A prescriptive approach to derive value-based requirements specification: application to the requirements engineering of commercial aircraft

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THESE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par : *INSA Toulouse*
Discipline ou spécialité : *Génie Industriel*

-

Présentée et soutenue par *Xinwei Zhang*
Le 30/01/*2012*

Titre :

Prise en compte de la valeur ajoutée client dans la spécification des exigences

-

JURY

Guillaume Auriol, Maître de Conférences, LAAS, INSA, Université de Toulouse, co-directeur
Claude Baron, Professeur, LAAS, INSA, Université de Toulouse, directrice
Merlo Christophe, Maître de Conférences, HDR, ESTIA Bayonne, Université de Bordeaux, rapporteur
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Table of contents

Abbreviations

Acronym / abbreviation	Definition
AHP	Analytical Hierarchy Process
AIAA	American Institute of Aeronautics and Astronautics
AIT	Arrow’s Impossibility Theorem
BDA	Behavioural Digital Aircraft
CBA	Cost-benefit Analysis
CFG	Customer Focus Groups
CRESCENDO	Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimisation
DARPA	US Defence Advanced Research Projects Agency
DBD	Decision-Based Design
EC	Engineering Characteristic
FP7	Framework Programme 7
QFD	Quality Function Deployment
RE	Requirement Engineering
TLAR	Top Level Aircraft Requirements
VDD	Value-Driven Design
WP	Work Package

Glossary of Terms

Term	Definition
Behavioural Digital Aircraft	The "Behavioural Digital Aircraft" is a federated information system that comprises all the capabilities and services to enable a more complete and robust (mature and reliable) definition of the behavioural, functional and operational aspects of an aircraft (and constituent systems) to be modelled and simulated (CRESCENDO-D222 2010).
Customer	A customer, is a potential buyer or user of a products, service or combination of these (CRESCENDO-D222 2010).
Expectation	Expectations are prejudged beliefs about a product/service and serve as standards with which subsequent products/services are compared (Parasuraman 1994). They are designated as initial customer statements that customers express for the system-to-be developed, and they are original ideas and expressions (Zhang *et al.* 2010).
Need	A need is the lack of something requisite and is independent from any particular solution developed to address it (Ulrich and Eppinger 2008).
Objective	Objectives are statements of something that one desires to achieve (Keeney 1992).
Requirement	A requirement defines what the stakeholders – users, customers, suppliers, developers, businesses – in a potential new system need from it and also what the system must do in order to satisfy that need (Ulrich and Eppinger 2008).
Requirements Establishment	A Requirements Establishment activity transforms the understanding of customers' needs and expectations to requirements and criteria used to drive development of products and solutions (CRESCENDO-D222 2010).
Stakeholder	A stakeholder in an organization is any group or individual who can affect or is affected by the achievement of the organization's objectives (CRESCENDO-D222 2010).
State of Practice	A State of Practice investigation outlines highest developments and upcoming practices from an industrial perspective related to a given set of activities.
State of Theory	A State of Theory analysis outlines highest developments and key findings from an academic, or theoretical, perspective on a specific domain of science.
Value	Value is what decision maker cares about in decision-making, and is typically measured with utility function, value function or preference function (Keeney 1992).
Value-Driven Design	"Value-Driven Design" is a movement to reform the systems engineering process so that design choices are made to maximize system value rather than to meet performance requirements (Collopy 2009).
Value model	A "value model" enables the assessment of a value for every design option so that options can be rationally compared and a choice taken (Collopy 2009). In this thesis, value model means multi-attribute utility function.
Value modeling	Value modeling is characterized as the relevant activities on modeling and usage of value.

1 Introduction

In this chapter, an introduction of the thesis is given. The introduction is organized as follows. In Section 1.1, the context of the thesis is discussed with regards to understanding customer value in requirements establishment. In Section 1.2, we introduce the scope of the thesis in order to focus our approach development. In Section 1.3, the problems about value-based requirements establishment are presented, which are followed with the objectives of the thesis in Section 1.4. Finally, the thesis outline is listed in Section 1.5.

1.1 Context

In market-driven design or user-centered design processes, understanding customer needs is routinely recognized as one of the most important activities in early product or system design and development. The essence of understanding customer needs is to identify, organize and possibly quantify what customer wants or desires in order to drive the construction of appropriate, solution-independent requirements specification for engineering design. By understanding customer needs, it is then possible to design, develop and provide high quality products and systems to satisfy customer needs, which will help forming or enhancing manufacturers' competitiveness around their competitors. *The underlying principle is customer needs first, and then there are design solutions to implement customer needs.* The requirements specification derived from this process is *value-implicit. No explicit clarification of value is made, e.g. what is value and how value can be measured.*

Concurrently, another important dimension in the market-driven design or user-centered design is to design and develop products that are of higher value to customers, which will also improve customer satisfaction and enhance manufacturers' competitiveness (Keeney 2004). Naturally, certain relationships between customer needs and customer value are necessary to be established, which are not obvious in the literature. *It seems logical that the products satisfying better customer needs are of higher value to customers. But this intuitive response to the challenge fails to answer our curiosity of how much more customer value is realized corresponding to how much customer needs are satisfied.*

A solution to proceed could be to derive value-based requirements specification from initial customer statements, which enables a transformation from value-implicit requirements specification to value-explicit requirements specification. The benefits of the transformation are obvious for several aspects:

- Value becomes *an explicit construct* that can be qualified and quantified to some extent enabling value modeling and simulation.
- Value-based requirements specification is used *for evaluating of design alternatives*, which helps selecting one or a subset of design alternatives with high value to customers. It is a kind of reactive way of using value-based requirements specification.
- Value-based requirements specification can be used *for designing for value in the life cycle of products*. Important value dimensions and value drivers are identified as pointers for designing. It is a kind of proactive way of using value-based requirements specification.

A simple example of smart phone can illustrate some of the benefits. Assume that one customer has two needs about a smart phone: (1) The smart phone should be of low weight, and (2) The smart phone should have long battery life. The customer needs, constraints and product alternatives are presented in Table 1.1.

Table 1.1: A simple example of smart phone to present some benefits of the thesis.

Customer needs	Low weight	Long battery life
Constraints	<160 gram	>6 hours
Product alternative 1	145 gram	7 hours
Product alternative 2	155 gram	8 hours
Product alternative 3	161 gram	9 hours

After a straightforward check, it is easy to find out that alternative 1 and alternative 2 satisfy the constraints set by the customer while alternative 3 is out of the scale of the constraint in terms of weight. Therefore, in traditional purchasing or design process the alternative 3 is rejected, as it is not a feasible alternative. However, there are still two alternatives and their value to the customer is hard to evaluate. Someone may then use satisficing or a lexicographic strategy (Bettman *et al.* 1998) to select the most desired one or two alternatives, which try to simplify the selection process. But if we want to distinguish different degrees of value attainment of the two alternatives, that is, the alternative 1 is of how much value comparing with that of the alternative 2, then these strategies fail to answer this question. Furthermore, the rejected alternative 3 may have larger value to the customer comparing with that of alternatives 2, because the customer may think that the lost of value by an addition of 6 gram (161-155) in terms of weight is fully compensated by the added value created through an addition of 1 hour battery life (9-8). Traditional requirements establishment processes do not address these value problems, and frequently introduce products with sub-optimal value. However, these value problems can be resolved if a value model or value-based requirements specification of product is developed.

1.2 Scope

The mission of this PhD thesis is to propose an approach that is applicable to transform initial customer statements to a value-based requirements specification. More precisely, *it is to propose an approach to develop value models to assist the traditional value-implicit requirements specification.* The value model is a kind of quantitative models to calculate the value of special design alternatives. Therefore, when the data of a set of engineering characteristics, such as the LCD screen, shutter speed, megapixel and sensitivity of digital camera, is available, a corresponding numerical value is calculated.

This development of approach is under background of a European project "Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimization (CRESCENDO)" (CRESCENDO 2011). The project is led by Airbus and brings together 59 organizations, including major aeronautics industry companies, service and IT solution providers, research centers and academic institutions. The ambition of the consortium is to make a step change in the way that Modeling and Simulation activities are carried out, by multi-disciplinary teams working as part of a collaborative enterprise, in order to develop new aeronautical products in a more cost and time efficient manner.

More precisely, the work of approach development is under and contributes to the work package 2.2 (WP 2.2) "Requirements Establishment". The main objective of WP 2.2 is to radically change the way product development is initiated by developing innovative mechanisms:

- To capture, model and understand customers' and stakeholders' needs and expectations.
- To incorporate the value dimension into preliminary design in the virtual extended enterprise.
- To identify criteria and indicators that can be used in preliminary design studies that affect customer perceived value.

To enable this development of approach, sets of theories and methodologies are relevant. It would be useful to show the thesis's relationships with relevant communities in Figure 1.1.

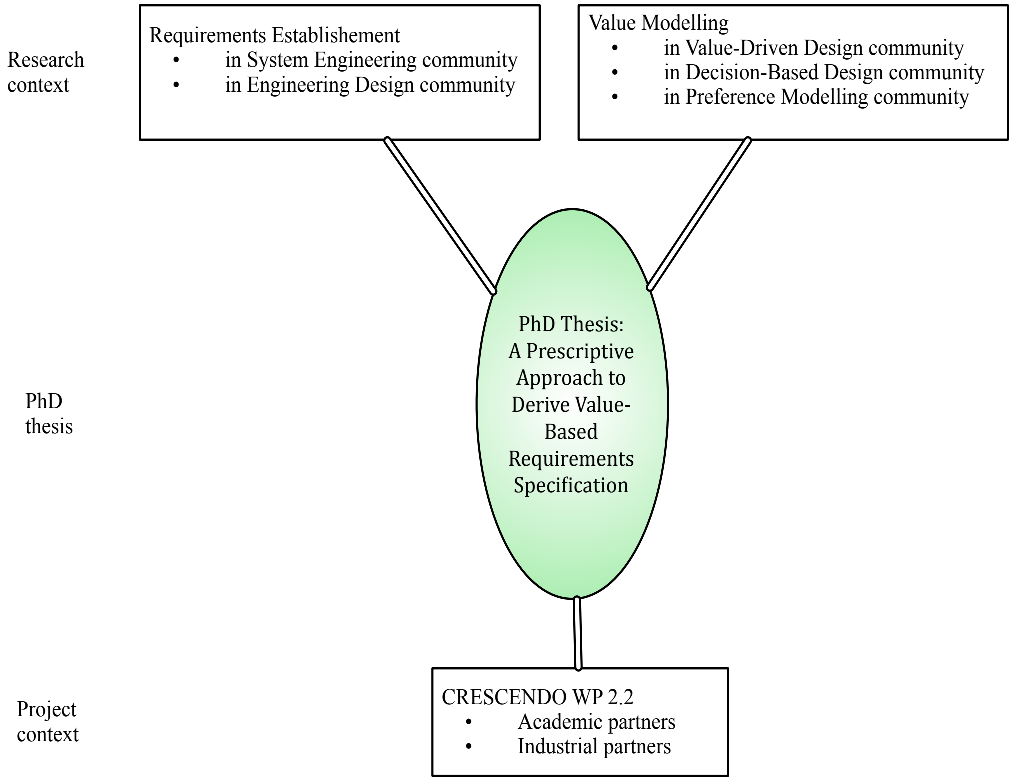


Figure 1.1: The scope of the PhD thesis.

The thesis and its approach development are indeed on basis of theoretical and methodological foundations of "requirements establishment" and "value modeling". Traditional requirements establishment activities focus on systematic processes and methods to derive value-implicit requirements specification. System engineering processes, standards, desired criteria and attributes of requirements are extensively discussed in system engineering community (e.g. the International Council on Systems Engineering). In engineering design community, e.g. Design Society, the focus on processes and methods of requirements establishment is also obvious, such as the process in (Pahl and Beitz 2007) and the method of quality function deployment (QFD). The interactions between these two communities are really close. For example, some methods, such as QFD and KANO, are used simultaneously in the two communities. Therefore, a clear separation is not achievable, although the two communities are of different focus in scale.

We characterize value modeling as the relevant activities on modeling and usage of value. Preference modeling is a critical activity in decision analysis to construct decision makers' preferences for decision-making (Keeney 1992, 1993). Recent research paradigms of decision-based design (DBD) in engineering design community (Wassenaar and Chen 2001)

(Hazelrigg 1998, 1999) and value-driven design in AIAA value-driven design community (Collopy and Hollingswort 2009) are two potential alternatives for designing for value. However, the value is narrowed to utility over profit or over surplus value, and they pay a lot of attention on the design optimization itself.

By integrating value-modeling techniques into the traditional requirements establishment activities, a prescriptive approach to derive value-based requirements specification is proposed. The approach contributes to value-based requirements engineering, engineering design and system engineering, and represents an innovative application of value modeling in requirements establishment. This development is applicable and is being applied to the project CRESCENDO and to requirements engineering activities of industrial partners.

A simplified example in context of development of commercial aircraft is used to illustrate the focus of this PhD thesis. In this selected case, the customers are airlines. After some interactions between airlines and aircraft manufacturer through meetings and interviews, a set of initial airline statements have been collected, and they are in different levels, granularities and forms of expression.

