., Zhang, T., He, Q., Zhang, H., & Li, Y. (2011). Applying combined ahp-qfd method in new product development: A case study in developing new sports earphone. In *Management science and industrial engineering (msie), 2011 international conference on* (p. 80-85). IEEE.

Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of operational research*, *169*(1), 1-29.

Wang, M., & Zeng, Y. (2009). Asking the right questions to elicit product requirements. *International Journal of Computer Integrated Manufacturing*, *22*(4), 283-298.

Wang, M., Zeng, Y., Chen, L., & Eberlein, A. (2013). An algorithm for transforming design text rom diagram into fbs model. *Computers in Industry*, *64*(5), 499-513.

Wang, Y., & Tseng, M. M. (2011). Integrating comprehensive customer requirements into product design. *CIRP Annals-Manufacturing Technology*, *60*(1), 175-178.

Wen-ying, L. (2009). Application of ahp analysis in risk management of engineering projects [j]. *Journal Beijing University of Chemical Technology (Social Sciences Edition)*, *1*, 46-48.

Yang, T., & Kuo, C. (2003). A hierarchical ahp/dea methodology for the facilities layout design problem. *European Journal of Operational Research*, *147*(1), 128-136.

Zein, A., Li, W., Herrmann, C., & Kara, S. (2011). Energy efficiency measures for the design and operation of machine tools: an axiomatic approach. *Glocalized Solutions for Sustainability in Manufacturing*, 274-279.

Zeithaml, V. A., Bitner, M. J., & Gremler, D. D. (2006). Services marketing: Integrating customer focus across the firm.

Zeng, Y. (2002). Axiomatic theory of design modeling. *Journal of Integrated Design and Process Science*, *6*(3), 1-28.

Zeng, Y. (2004). Environment-based formulation of design problem. *Journal of Integrated Design and Process Science*, *8*(4), 45-63.

Zeng, Y. (2008). Recursive object model (rom)modelling of linguistic information in engineering design. *Computers in Industry*, *59*(6), 612-625.

Zeng, Y. (2011). Environment-based design (ebd). In *Asme 2011 international design engineering technical conferences and computers and information in engineering conference* (p. 237-250). American Society of Mechanical Engineers.

Zeng, Y. (2015). *Redesign of a journal editorial workflow management system* (Unpublished doctoral dissertation).

Zeng, Y., & Cheng, G. (1991). On the logic of design. *Design Studies*, *12*(3), 137-141.