The thesis then proposes an approach to help transforming these initial airlines' statements into individual airline's value model, group value model, or aircraft value model. The expected benefits of this application case then can be obtained, which are closely corresponding to the above-discussed benefits:

- Value can be explicitly qualified (what it is and its internally structural relationships) and quantified (how much), and can be modeled (value model) and simulated (say, Monte-Carlo simulation) in the design and development of commercial aircraft.
- Airline value model and its derived aircraft value model are used for evaluating of the available or potential commercial aircrafts and helping the decision process of selecting aircraft(s).
- Airline value model and its derived aircraft value model are used for identifying highly influencing value dimensions and drivers and for designing alternatives with high value.

1.3 Problems

While requirements specifications are usually established for design activities, it is difficult, if not impossible, to validate and verify the correctness or sufficiency of this subjective understanding, especially at an early stage of development. Although there are many informal or formal methods and tools existing in literatures and practice, such as brainstorming, interview, QFD and conjoint analysis, customer needs, requirements and value are always the least understood elements in product design and development (Agouridas *et al.* 2008) (Bayus 2007) (De Chazelles *et al.* 2004) (Griffin and Hauser 1993) (Gause and Weinberg 1989) (Hull *et al.* 2005) (Krishnan and Ulrich 2001) (Pahl and Beitz 2007) (Ulrich and Eppinger 2007). Empirical studies have shown the high-failure rate of new product development due to lacking of a clear understanding of customer needs (Keeney 1987) (Bayus 2007). Others such as (Alexand and Stevens 2002) reported that five of the eight major reasons for project failure are requirements-based.

The difficulty lies in what should be understood and how it can be reasonably understood in this subjective, human-centric process. Traditional approaches may have more or less systematic processes and complementary techniques to understand customer needs and value, but they do not carefully distinguish the differences between the elicited statements, which are possibly of different levels and granularities (Agouridas *et al.* 2006(a), 2008) (Zhang *et al.* 2010(c), 2011(a), 2011(b)). Statements are generally combined according to their relevance or similarity, resulting in several categories with usage of infinity diagram or certain cluster algorithm. Significant opportunities to structure the customer statements and discover hidden needs and value are lost.

Even if customer statements are structured to some extent, they tend to be qualitative in nature as it is thought that it is too difficult to identify quantitative information of customer needs and value. It may be reasonable at this fuzzy front-end stage for product performance or design parameters as the information has to do with the conceptual design or embodiment design. It is, however, not true for information on customer needs and value as they all are residing in customers' mind. It should be elicited and constructed with appropriate approaches without biasing customer value. Customer needs and their value, e.g. weight of needs and risk attitudes towards uncertainty, should necessarily come from customers, although sometimes iterations between understanding customer needs (or value) and design activities are necessary.

1.4 Objectives

Our research intention is to propose a prescriptive approach for deriving value-based requirements specification for further design activities. The prescriptive approach helps customers or engineers to think systematically about customer needs and value by using normative theory with careful awareness of the typical ways they use in problem solving (Edwards *et al.* 2007). That is, while we want to develop a practical approach to support value-based requirements establishment, with certain consideration given to the complexity of problems and human cognitive capabilities, we also want the approach to have a basis of theoretical accuracy to enhance the soundness of the approach.

The development is realized by integrating a set of theory and methods into existing processes of requirements establishment. The approach is intended to be generally applicable, although a special focus is given on commercial aircraft domain. More precisely, we try to provide answers to the following questions:

- Given a set of initial customer statements that are possibly in different levels, granularities and formats of expression, is it possible to structure them in a logical way according to their inherent abstraction relationships? Can certain methods be proposed to support this process of structuring? Can implicit customer needs and value be uncovered?
- Given a set of initial customer statements that are possibly in different levels, granularities and format of expression, is it possible to derive an appropriate quantitative value model according to sound theories and methods? Can the traditional quantification, such as weighting, ranking and customer satisfaction, be reasonably explained and connected by the quantitative value model?

1.5 Thesis Outline

Chapter 2 introduces the terminology and presents a review of both *state of theory of requirements establishment and value modeling* and *state of practice of requirements establishment* of three main industrial partners in the CRESCENDO project. After these reviews, a benchmarking of four existing approaches selected from state of theory and state of practice of requirements establishment is deployed in order to select one existing approach, in this case QFD, for further development.

Chapter 3 gives an introduction to the foundations of approach development of the thesis. Section 3.1 introduces QFD and presents in detail its underlying methodological problems as an approach to derive value-based requirements specification. This set of methodological problems includes seven aspects, such as confusion between means-ends relationships and part-whole relationships (Zhang *et al.* 2011(a), 2011(c)), confusion between ranking and weighting, missing of attributes for measuring attainment of customer needs and using of linear additive function form directly without verifying underlying assumptions. A set of theories and methods is then introduced in Section 3.2, which includes concepts (objectives, attributes, value model and consequence model), methods (Means-ends objectives network, fundamental objectives hierarchy, response surface methodology) and theory (multi-attribute utility theory). We also make some assumptions about the approach development and declare its desired effects to be achieved.

Chapter 4 introduces the proposed approach aiming to mitigate the methodological problems of QFD as an approach to derive value-based requirements specification. Step by step procedures of the approach are presented, which is generally applicable to transform a set of initial customer statements to a customer value model to a system value model to component value models. It also introduces a case study to illustrate the approach's applicability to the context of requirements establishment of commercial aircraft. Airlines' group value model is finally derived from a set of initial airlines statements and implemented in the commercial software Vanguard Studio. But, due to the complexity of case study itself, we limit our focus to the first two-steps of the approach. Discussions are then made about the approach and about some practical concerns in its applications.

Chapter 5 concludes the work made in this thesis and lays out future work directions to further improve the approach.

2 State of Theory and State of Practice

In this chapter, state of theory and state of practice relevant to the approach development of the PhD thesis is reviewed, which helps to clarify the current states and potential problems regarding to value-based requirements establishment. This chapter is organized as follows. In Section 2.1, the relevant terminology is characterized in order to facilitate common understanding. Then state of theory is reviewed in Section 2.2, which includes requirements establishment and value modeling that is intended to been integrated into traditional requirements establishment. In Section 2.3, state of practice of requirements establishment of the industrial partners in the CRESCENDO project is reviewed to which the developed approach of value-based requirements establishment can be applied. In Section 2.4, one of the existing requirements establishment approach is selected through a benchmarking process as the basis of further Subject: development. In Section 2.5, conclusions are drawn.

2.1 Terminology

Some core concepts, including *Expectations, Needs, Requirements and Value* are presented in some more detail, as these concepts are critical for common understanding in the thesis.

2.1.1 Expectations

There is consensus that customer expectations are prejudged belief about a product/service and serve as standards with which subsequent product/service are compared in customer satisfaction and service quality literatures (Parasuraman 1994).

However, there is no consensus on such topics as: (1) the specific nature of expectation standard, and (2) the number of expectation standards used. As discussed in these literatures (Parasuraman 1994) (Zeithaml 1988, 1990), there are mainly 3 kinds of expectation standards used.

- *Predictive expectations* (also called will expectation): expectations are viewed as predication made by customers about what is likely to happen during an impending transaction or exchange. It is the main standard adopted in customer satisfaction.
- *Desired expectations* (also called wished, wanted, ideal or should expectations): expectations are viewed as desires, wants of customers, i.e. what they feel a service provider should offer rather than would offer. It is the main standard adopted in service quality.

- *Adequate expectations* (similar to experience-based expectations): customers realize that it is not always possible to realize the desired expectation according to their experience. They have another low level of expectations for the threshold of acceptable service. It is another main standard adopted in service quality as an accompanying low level standard with desired expectations.

We do adopt Parasuraman's characterization of the term expectations (Parasuraman 1994):

- Expectations are the standards against the provider's performance and they reflect the anticipated performance, which strongly related to customers satisfaction.
- They are influenced by personal needs, past experience with the product and service, word-of-mouth communication and external communication.
- Expectation also fall into several dimensions, such as reliability, security, which is varying from product to service. And every dimension has both the acceptable level and desirable level.

2.1.2 Needs

A need is the lack of something requisite and is independent from any particular solution developed to address it (Ulrich and Eppinger 2007). Thus needs are of essential and logical property, and are bound in the problem context.

Operationally, expectations are designated as initial customer statements that customers express for the system-to-be developed, and they are original ideas and expressions (Zhang *et al.* 2010(b)). Needs are different, which represent the fundamental reasons of interests about the system to-be developed. There is a transformation process from expectations to needs.

Customer needs and expectations are typically expressed in the language of the customer in terms of subjective value-related statements. However, while such expressions are helpful in developing a clear sense of the issue of interest to customers they provide little specific guidance about how to design and engineer the product (Ulrich and Eppinger 2007).

2.1.3 Requirements

Requirements are the basis for every project, defining what the product or system must do in order to satisfy stakeholder needs. They also tell the teams what the product must be able to achieve in terms of performances (Ulrich and Eppinger 2007). Development teams usually establish a set of requirements, which spell how in precise and measurable detail what the product has to do.

In an ideal world, the design team would establish the requirements specification once early in the development process and then proceed to design and engineer the product to exactly meet those specifications. For technology intensive product it is rarely possible. Immediately after the customer needs analysis the team sets targets, which represent the hopes and aspirations of the team before knowing what constraints the product technology will place. The team may fail to meet some of the requirements and may exceed others; therefore there is the need to iteratively refine them as soon as new constraints become visible. To set the final requirements specification several trade-offs have to be solved (Ulrich and Eppinger 2007).

2.1.4 Value

The literature review reveals a wide diversity of opinions and many speculative assertions on the real meaning of value. In spite of the centrality of the value concept, there is still relatively little knowledge about what value is, what its characteristics are and how customers determine it.

Although value is a unique concept, the term is often interchanged with other notions and no accepted definitions of value exist. Some of the most commonly in use definitions in the literature are the following:

- Value is what decision maker cares about in decision-making, and is typically measured with utility function, value function or preference function (Keeney 1992).
- Utility based on what is given and what is received (Zeithaml 1988).
- Perceived benefits received relatively to the price (Monroe 1990).
- An emotional bond established between a customer and a producer (Butz and Goodstein 1996).
- A Perceived trade-off between the positive and negative consequences of product use (Woodruff and Gardial 1996).

The perceptual nature of value is one of the most universally accepted aspects of the concept. It also means that value is dependent on the context and temporally determined, thus the perceived value for a product is expected to vary in time and space. The concept is often used as synonym of *quality*, *satisfaction* and *values*, although these terms are different in nature and refer to different things:

- *Quality* is the means, while *value* for the customer is the end (Band 1991).
- *Satisfaction* is the emotional response generated through the delivery of *value* (Rust *et al.* 1996).
- *Value* refers to a preference judgment while *values* refers to the criteria by which such judgments are made (Holbrook 1994).

Obviously, the term value may mean different things to different people. Its meaning may vary in time and space, and it is difficult to converge on a commonly agreed definition. As a consequence, it is intricate to establish a scientific discussion on its meaning due to the large amount of different constructs in literature. Then it makes difficult to capture and model the concept. In order to reduce confusion, the characterization of value by Keeney is adopted in this work.

2.2 State of Theory on Requirements Establishment and Value Modeling

In this section, the methodologies (processes, methods and tools) and theories relevant to the approach development of the PhD thesis are reviewed. This review is organized into two parts. The first part concerns about the traditional requirements establishment methodologies and theories while the second part concerns about value modeling methodologies and theories. This separated review between requirements establishment and value modeling is deliberate as always the traditional requirements establishment methodologies and theories play limited attention on value and value modeling. Furthermore, preference modeling is a mature field in Decision Analysis and has many applications in design processes themselves, such as value-driven design and decision-based design, which also supports a separate review.

The structure of the review process is organized as following as shown in Table 2.1.

Table 2.1: The structure of the review of state of theory.

2.2.1 Requirements Establishment
• 2.2.1.1 System Engineering context
  ○ System engineering processes and standards
  ○ Requirements definition process
  ○ Criteria and attributes of requirements
• 2.2.1.2 Engineering Design context
  ○ Requirements establishment processes
  ○ KANO model
  ○ Affinity diagram
  ○ QFD
  ○ Other recent researches
	2.2.2 Value Modeling
	• 2.2.2.1 Preference Modeling
	  ○ Analytical Hierarchy Process
	  ○ Multi-attribute Utility Theory
	• 2.2.2.2 Value-Driven Design
	• 2.2.2.3 Decision-Based Design

2.2.1 Requirements Establishment

In this subsection, we briefly summarize existing methodologies for engineering requirements from needs and expectations. There is plenty of research literature on RE in other disciplines, especially in software engineering, and they include problem frame (Jackson, 1995, 2000) (Zhang *et al.* 2010(a)), intent specification (Leveson 2000), goal-based RE and scenario-based RE (Nuseiben and Easterbrook 2000). Although they are obviously beneficial to product/system RE, there is the inclination to develop semiformal or formal requirements specification using different kinds of languages, for instance united modelling language, computer logic or automata. They are usually used for rigorous, mathematical reasoning and formal verification. However, RE of tangible products is distinctive from that of software in many aspects, and the review is limited to system engineering and engineering design contexts.

2.2.1.1 System Engineering Context

System engineering is an interdisciplinary field of engineering that focus on how complex system should be designed and managed over the life cycle of the system. It uses a host of tools that include requirements analysis, modeling and simulation and scheduling to manage complexity. The review includes three aspects: (1) system engineering processes and standards, (2) requirements definition process, and (3) criteria and attributes of requirements.

- System Engineering Processes and Standards

Systems engineering focuses on analyzing and eliciting customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem, the system lifecycle. There are several process models of system engineering, such as the waterfall model and the V-model that is shown in Figure 2.1 (INCOSE 2007). In the figure it is straightforward to find out the special stage of requirements establishment within the whole process.

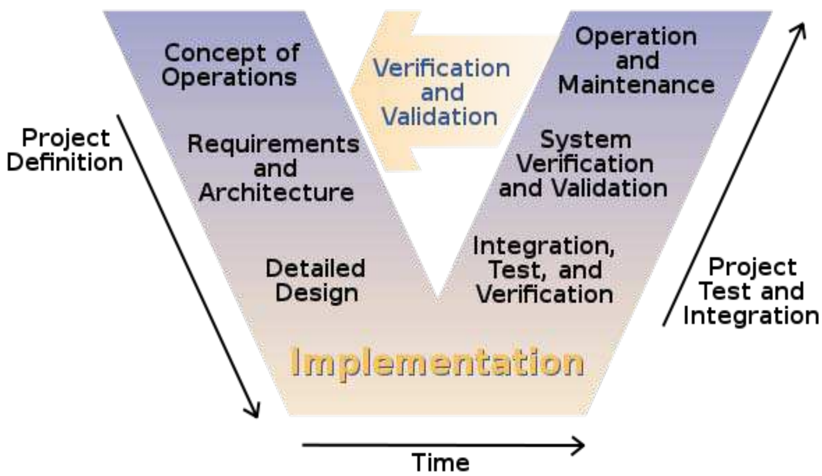


Figure 2.1: The V-model of the Systems Engineering Process.

There are several available systems engineering standards, such as EIA 632 (EIA632 1998), ISO 15288 and IEEE 1220. Grantzer (2007) extensively discusses the relationships among these standards and the evolution of these standards. EIA 632 (EIA632 1998) is a typical standard of processes for engineering a system, commonly adopted in industrial practice, e.g. Airbus and Boeing used it for engineering aircraft systems. It identifies the necessity of eliciting stakeholder needs and expectations to drive the system development, and it outlines the requirements for achieving this elicitation and for corresponding transformation from needs and expectations to requirements. However, this standard is about what to do, identifying the tasks to be performed and criteria to be satisfied. As it is a general standard for many industries, the tasks and processes needed to be further refined to coordinate with special development context. Actually, endeavor has also been made by companies and academics to adapt the general EIA 632 standard to the special contexts. For example, "Framework for the Application of Systems Engineering in the Commercial Aircraft domain" (INCOSE 2000) is developed for commercial aircraft domain.

- Requirements Definition Process

A four-step requirements definition process is shown in Figure 2.2. Every step in the process is necessary to be refined to a certain degree to enable systematic and operational implementation of requirements definition.

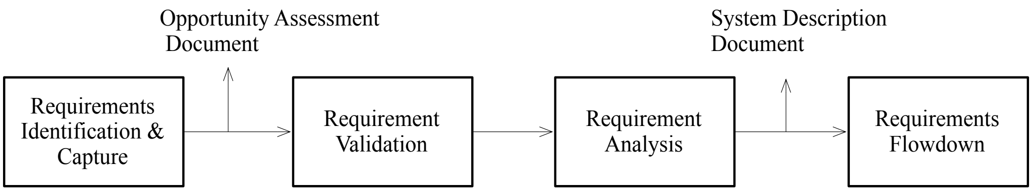


Figure 2.2: Requirements definition process (INCOSE 2000).

The first step in the requirements definition process is to identify what top-level requirements will be needed to develop a system. These requirements may be classified in accordance with their impact on the design. Requirements types include: functional, performance, operational, interface, physical, financial, design and construction standards & "ilities". Once requirements identification at the top level has been completed, then requirements capture is implemented. All the collected top-level requirements must be reviewed and checked with some criteria and there is an agreement with stakeholders. Any discrepancies during this process are resolved in consultation with stakeholders. Requirement analysis is a process by which the system requirements are developed from general statements of operational and functional needs to specific technical requirements. There are in general two kinds of requirements analysis: analysis for what must be done (functions) and analysis of how well the functions have to be done (performance). After requirements analysis, the top-level requirements (assigned to system level) need to be flowed down to next lower level and subsequently to lower levels.

- Criteria and Attributes of Requirements

A set of criteria is defined in EIA 632 for verifying quality of requirements (EIA632 1998), which may be called as the desired properties of requirements:

- **Singularity**: a requirement is singular if the requirement statement is not expressed as two or more requirements having different actors, actions and objects.
- **Feasible**: a requirement is technically feasible if it can be realized within the constraints of the project (limit of cost, schedule, technical constraints, respecting standards…)
  Note: feasibility shall be a criterion, but it shall not prevent the research for solution.
- **Clear/Unambiguous**: a requirement is clear and unambiguous if every participant can easily understand it and if there is only one meaning. This means without semantic interpretation, semantic analysis, and additional information to be found elsewhere (other document…), a requirement can be easily and appropriately understood.
- **Complete**: a requirement is complete if the statement is providing the information to enable the requirement to be implemented. This includes all constraints and conditions.
- **Verifiable**: a requirement is verifiable if the statement is using quantified valued and its implementation can be tested.
- **Consistent**: a requirement is consistent if the statement is not in conflict with any other requirements, or any linked information is in correspondence.
- **Traceable**: a requirement is traceable when the upper level requirement from which it is derived is identified.

There are also literatures that discuss about the syntax and operational procedures to write goods requirements (Hooks 1993) (Agouridas *et al.* 2008). These discussions are useful and operational and help avoiding common mistakes in writing requirements. Furthermore, one requirement may have many attributes and other relevant information. The attributes and relevant information of one requirement are numerated in Figure 2.3, although it is not exhaustive. This set of attributes and relevant information helps understanding of requirements and collecting necessary information.

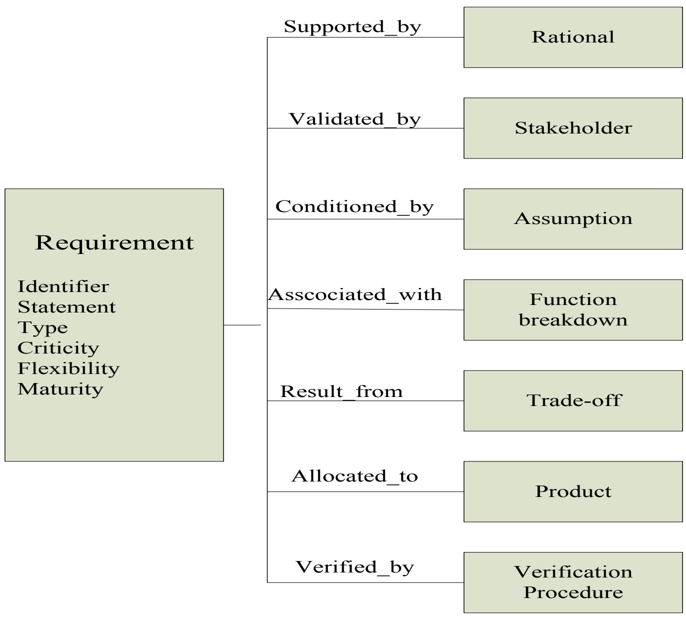


Figure 2.3: Attributes and relevant information of one requirement.

2.2.1.2 Engineering Design Context

The review of requirements establishments in the engineering design context include the following five aspects: (3) requirements establishment processes, (2) KANO models, (3) Affinity diagram, (4) QFD, and (5) other recent researches.

- Requirements Establishment Processes

Two similar processes for establishing product requirements are described by (Pahl and Beitz 2007) and by (Ulrich and Eppinger 2007), respectively, as shown in Table 2.2. They are intended to provide systematic processes for identifying and structuring customer needs with some clarification on the question "what are desired by customers concerning the product to be developed". The inputs and outputs of the two processes are almost the same, product planning document and requirements specification, respectively. And yet the two processes are deeply influenced by other popular methods, e.g. KANO model, affinity diagram and QFD. Then the two processes unavoidably inherit the intrinsic pros and cons of the underlying methods.

Table 2.2: The requirements establishment processes in engineering design context.

(Pahl and Beitz 2007)	(Ulrich and Eppinger 2007)
Input: product planning	Input: product planning
1. Define basic market demands 2. Define attractiveness demands of the market segment	1. Collect original data from customers 2. Understand original data from customer viewpoint

3. Document customers' specific technical performance requirements 4. Refine and extend the requirements using the checking list and scenario planning 5. Determine demands and wishes	3. Organize customer needs into hierarchy 4. Identify the importance of customer needs 5. Prepare the list of measure criteria 6. Collect benchmarking information from competitors 7. Set ideal value and acceptable value for each measure criteria
Output: requirements specification	Output: requirements specification

- KANO Model

KANO model of customer satisfaction (Bayus 2007) categorizes customer needs into three types as shown in Figure 2.4. Different types of customer needs are recognized distinctly by their different degree of implications to customer satisfaction, which appears implicit in three different kinds of curves. The model helps recognizing a hidden fact that customer satisfaction is not always linear with the attainment of special customer need. However, it does not provide any quantitative mechanism to model the function form between different levels of achievement of the customer need and different levels of customer satisfaction or value. It also does not provide any mechanism to make value trade-offs among customer needs for conjoint measurement of customer satisfaction and to drive design value trade-offs among design parameters.

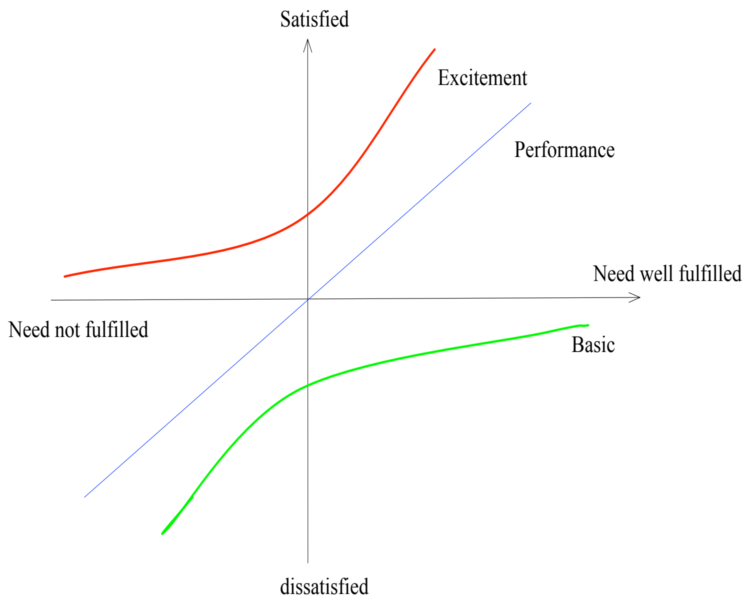
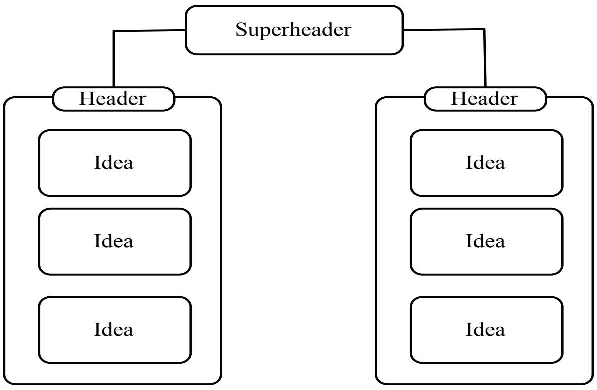


Figure 2.4: KANO model of customer satisfaction.

- Affinity Diagram

Affinity diagram (Ulrich and Eppinger 2007) is a business tool typically used for organizing initially elicited customer statements. The structure and process of affinity diagram is presented in Figure 2.5.



A process underlying affinity diagram:

Step 1: Generate ideas
Step 2: Display ideas
Step 3: Sort ideas into groups
Step 4: Create header cards
Step 5: Draw finished diagram

Figure 2.5: Affinity diagram

It allows large numbers of customer statements to be sorted into groups according to similarity or relevance for further review and analysis. It does help to organize customer statements to some degree, but it does not carefully distinguish the types of the statements in the groups or the relationships among the statements. As there possibly are customer needs, product features, engineering characteristics, goals, attributes, constraints or design parameters in the elicited statements, simple inclusion of all related or similar statements in the same groups is not appropriate and introduces unnecessary complexity to quantitative modeling in the later stage. Further, an important opportunity to uncover implicit customer needs is missing.

- Quality Function Deployment

QFD is widely researched in academics and adopted in industry as an approach for developing customer-focused products based on “house” diagram (Hauser and Clausing 1988) (Bode and Fung 1998). The structure of first house of QFD is shown in Figure 2.6.

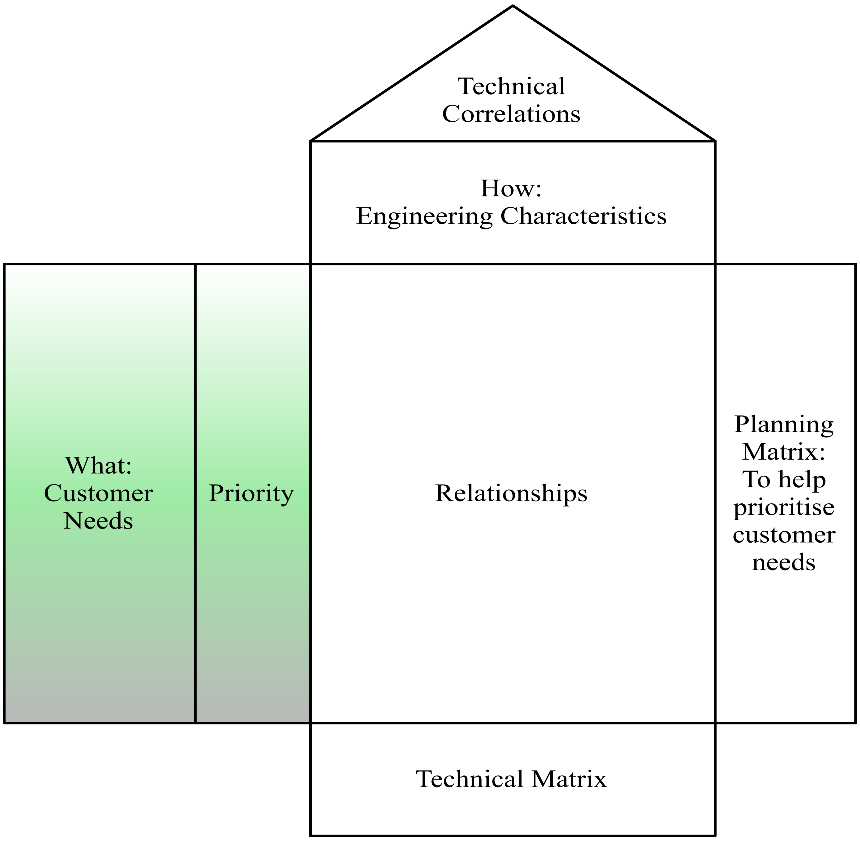


Figure 2.6: the structure of the house of quality.

The voice of customer (**what** & **Priority** in Figure 2.6), an integrated component in the house of quality, includes identifying a set of customer needs and organizing them into a hierarchy. Each customer need in the leaves of the hierarchy is given a corresponding weight importance according to certain weighting techniques, e.g. 9-point direct-rating scale, constant-sum scale (like 100 points), or *Analytic Hierarchy Process* (Saaty 1980) (Dyer 1990). The procedure is not difficult to understand and successful in business, but QFD itself does not support identification of implicit customer needs from expressed statements. Also, weight of each customer need is always assigned independently of the range information of the attributes for measuring the degree to which the needs are met. Furthermore, two assumptions are implicit in the process: (1) all the customers or stakeholders have the same preferences for the weights of customer needs, (or implicitly, customers have made a compromise about the weights of the needs) and (2) customer satisfaction of a special customer need is of a linear additive function form regarding to different attainments of customer need. The first one is a strong assumption, and it is not reasonable for multiple stakeholders with distinct preferences. The 2nd assumption means that the condition of additive independence among the customer needs is satisfied and that there are linear relationships between customer satisfaction and different levels of achievement of corresponding need. The result is that the finally chosen design solution may be suboptimal in terms of customer value.

- Other Recent Researches

(Agouridas *et al.* 2006(a), 2006(b), 2008) proposed a process for defining new product requirements from stakeholder needs to design requirements, and applied it in requirements establishment of the micro-energy solution and medical devices, respectively. The developed process is supported by corresponding techniques, e.g., Needs, Attributes and Solutions for identifying real stakeholder needs and Motivational Rational Traceability Matrix for analyzing intents. However, the techniques need to be further refined and rationalized, e.g., identifying appropriate stopping point to stop asking the why questions regarding to the special decision context, substituting network structures for tables in order to organize needs, attributes and solutions in a more visual and intuitive way. And more quantitative analysis about customer needs should be provided.

Others emphasize cross-fertilization of research on customer needs (Bayus 2007) (Michalek *et al*, 2005) from viewpoints of customers, engineering and marketing as shown in Figure 2.7. That is, customer needs should be: (1) desirable for customers, (2) feasible for engineering, and (3) salable for marketing. Typically, optimization techniques are used to solve the problems of maximizing customer satisfaction or enterprise profit under technical and cost constraints, but there are possibly poor structure and understanding of customer needs.

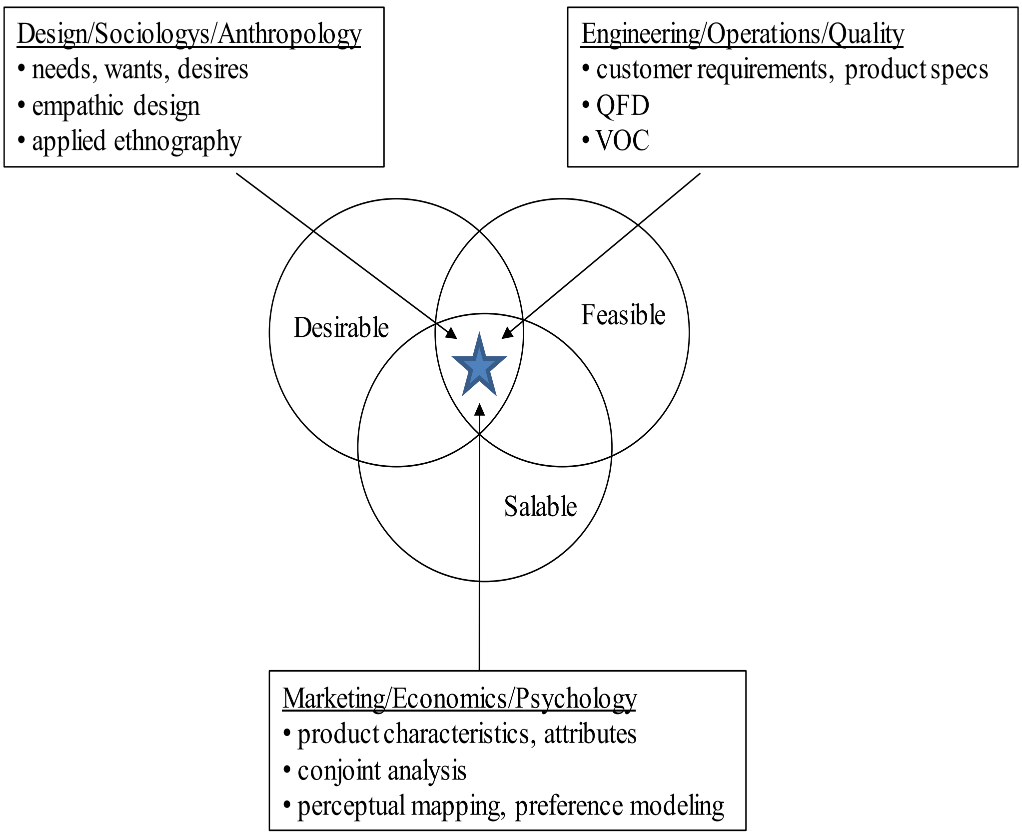


Figure 2.7: The cross-fertilization of research on customer needs (Bayus 2007)

2.2.2 Value Modeling

Increasingly, there are research communities focusing on modeling value and utilizing value models for design evaluation and optimization, such as the recent research paradigms of Value-Driven Design (VDD) and Decision-Based design (DBD). As said by George Hazelrigg (Hazelrigg 1998): "The purpose (of this framework) is to enable the assessment of a value for every design option so that options can be rationally compared and a choice (can be) taken." Although there is analogue spirit between VDD and DBD, they are different in many aspects that are better illustrated in the following sections. Before presenting of VDD and DBD, preference modeling is discussed from which VDD and DBD are derived.

2.2.2.1 Preference Modeling

Decision analysis is the discipline that is necessary to address important decisions in a former manner. There are two major part of decision analysis. One is about modeling factual relationships between means and fundamental objectives, and possibly, the relationships are modeled with probability theory. The others concern about modeling preferences of decision maker(s) using multi-attribute preference theory. Value modeling in decision analysis is implemented with the assistance of multi-attribute preference theory. The most popular theories and methods in the multi-attribute preference theory are multi-attribute utility theory and Analytical Hierarchy Process (AHP), which together basically construct the American school. There are also methods on basis of a partial ordering of alternatives such as ELECTRE and PROMETHEE (Wallenius 2008), which may be categorized into the French school. In view of the large body of knowledge in this field, we only limit our investigation to multi-attribute utility theory and AHP.

- Analytical Hierarchy Process

AHP is a methodology for multi-criteria analysis and decision-making developed by Thomas L. Saaty (Saaty 1980). The basic idea in the AHP is that it is much easier for a person to determine qualitatively relative importance between a pair of criteria than determining how much times importance. "Hierarchy" in the name reflects the notion that value judgments must be made in several levels and finally combined together to provide an overall evaluation. At each level of the hierarchy the process proceeds by asking the people to make rough pair-wise comparisons between criteria. For example, people may be asked to compare relative importance of two criteria, say unit cost and time to market, with the question of "which one is more important". For n criteria in one special level, there are $\frac{n(n-1)}{2}$ comparisons. These pair-wise comparisons are required to produce the relative weights of criteria.

The process is repeated at the next level till all the criteria are assigned relative weights. The procedure is easy to understand and perform because it uses only simple judgments. Lots of applications of AHP are available in literatures and practice (Vaidya and Kumar 2006).

However, AHP is controversial for three reasons:

1. The underlying axiomatic structure of AHP is not formally proved and it does not guarantee the consistency between the produced ratings and preferences of decision marker (Dyer 1990). There are possibilities of rank reversal when the set of alternatives for evaluation is not fixed, which is not desired in decision process,
2. AHP has difficulty with uncertainty, and there is no explicit modeling about uncertainty,
3. It cannot provide sensitivity analysis that supports robust analysis of alternatives.

- Multi-Attribute Utility Theory

Utility is a measurement of relative satisfaction. Existence of utility and utility function has been provided under a set of axioms (Von Neumann and Morgenstern 1953). It is one of top important topics in decision analysis. Many sages have worked on this topic, including von Neumann, Morgenstern, Arrow, Harsanyi, Sen, Raiffa, Keeney and others.

Multi-attribute utility theory is a systematic theory to quantify personal and group preferences. It is a theory of cardinal utility, thus the strength of preferences are quantified, although it subjects to impreciseness. "Multi-attribute" is the name of multi-attribute utility function means that the theory is used to aggregate decision maker's preferences in several criteria that are always conflicting. A set of multi-attribute utility functions is available as aggregation functions, which are robust enough to accommodate different decision problems. To measure utilities of different levels of achievement of attributes, single attribute utility functions are constructed. A hierarchy of attributes provides a convenient mechanism to compose utility function when the number of the set of attribute is large. Three core elements in the multi-attribute utility are:

1. Value trade-offs between attributes are used to determine relative weights of attributes. It is a rigorous process on basis of attribute information that are generally ignored in some approaches,
2. Uncertain attainment of attributes and risk attributes of decision makers are incorporated into assessing single attribute utility function, and
3. It is possible to model the preference of time, which is especially important in business situations.

Sets of applications of multi-attribute utility theory can be found, such as applications in facility selection, medical decision and design decision (Keefer *et al*. 2007).

Compared with AHP, multi-attribute utility theory is advantageous:

1. It is established on basis of sound axioms,

2. It is able to model uncertainty, and
3. It supports sensitivity analysis to obtain robust alternative.

The difficulties of the application of multi-attribute utility theory lie in the time it demands and hard work it places on decision maker.

2.2.2.2 Value-Driven Design

VDD may be intended as a movement aiming to reform the systems engineering process so that design choices are made to maximize system value rather than to meet performance requirements (Collopy 1996, Collopy 2001, Collopy and Horton 2002, Collopy and Horin 2007, Collopy 2008(a), Collopy 2008(b), Collopy 2009, Collopy and Hollingswort 2009)). Within the VDD, the system value can be treated as the single objective function of the design optimization process. By using value as the systems' most characteristic attribute one can evaluate all possible designs and select the best one rather than selecting a design that meets the engineering requirements. For a traditional design optimization system, if the system attributes meet the requirements the design cycle is terminates; however, for a value-driven design optimization cycle, all of the system attributes are assessed with a value model (Collopy 2009). The value model can be visualized as a function that accepts a vector of attributes as its argument and assigns a scalar score to system value. This allows designers to run formal optimization algorithms for a vast number of input parameters and, if needed, perform what-if and sensitivity analyses easily. The value-driven design process is showing in Figure 2.8. The system value is typically surplus-based and there is a single attribute utility function over surplus value of system.

The idea that, given a set of alternative actions, a rational person would choose the action that is expected to yield the outcome that is most preferred, was already stated by economists such as Debreu (1959), but it took until the 1970's before the concept of Value System Design for large scale systems engineering and systems analysis began to appear (Sage 1977, 2000).

Miles (1972) first introduced the *value analysis* concept, intended as a problem-solving system and an organized creative approach for the efficient identification of unnecessary cost, i.e., cost that provides neither quality nor use nor life nor appearance nor customer features. From such a perspective, a product or service is generally considered to have good value if it has appropriate performance and cost. By reverse definition, a product is considered not to have good value if it lacks either appropriate performance or cost.

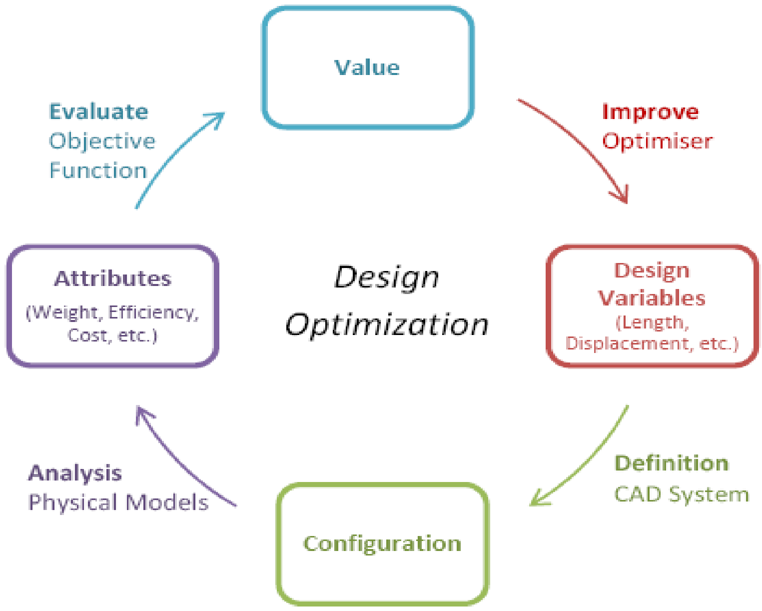


Figure 2.8: The design process showing value as the main objective function.

Moving from the initial value system design definition, intended as "the transformation of the properties of a thing into a format amenable to instrumental or extrinsic valuation", (Sobieszczanski-Sobieski *et al*. 1985) in the 80's elaborated the idea of structural design optimization to integrate engineering modeling codes into decomposed optimization structures launching the field of multidisciplinary optimization. In the late 1990's, (Collopy 1996) developed a value-based communication and control process and a distributed optimization process built around flowing component design objectives down from a system value model.

During the early 2000's, a great deal of research on economically directed systems engineering was produced by the Engineering Systems Division of the Massachusetts Institute of Technology (Joppin and Hastings 2003) (Long *et al.* 2007). Within this group, Olivier de Weck (De Weck *et al.* 2003) developed new methods for exploring a design tradespace using *Generalized Information Network Analysis*, while Rhodes and Ross (Ross and Rhodes 2008) developed value-driven design processes for the conceptual and preliminary phases of design. These studies have particularly investigated flexibility in the face of requirements changes over time. Both Ross and de Weck have employed a graphic form of optimization, tradespace exploration, in which designs are plotted against two axes that measure components of value by their position.

Saleh (Saleh *et al.* 2003) continued the investigations into value-based design developing several spacecraft value models, exploring alternative ways of thinking about satellite design and how designers create value. Later on Brown and Eremenko developed another incarnation of VDD at the US Defence Advanced Research Projects Agency (DARPA) a process called Value-Centric Design.

Nowadays several initiatives and groups are working in the area of VDD. The DARPA F6 program (Brown *et al.* 2008, 2009) is employing a value-centric system design methodology, incorporating value-driven architectural decision-making, to make value and cost commensurable and to mitigate risk using value variance as a risk metric.

The University of Southampton in the U.K. is developing a VDD process called DECODE (DEcision environment for COmplex DEsigns) aiming to support teams in performing concurrent design and multidisciplinary analysis activities organized around a spine of value-based objective functions for component optimization.

The Centre of Excellence in Integrated Aircraft Technologies at Queen's University, Belfast, is developing value-driven design strategies for aircraft structures and has demonstrated how the profitability of commercial aircraft can be improved by using a value model for fuselage section design, looking at weight, strength, and cost (Castagne *et al.* 2009).

Researchers at MIT's Systems Engineering Advancement research initiative are developing new value-driven methods and decision approaches for use by designers during the concept phase. The intent is to create knowledge in that phase by exploring relationships between design alternatives and stakeholder value, which can be used in later phases of design to facilitate optimization. The exploration approach supports designing for value robustness, leading to systems that deliver stakeholder value in a changing world (Ross and Rhodes 2008).

2.2.2.3 Decision-Based Design

DBD prescribes a methodology to make unambiguous design alternative selection under uncertainty and risk wherein the design is optimized in terms of the expected utility. It recognizes engineering design as a decision-making process that follows rational principle and other axioms. The preferred design solution is the one whose expected utility has the highest scalar value. There are many DBD related research developments during recent years (Wassenaar and Chen 2001) (Hoyle and Chen 2006, 2007) (Hazelrigg 1998, 1999). However, there is still no consensus on how the DBD approach should be implemented for engineering design. One critical problem is about how to properly construct the design utility under uncertainty to reflect the interests of both the manufacturers and customers. Two viewpoints are obvious. One is that profit is appropriate as the single criterion to be maximized and there is single attribute utility function over profit. The other is that multi-attribute utility functions are appropriate to model the different aspects of preferences of different stakeholders (Multi-attribute utility theory will be introduced at next section).

A framework proposed by Hazelrigg for DBD is presented in Figure 2.9 (Hazelrigg 1998). Two assumptions are made in this framework:

- While it recognizes the possibility of a multi-attribute utility, it is on basis of notion to maximize profit and then single attribute utility function over profit.

- The focus of the framework is on customer products, that is, products that may be purchased and used by a plenty of consumers.

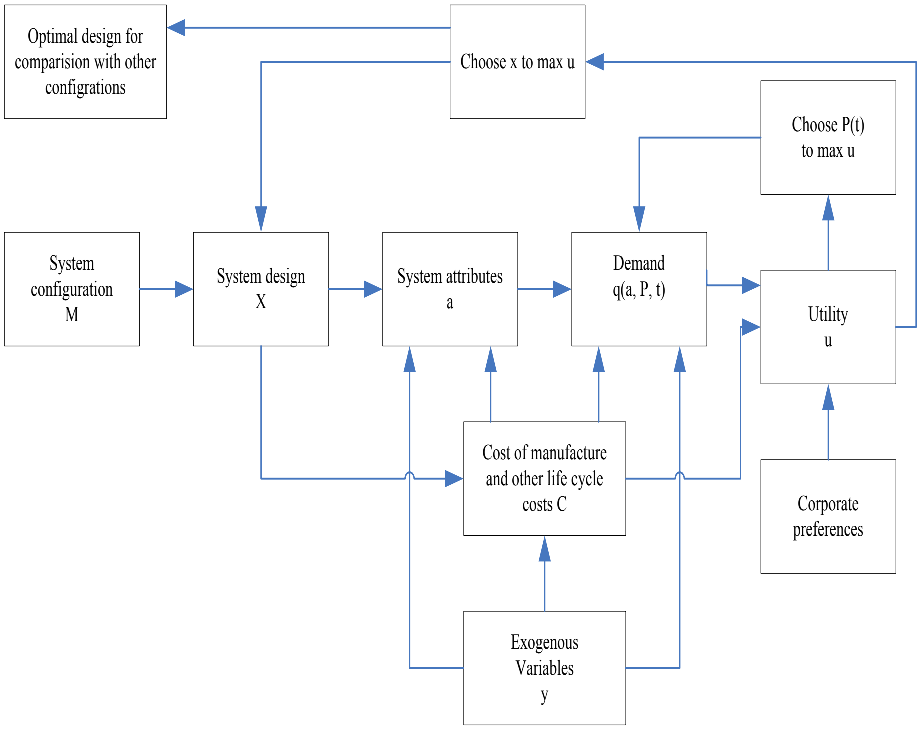


Figure 2.9: A framework for decision-based engineering design.

Profit is represented as net present value, which consists of revenues less costs and is discounted to account for the fact the revenues and costs happen over time. Typical economic equations are used for computing revenues and costs. The point is how to model customer demand for the product, which is a function of system attributes, price and time. (Hoyle *et al.* 2006, 2007) proposes an approach to model customer demand using discrete choice analysis and apply it to a motor design example. Utility function u is constructed over single attribute profit, which may be uncertain in attainment. To maximize u, there are three sub-processes to optimize:

- Given system configuration M, system design x and exogenous variables y, choose P to maximize u,
- Given system configuration M, system design x, exogenous variables y, P and their corresponding utility, select the largest utility when x changes, and
- Select the best system configuration to maximize utility when system configuration changes.

Thurston and her colleagues extensively explore applications of multi-attribute utility theory in DBD, and formulize the DBD as a multi-criteria decision-making problem (Thurston *et al.* 1990, 1998, 2001). Their philosophy is to maximize a multi-attribute utility function under various constrains. It is analogue to that of (Simon 1969):

> *The optimization problem is to find an admissible set of values of the command variables, compatible with the constraints, which maximize the utility function for the given values of the environmental parameters. (In the probabilistic case we might say, "maximize the expected value of the utility function," for instance, instead of "maximize the utility function.")*

More formally, it can be modeled by

$$\text{Maximize} \quad u(x_1, \dots, x_i, \dots, x_M) \tag{1.1}$$

Subject to:

$$x_i = f_i(y, z) \tag{1.2}$$

$$x_{iw} \le x_i \le x_{ib} \tag{1.3}$$

$$y_{jw} \le y_j \le y_{jb} \tag{1.4}$$

where $x_i, i = 1, \dots, M$, is the i^{th} objective to achieve in the design problem, u is a multi-attribute utility function over vector $x = \{x_1, \dots, x_M\}$, $y = \{y_1, \dots, y_Q\}$ is a vector of engineering design parameters that can be controlled by engineers, $z = \{z_1, \dots, z_p\}$ is a vector of environment variables that are not under controlling of engineers in current decision context, f_i is a response function modeling the functional relationships between the response x_i and a set of predictors y and z, x_{iw} and y_{jw} are the worst tolerant level of x_i and y_j, respectively, x_{ib} and y_{jb} are the best achievable level of x_i and y_j, respectively.

With above established formulation, approaches for solving multi-attribute optimization problems are then applicable. These approaches may include interactive methods, goal programming, vector-maximum algorithms, and evolutionary procedures (Thurston *et al.* 1998), to name a few.

There are a plenty of applications of the multi-attribute based DBD, such as turnbuckle example (Thurston 2001) and material selection example (Thurston 1990). Thurston also apply multi-attribute utility function to transform QFD into a multi-objective optimization problem. However, multi-attribute based DBD is controversial as it may be a time-consuming process to construct multi-attribute utility function and customers may have difficulty to clearly clarify their preferences. This problem will be further discussed in the Chapter 4.

2.2.3 Synthesis

We have reviewed the state of theory of requirements establishment and value modeling in separated two sections. As it is shown in the section of requirements establishment, there are a plenty of diverse processes and methods for understanding customer needs and deriving requirements. The processes may be systematic and effective to certain extent, such as the requirements definition process in system context and the two requirements establishment process in engineering design context. And methods are available to support the whole processes or part of the activities. KANO model is used to analyze the relationships between the achievement of special customer need and the degree of customer satisfaction. Affinity diagram is used for organizing customer statements or needs into a hierarchy. QFD is a method or methodology that can be used for establishing requirements specification. There are also some recent researches to improve effectiveness of the processes and methods. But we realize two main problems:

- Although the availability of the set of processes and methods is obvious, it is difficult to say that they have been logical enough about structuring all customer statements. It is still difficult to trace their inherent abstraction relationships, and implicit customer needs and value are not discovered. This problem can be resolved by investigating inherent abstraction relationships underlying customer statements and by collecting or developing methods that supporting these abstractions.
- The quantification in this requirements establishment process is really rough and oversimplified. There is little discussion of value in the requirements establishment process. This problem poses a difficulty to bridge between requirements establishment and design simulation that is quantitative in nature. After investigation, we find that theories and methods are available to mitigate this concern. Requirements establishment can benefit from value modeling that help to establish a value-based requirements specification.

In the section of value modeling, we discuss two recent paradigms of VDD and DBD, which focus on using of value and value models in the design process and are out of our research scale. But common foundations of these two paradigms can be found, that is, preference modeling. We realize that preference modeling can also be used in requirements establishment for identifying value and constructing value models. In the Chapter 4, we will show how QFD and multi-attribute utility function can be reasonably integrated for developing a prescriptive approach to derive value-based requirements specification.

2.3 State of Practice of Industrial Partners on Requirements Establishment

In this section, state of practice of industrial partners in requirements establishment is presented. The industrial partners include Airbus, Rolls Royce and Volvo Aero that come from the CRESCENDO project and are representative enterprises in aerospace industry.

2.3.1 Airbus Practice

Airbus uses Common Airbus Requirements Engineering process and system engineering process and standard for engineering requirements from customer expectations (in her term, requests). Customer Focus Groups (CFG) is an Airbus practice to capture needs and expectations from customers for A380 program (De chazelles *et al.* 2004). It is in the life cycle of transforming needs into product as presented in Figure 2.10.

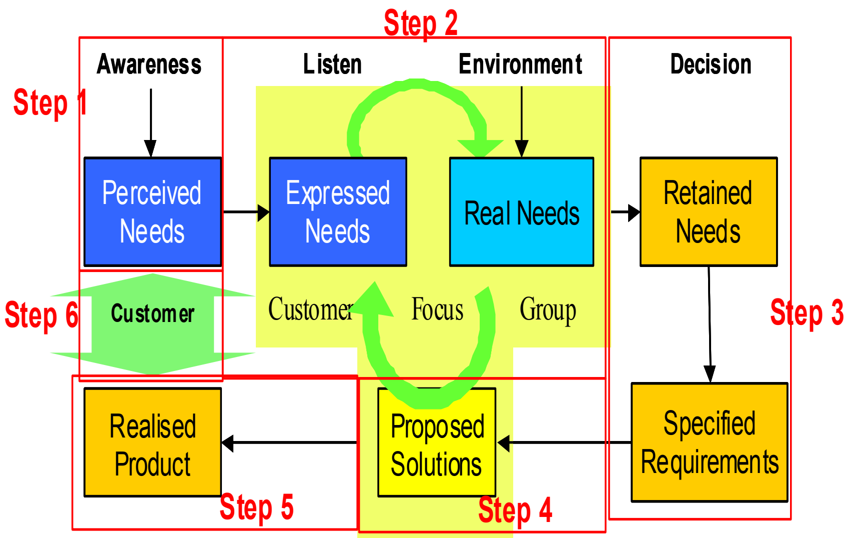


Figure 2.10: A life cycle for translating needs to products at Airbus.

The life cycle presented in Figure 2.10 reflects the experience acquired by Airbus, especially during Customer Focus Groups (CFG) workshops. Actually, the perceived needs and expressed needs are customer expectations in the context of this PhD thesis, and they are the initial customer perception and statements of their expectations.

In detail, the process underlies the CFG is following:

- Before the CFG

Before CFG, some preparatory tasks have to be done. These tasks may include identification of "topics", identification of "concerns", proposition of positive statement to capture the request, review of agenda, Customization of the Capture feedback process presentation and customization of the database to record the requests. The "capture sheet" itself is an important media in support of the capture customer requests. An example of "capture sheet" is shown in Figure 2.11.

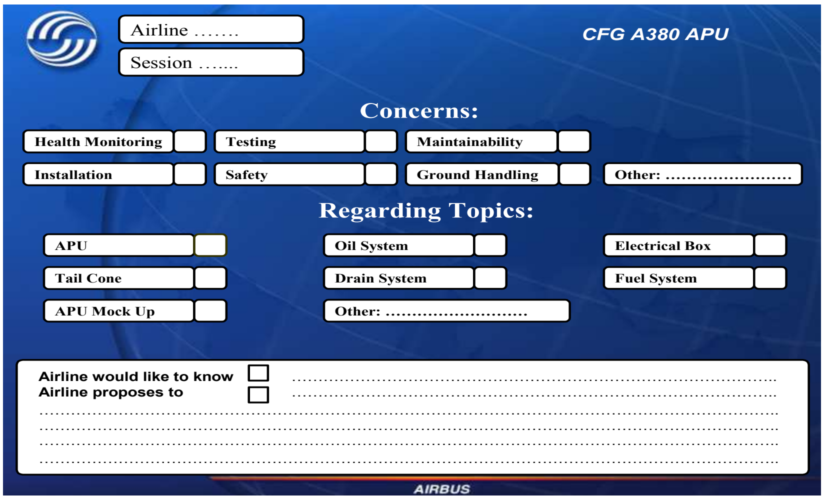


Figure 2.11: An example of Capture sheet for a CFG dedicated to APU.

- During the CFG

A series of activities is deployed as shown in Figure 2.12. The objective is to capture as much customer requests as possible and to ensure these requests are appropriately understood by Airbus.

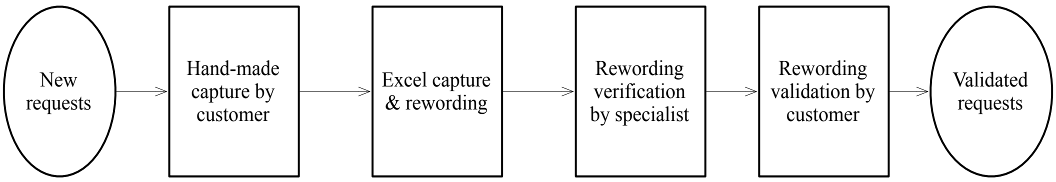


Figure 2.12: Process for ensuring quality of the requests captured during CFG.

In addition to the list of requests they have to validate, customers have the possibility to provide additional comments/answers to all requests that have been recorded. This is done by showing the complete list of requests somewhere in the meeting room all along the CFG. Before the end of the meeting, specialists and customers are provided with a list of all requests sorted by topics through affinity diagram. Customers are also invited to provide Airbus with a summary of their highest priorities.

- After the CFG

In the week following the CFG, a report is established that contains the entire list of requests sorted by topic and by customer. Some indicators are provided that show:

- The ratio of requests per topic.
- The ratio of requests per concern.
- The ratio between question and proposal.

Requests are managed by Airbus until all requests have received adequate answer. Requests and answers are the source for the specified requirements. Before the next CFG, customers are provided with the complete list of requests and associated answers. The activities after the CFG are shown in Figure 2.13.

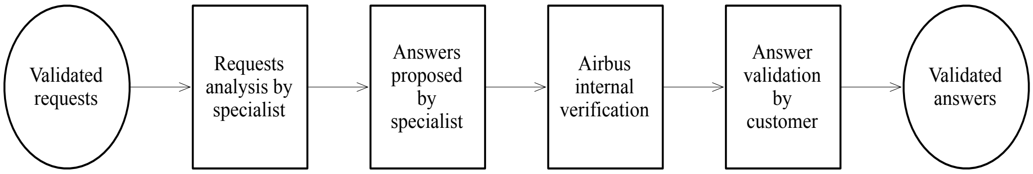


Figure 2.13: Process for ensuring quality of the answer after CFG.

2.3.2 Rolls-Royce Practice

Rolls Royce has established methodologies and tools for requirements establishment. Best practices are based on their recent project experiences, including the Trent XWB.

The practices are listed in Table 2.3.

Table 2.3: A list of methodologies and tools used at Rolls Royce.

Methodologies and tools:
1. Basic stakeholder requirements elicitation
2. Systematic textural analysis
3. Viewpoint analysis
4. Quality function deployment
5. Functional analysis
6. Sensitivity analysis
7. Scenario/use cases

- Basic Stakeholder Requirement Elicitation

A key issue is to understand what is needed and to ensure the context is understood, e.g. is it a tangible product, a less tangible service or some product-service combination that is needed.

A two-way bottom up and top down approach is suggested. The solution provider can identify what requirements are needed to enable the development of a solution. The caveats are to check the source of the requirements and to beware that solutions can be generated without considering all of the stakeholder requirements, i.e. the solution provider may think he knows all the requirements based on past experience, whereas in fact ‘unexpected’ requirements may now exist. This is often reflective of a situation where derivative design dominates the approach.

For each identified stakeholder, establish what are the principle functions/requirements they require and what are the secondary functions/requirements they need. The secondary requirements may well be implicit but equally expected and generally more difficult to capture. For each requirement, a detailed assessment is needed to ensure clarity and to check for quality, consistency, understanding and completeness.

- Systematic Textual Analysis

This looks at the requirements that have been expressed and starts the process to structure them and identify any gaps or shortfalls. The start point is to consider the requirements from a system viewpoint and classify them into operational, functional and non-functional (NF). The NF requirements further sub-divides into NF-Performance, NF-System and NF-Implementation requirements.

The operational requirements define the major purpose of a system, i.e. what it fundamentally does. The Functional Requirements specify what the system has to do in order to satisfy the operational requirements and are usually expressed as a verb (or verb noun phrase). The aim should be to write the functional requirements in a way that does not pre-suppose a solution. The NF requirements do not contain a verb and provide constraints on the system/product. The performance is the constraints on the particular functions. Typically they comprise a measure and a target value, (e.g. Range >3500 Km). The NF-System requirements define constraints that affect the whole system, (e.g. weight, reliability, maintainability, system cost). The NF-Implementation requirements are specific solution orientated requirements stated by the customer.

- Viewpoint Analysis

This technique exposes the basic requirements and can be used to help identify and structure the functional and NF requirements of a system. This approach is important because the basic requirements are often not explicitly expressed. They may be low in customer satisfaction and excitement but they are an enormous source of customer dissatisfaction if they are not met (partly because they are so basic).

- Functional Analysis

This technique is a key methodology for bridging between requirements and solutions. Generally this technique is powerful for identifying interfaces and dependencies between requirements, it can also identify functions or requirements that have not been asked for or assumed.

- Sensitivity Analysis

Sensitivity Analysis looks at the issues that would delight the customer. When using this technique, be sure that the identified functions are ones whose value customers or stakeholders are prepared to pay for or invest in. The increase in complexity of systems/products has resulted in many systems displaying undesirable emergent properties. This approach can also be used to gauge interaction between the functions and therefore associated risk.

- Quality Functional Deployment

Quality Function Deployment, particularly the house of quality, is used to integrate the whole together. The house of quality is an essential technique to ensure robust flow down of customer needs through functional definitions. It is especially useful at the stage when the customer needs are not yet specific and quantified. The house of quality is centered on translating customer needs into functional/technical requirements.

- Scenarios planning/Use cases

These are most appropriate when there is an attempt to change the market by pushing a new capability that customers and other stakeholders are not really aware of, (at least for the first iteration) or in a situation well into the future where some form of possible external environment is assumed. In other words the customers/stakeholders may not be aware or understand that something could be a needs. This tends to need some form of demonstration to help understand the potential relevance. This approach is often used in capability acquisition programs.

2.3.3 Volvo Practice

The area of requirements establishment at Volvo Aero encompasses several disciplines and routines. In the Table 2.4 below is a series of activities at Volvo Aero wherein methods/activities are presented.

Table 2.4: Requirements establishment practices at Volvo Aero.

Activities:
1. Foresigthing
2. Requirements identification
3. Requirements decomposition
4. Requirements management
5. Customer satisfaction survey
6. Brand survey

- Foresigthing

The objective of “foresigthing” is to organize and clarify forthcoming needs and expectations of customers and markets in general. The results are used as input to strategic product planning. The reason is that lead-time to introduce new technology spans over several decades.

The work is typically Workshop-based, highly visual and performed with several stakeholders simultaneously. It ranges from sketching out needs, expectations, occasions, key events and status of solutions graphically in a sheet or at a whiteboard. Subsequently there is a search-phase for finding facts to the events initially mapped out. Identification can be made forward-looking (what can/may happen) and backward looking (what has happened and when). This work with “foresigthing” is more "scientific-like" than scenario planning, which is still the dominant technique used in early phases. The actors are internal stakeholders mainly. It is also undertaken together with major partners.

- Requirements Identification

The objective is to identify and decompose strategic (often publicly) requirements, such as the (political) objectives/targets of Advisory Council for Aeronautic Research in Europe and international governing organizations, such as International civil Aviation Organization, Federal Aviation Administration and European Aviation Safety Agency.

This is conducted by strategic technologist work. Another important technique is systems performance modeling and simulation. The characteristics of forthcoming engines are compared to targets and eventually expected pre-conditions for Volvo Aero technologies and solution strategies. Actors within the work can be either fully internal by specialists in technology or together with key partners (bi-lateral). Part of the work is conducted within European programs such as the Clean Sky initiatives. Eventually the work is a part of establishing contracts with engine OEM's where Volvo Aero's role in engine development programs is defined.

- Requirements Decomposition

The objective is to derive design requirements specific and internal to the subsystem, which Volvo Aero is to design. This is done as an early activity in the product development process. Requirements are extracted and defined following internal requirements engineering procedures under leadership of design leaders in the product development team. Typically, the OEM's Engine development team is tightly involved in the process.

- Requirements Management

Throughout development, changes to requirements and their verification status are continuously managed. Traceability and version management are important during this phase.

- Customer Satisfaction Survey

The objective is to gather how we perform as a partner and what high level expectations do the customer have on Volvo Contributions/products. Methods used is a survey comprising of a set of questions, such as "What is the perception of Volvo Aero's performance in {this aspect}", comparing to competitors. The surveys are web-based surveys and directed to key stakeholders with whom we already work. Frequency is bi-annual.

- Brand surveys

The objective is to gather general expectations on Volvo Aero as a company and its products and services. Examples are what attributes are relevant/associated with the Volvo brand. These surveys are interview-based as a contrast to "Customer Satisfaction" surveys. Customers are asked to relate the Volvo brand to values and perceptions. Actors are typically senior representatives within existing customers and potential customers, and these surveys are conducted bi-annually.

2.3.4 Synthesis

These practices represent a set of current best practices adopted in main companies in European aerospace industry. They are systematic and operational to some extent and help engineering requirements for airplane, engine and engine sub-component, respectively. Airbus uses the CFG for capturing customer expectations and needs, and deploys a life cycle from customer expectations to product on aircraft level. Rolls Royce emphasizes methodologies and tools used for requirements establishment on engine level. Volvo describes activities and its supporting methods necessary for a sub-system provider that needs to understand the conditions that drive the need to sub-systems. Although there are difference about levels in aircraft development and a little inconsistencies about the presented practices (Airbus and Volvo Aero practices are process-focused (or activities-focused) while Rolls-Royce practice is methodological-based. And the granularities and scales of the three practices may not be at the same level. In fact, it is really too difficult for us to coordinate and align these inconsistencies because of some communication and confidential reasons), one important aspect is obvious: they fail to clarify clearly the value and value model in the requirements establishment process, which is necessary to make value trade-offs and design trade-offs.

A table will clearly show the relationships between the three practices and the contribution of the PhD thesis with regards to requirements establishment and value modeling, which is given in Table 2.5.

Table 2.5: Relationships between the three practices and the contribution of the PhD thesis

	Airbus practice	Rolls-Royce practice	Volvo practice	The PhD thesis
Requirements establishment	Yes	Yes	Yes	Yes
Value modeling				
VDD	No	Yes	No	Contribute to
DBD	No	No	No	Contribute to
Preference modeling	AHP only	Not sure	No	Yes

All these three practices are used for requirements establishment but have little focus on value modeling. Some exceptions can also be found. For example, VDD is being deployed in Rolls Royce. Critically, the missing of value concern in the requirements establishment is obvious, which the PhD thesis focuses on. More precisely, the thesis proposes an approach to derive value-based requirements specification through integrating a selected requirements establishment approach (QFD is finally selected as shown in the next section) and preference modeling (multi-attribute utility theory). And it contributes to requirements establishment and value modeling practices in the companies.

2.4 Approaches Evaluation and Selection for further Development

The state of theory and state of practice analysis have shown several potential different approaches that are used for understanding customer needs and engineering of requirements, such as CFG, QFD, Ulrich and Eppinger approach (Ulrich and Eppinger 2007) and advanced product planning (Agourida 2006(a), 2006(b), 2008). Although they are problematic as approaches to drive value-based requirements specification, they form the foundation of developing appropriate approach to understand customer value in the requirements establishment. Therefore, an evaluation among these selected approaches is deployed in order to select one of them for further development. That is, the finally selected approach will be further developed by integrated with approaches from value modeling.

2.4.1 Evaluation Criteria

The discussions with the CRESCENDO industrial and academic partners in WP2.2 workshops have helped identifying the gaps and ideal consequences for value-based requirements establishment. Analyzing and synthesizing on these information it is possible to extract a set of guidelines for comparing the approaches:

- The approach shall be systematic and structural. It helps transforming customer needs into requirements in a systematic way. It also helps tracing of strategic intent and their inherent abstract relationships.
- It should provide the mechanism to establish real needs from initially collected statements. Tacit (conscious) and latent (subconscious) needs shall be identified from expressed statements, although it is impossible to elicit all the tacit and latent needs.
- Before measurement of value is possible, attributes are necessary to measure attainment of customer needs. Without consciences of attribute attainment, it is impossible to appropriately measure value.
- Value measurement means to quantify the value contribution of design alternatives. If there is a set of design alternatives, the value contribution of every design alternative can be reasonably calculated and used for design decisions. To enable value measurement, objective functions or value models are necessary.
- Needs, requirements and value model are outputted visually, and simulation of value fulfillment is possible. Visualization and value simulation will enable the developed models as integrated part of simulation world through which the desired benefit can be obtained.

2.4.2 Evaluation and Selection

An evaluation among the four approaches of requirements establishment is deployed on the basis of these guides. It is shown in Table 2.6. Other methods, such as affinity diagram, KANO models are not in the list for comparison, as they are possibly acting as supporting methods or tools in a more systematic approach, such as QFD and Ulrich and Eppinger approach (Ulrich and Eppinger 2007).

Table 2.6: A benchmarking of four requirements establishment approaches.

	CFG (De Chazelles *et al.* 2004)	QFD (Hauser and Clausing 1988)	Ulrich and Eppinger approach (Ulrich and Eppinger 2007)	Advanced product planning (Agourida 2006(a), 2006(b), 2008)
1. Systematic and structural	Yes	Yes	Yes	Yes
2. Real customer need needs	Not sure	A set of tools is used, such as affinity diagram, voice of the customer table, but there is a potential to confuse means-ends and part-whole relationships.	Yes	Yes
3. Attributes for customer needs	No	No	No	No
4 Value measurement	No	An additive linear function form is used directly without verifying appropriateness of underlying assumptions	(1): Weights of customer needs are given qualitatively, or (2): conjoint analysis is used to derive weights	Weights of customer needs are given qualitatively
5 visualization and simulation	No	Yes	Similar to QFD	No

This comparison provides insights for developing another approach to combine the advantages of existing approaches. In view of effectiveness regarding to the listed criteria and popularity of QFD-based approach in industry practice, QFD is finally selected as the basis for further development.

2.5 Conclusion

In this Chapter, we review the state of theory of relevant researches that contribute to establishing of value-based requirements specification, and the state of practice of three industrial partners in requirements establishment.

The investigation of state of theory is categorized into two main topics:

- Requirements establishment. Two relevant contexts of system engineering and engineering design are examined to clarify how requirements specification is established in respective context. Some typical standards, processes, methods and/or tools are identified and analyzed with regards to their appropriateness to derive value-based requirements specification, and

- Value modeling. There are two relative new research paradigms about value modeling for system development. One is the VDD in the AIAA community, and it is usually used for development of aerospace and defense system. The other is DBD in the engineering design community, and it is usually used for development of consumable products. VDD and DBD are analogue in the spirit that is to design product with maximum value, and they all declaim their strong dependence on preference modeling. But they are different in how the value is formulated, such as the methods used to model value and dimensions of value. After discussion of VDD and DBD, preference modeling is then discussed, such as multi-attribute utility theory, which is used in our later chapters for value modeling in requirements establishment.

We realize the large body knowledge of requirements establishment and value modeling, and the review is not exhaustive because of time limit and other constraints. But it constructs useful inputs to develop a new approach to derive value-based requirements specification.

Three industrial partners' practices in requirements establishment are also exanimated. The missing of value and value model in their practices is obvious. The positioning of the thesis with regards to the three practices is also discussed, which helps forming the idea of application context.

A benchmarking of four approaches for requirements establishment is deployed in terms of a set of evaluating criteria. QFD is finally selected as the basis for further development. In the next Chapter, we will discuss the potential methodological problems of QFD in detail with regards to an approach to derive value-based requirements specification from initial customer statements.

3 Foundations of Approach Development

The aim of this research work is to develop a practical approach to derive value-based requirements specification from initial customer statements on the basis of sound theory and methods. It should be applicable to engineering requirements of complex systems, such as commercial aircraft, space systems and so on. After a thorough investigation, discussion and comparison in Chapter 2, QFD is finally selected as the methodological foundation for further development. The objective is then to then to integrate QFD with theory and methods from value modeling. However, QFD suffers from several methodological problems that might hinder value-informed design decisions. Therefore in this chapter, an introduction to QFD and its methodological problems is given in Section 3.1. In order to resolve these methodological problems, a set of theories and methods are introduced in Section 3.2. In Section 3.3 two assumptions are made about the approach to be developed. In Section 3.4 the desired effects to be achieved are discussed. Finally, in Section 3.5 conclusions are drawn.

3.1 Quality Function Deployment and its Methodological Problems

3.1.1 Introduction to QFD

QFD was originally developed in 1972 at Mitsubishi's Kobe shipyard site in Japan (Hauser and Clausing 1988) (Bode and Fung 1998). It is now widely used not only in Japan, but also in worldwide. There are wide applications of QFD in aeronautical industry, such as in Airbus and Rolls-Royce, plc. The foundation of QFD is the belief that products should be designed to reflect customers' desires and tastes, so marketing, design and manufacturing departments must work closely together from the time a product is first conceived (Hauser and Clausing 1988).

It is a systematical methodology to implement customer needs in product design and development by deploying four-stages of quality planning, that is, product planning, product design, process planning and process control. Customer needs act as the drivers of engineering design and manufacturing activities and play an important role in QFD. We focus our attention on the first house, that is, house of quality, which is mainly for establishing requirements specification. An example of the structure of house of quality and its application are shown in Figure 3.1(Hauser and Clausing 1988).

A process underlying the house of quality for thinking about customer needs (called customer attributes in QFD) includes the following steps (see Figure 3.1):

1. Identify and structure customer attributes,
2. Assign relative weights to customer needs,
3. Incorporate customer perceptions with a perception map,
4. Transform customer needs into engineering characteristics (ECs) with a relationship matrix,
5. Make trade-offs between ECs with a correlation matrix, and
6. Set targets of ECs for maximizing customer satisfaction.

It is believed that systemic thinking of these elements necessarily contributes to the understanding of customer needs to some extent, even if they are made qualitatively (Hauser and Clausing 1988). The house is also useful for organizing the available information and for inter-functional planning and communication. Those are possibly the reasons why QFD has been successfully applied in industrial and engineering practice for customer-focused product development. However, the quantification within the QFD is problematic as the quantification is made on the basis of strong assumptions.

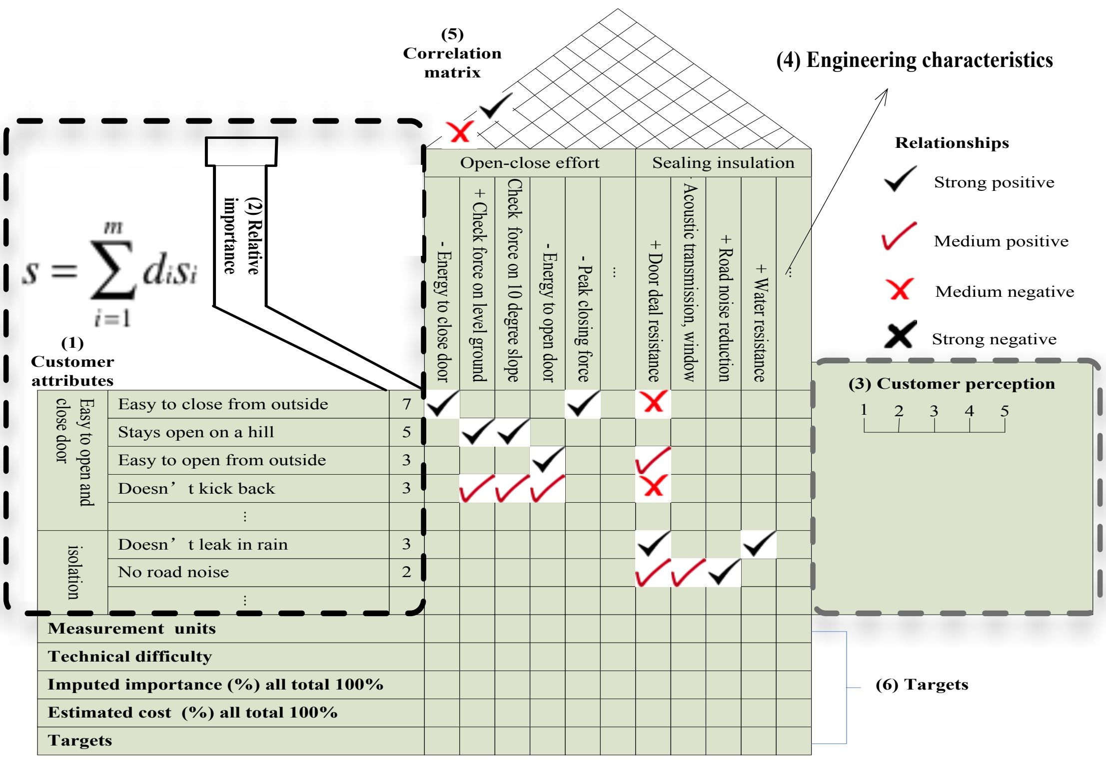


Figure 3.1: The structure of the house of quality and its application (Hauser and Clausing 1988).

Typical variables and calculations in the house of quality are introduced in Table 3.1. They are introduced to facilitate illustrating the methodological problems in terms of quantification. De Poel gives extensive discussion about some of the methodological problems in (De Poel 2007). We also find out other possible methodological problems. The list of the methodological problems is listed in Section 3.2.

Table 3.1 Typical variables and calculation in the house of quality from (De Poel 2007)

d_i	Degree of importance of the i^{th} customer need
s_i	Degree of attainment of the i^{th} customer need
e_j	Degree of attainment of the j^{th}engineering characteristic
a_{ij}	The intensity with which the j^{th}engineering characteristic affect the attainment of the i^{th}customer need
w_j	The weight of the j^{th}engineering chracteristic
z_{jk}	The correlation between the $j^{th}$and k^{th} engineering characteristic
B	Available budget
S	Overall customer satisfaction: $s = \sum_{i=1}^{m} d_i s_i = \sum_{i=1}^{m} \sum_{j=1}^{n} d_i a_{ij} e_j = \sum_{j=1}^{n} w_j e_j$

3.1.2 Methodological Problems in QFD

The thesis identifies seven methodological problems in QFD that may hinder the design optimization based on customer values. There are possible other problems, but we limit to these problems that will be resolved by the proposed approach in the thesis. These methodological problems are:

P1. Different levels of customer statements are not structured with sound logic. There are many possible customer needs, product features and forms, ECs, goals, attributes, constraints or design parameters in the elicited customer statements (Zhang *et al.* 2010(c), 2011(a)). Simple inclusion of all related or similar statements in the same groups is not appropriate and introduces unnecessary complexity to quantitative modeling in later stages of the design process. Furthermore, an important opportunity to uncover implicit customer value can be overlooked and missed. This problem is common in the whole class of affinity diagram based approaches or when a certain cluster algorithm is used to cluster statements on the basis of similarity. Typically, a hierarchy is produced with these methods. For example, a hierarchy of "It is easy to use" of digital camera is given in Figure 3.2 (Bayus 2007). An intuitive thinking might consider this hierarchy as a useful structure. However, in reality, it actually poses some problems. The customer needs "Take great photos" and "Is portable" are two parts of the whole "It is easy to use". These part-whole relationships are modeled in a hierarchy. However, features, such as "Scene mode" and "Auto flash", are means to influence "Take great photos" with means-ends relationships between them. Not only will "Optical and digital zoom lens" influences "Take great photos", but also influences

"Light weight". It is not possible to combine these two types of relationships together in a hierarchy and these means-ends relationships would be more appropriately modeled with network. This basically hinders uncovering implicit customer needs and poses difficulty to verify independence conditions of preferences.

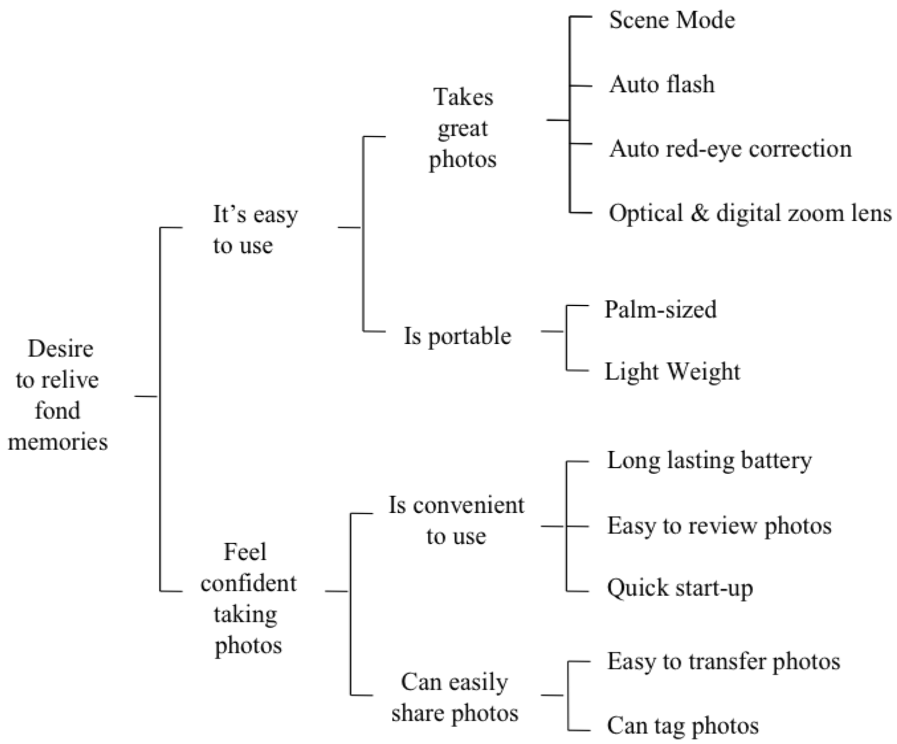


Figure 3.2: A hierarchy of customer statements about a digital camera (Bayus 2007)

P2. Weights of customer needs are usually assigned without considering attributes for measuring customer needs. The reason is obvious as there are always no available measurable attributes for customer needs in the house of quality. However, it introduces another difficulty, i.e. assigning meaningful weights for customer needs as shown in Figure 3.3. In this example, the relative weights of "acquisition cost" and "environmental cost" are all depending on how much "acquisition cost" and how much "environmental cost".

Therefore, it is necessary to consider attribute information of customer needs in order to assign reasonable, relative weights or orderings. This includes attribute information of the selected customer needs' and other attributes' information. When the set of attributes is large, it will be more difficult to assign consistent weights for attributes in the set. Then equations on basis of value trade-offs shall be established and consistency checking shall be performed. For more sophisticated applications involving uncertainty in attribute achievement and non-linear function form over single attribute, theory is still needed to provide rigorous basis to assign appropriate weights.

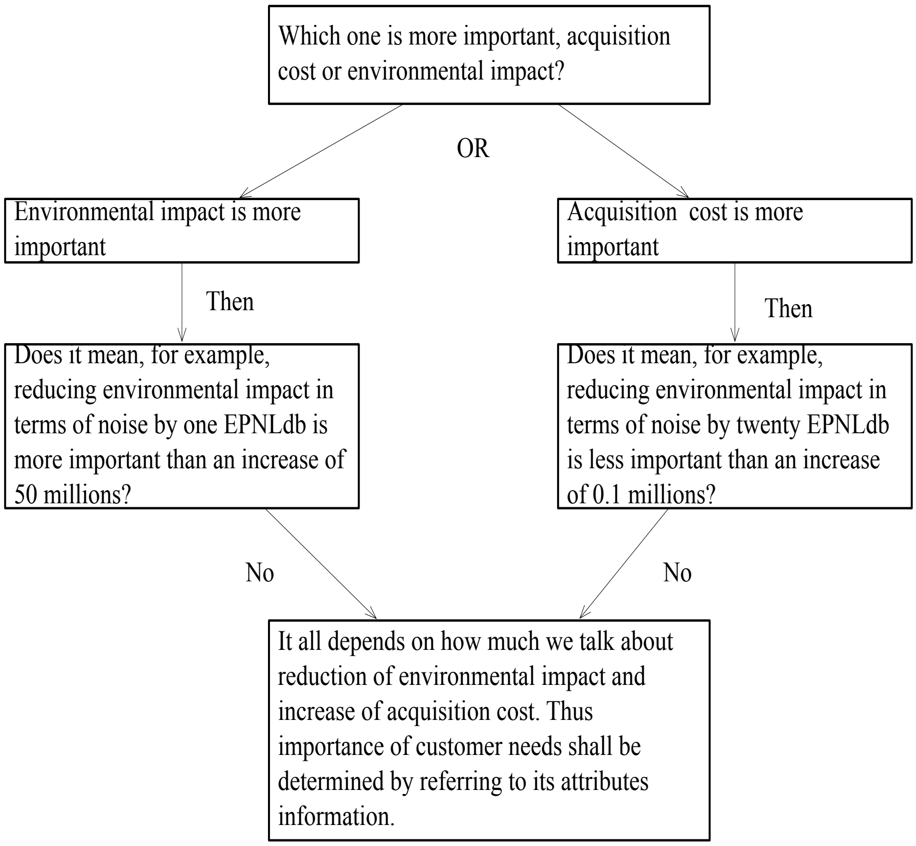


Figure 3.3: Which one is more important in context of selecting commercial airplanes?

P3. Ranking and weighting are two different kinds of preferences as the former is ordinal while the latter is cardinal. Rankings, such as 1-5 or 1-3-5-7 are not allowed to arithmetical operations, e.g. add, subtract, multiply, and divide. But it is possibly violated in QFD in which the ordinal rankings are used arithmetically to compute the importance of ECs. There is also a controversy about QFD's inability to aggregate group preferences. However, it is not the problem of QFD itself. Instead it is the problem from the methods of assigning importance. When ordinal rankings are used for importance measurement, it is impossible to derive group preferences from individual preferences without violating a set of reasonable assumptions defined by Arrow (Keeney and Raiffa 1993):

A1. *There are at least two individuals in the group, at least three alternatives, and a group ranking is specified for all possible individual rankings,*

A2. *(Positive association of social and individual values): If the group ranking indicates alternative **a** is preferred to alternative **b** for a certain set of individual rankings, then the group ranking must imply **a** is preferred to **b** if:*

*I. The individual's ranking of alternatives other than **a** are not changed,* *II. Each individual's ranking between **a** and any other alternative either remains unchanged or is modified in favor of **a**,*

A3. *(Independence of irrelevant alternatives): If an alternative is eliminated from consideration, the new group ranking for the remaining alternatives should be equivalent to the original group ranking for these same alternatives,*

A4. *(Individual's sovereignty): For each pair of alternatives **a** and **b**, there is some set of individual rankings such that the group prefers **a** to **b**,*

A5. *(Non-dictatorship): There is no individual such that whenever he prefers alternative **a** to **b**, the group will also prefer **a** to **b** regardless of the other individual's rankings.*

This result can be better illustrated using a simple example with three customers and three customer needs in Table 3.2.

While 66% of customers (A and B) think that acquisition cost is more important than safety, and 66% of customers (A and C) think that safety is more important than environment impact, it is expected that the group (A, B and C) will rank acquisition cost as more important than environmental impact according to "transitive" principle of rational decision-making. However, 66% of customers (B and C) give a higher ranking to environment impact than that of acquisition cost. This demonstrates the impossibility of deriving group rankings from individual rankings of customer needs.

Table 3.2: Implications of AIM in deriving group ranking of customer needs

Customer	**Acquisition cost**	**Safety**	**Environment impact**
A	1	2	3
B	2	3	1
C	3	1	2

On the other hand, as ranking and weights are two different kinds of preferences, it is possible to do arithmetical operations on cardinal weights, and it is also possible to transform individual weights into group weights as proved by (Keeney 1975, 2009). This confusion between rankings and weightings leads to a misconceived limitation of the QFD method.

P4. Linear additive function form:

$$S = \sum_{i=1}^{M} d_i s_i \qquad (3.1)$$

is directly used to calculate (relative) customer satisfaction.

It is a variant of cost-benefit analysis (CBA). However, in fact we do not know what the composite measurement is while it is sometimes called merit or goodness, as there are no available axioms and theories about them. As cost is always an important dimension in customer decision of buying, we substitute equivalent monetary value in CBA for merit or goodness for illustration, which results in the same implications.

The CBA estimates and combines the equivalent money value of the benefits and costs to make an informed decision on the basis of net present benefit or benefit-cost ratio. Three implicit assumptions are made:

- A common composite measurement, in this case, the equivalent monetary value measured in certain year dollars, is used. All other benefits and costs are transformed into an equivalent monetary value directly by using a set of conversion factors. However, all too often, important benefits may not be included in the list because it is not clear how a market mechanism may be conjured up to "price out" the particular benefits (Keeney 1993).
- An additive function form is used to compose benefits and costs, respectively. This implies that certain preference independences among benefits or costs are satisfied, which in fact should be subjected to a rigorous verification process. In practice, a set of measurements is usually used as a basis of conjoint measurement, but sometimes they are not in the same level and fail to satisfy certain conditions of preference independence. If they are used directly in CBA, it may result in double counting and, consequently, in an arbitrary decision.

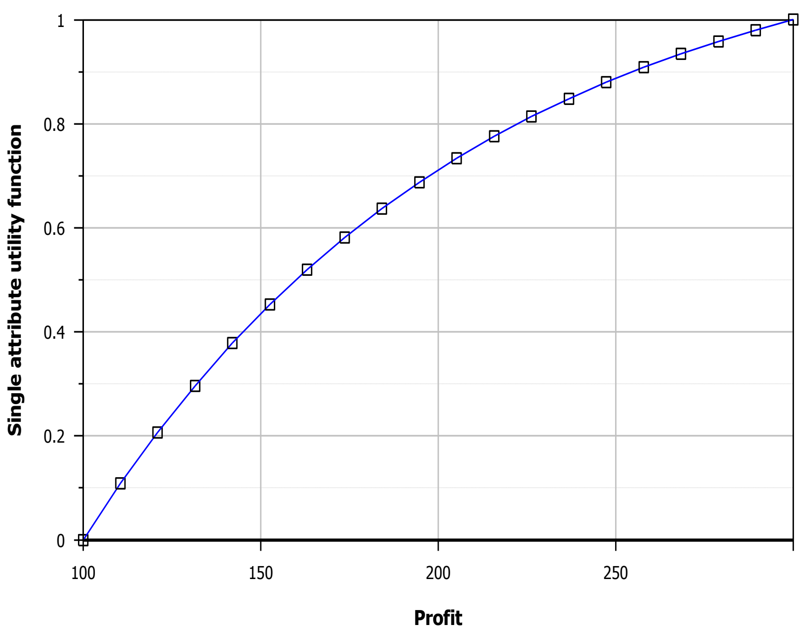


Figure 3.4: An example of single attribute utility function with a concave form.

- Linear function forms are assumed regarding to the relationships between equivalent monetary value and the achievement of benefits or costs, that is, every unit of benefit has the same equivalent monetary value. However, it is again only reasonable in certain situations. Counter examples can be found in the KANO model, marginal rate of substitution in economics and non-linear utility (or value) functions over single attributes. An example of single attribute utility function with a concave form is presented in Figure 3.4. In this example, 100 units has a utility of zero, 300 units a utility of one and 160 units a utility of half, which shows its nonlinear characteristic.

The forms suffer from inabilities to cope with uncertainties in objectives' achievement and corresponding risk attitudes of decision makers in operationally reasonable manner. However, it is necessary to incorporate this consideration in value assessment for rational design decisions, because there are always uncertainties in the design, and this is especially true about the economic parameters that are not under the direct control of designers. For example, fuel price is always a variable that is not under the control of designers, which cause uncertainty in the achievement of direct operational costs. Let's assume that there are two design alternatives with different consequences with regards to direct operational costs: one is a lottery with half possibility of achieving 100 units and half possibility of achieving 200 units, and the other has certain achievement of 140 units. Which one is more preferable? The answer is that all depends on the decision maker's risk attribute towards the uncertainty. If the decision maker is of risk neutrality or risk averseness, then direct operational cost of 140 units will be preferred. If the decision maker is of risk proneness, then further details are necessary to judge their relative priority.

P5. Two qualitative levels (strong and medium) are typically used to measure the strength of influence from ECs to customer needs in positive and negative cases, respectively. In this case, it is only qualitative as shown in Figure 3.1. There are also cases where the entries are filled with numbers, for example, by using 1-3-9 scales. In such a situation, the number is always positive (Hauser and Clausing 1988). Thus the negative influence is ignored. Then some ECs that have positive influences on some customer needs and negative influences on other needs will have higher weights. Even if negative influences is considered, a linear additive form:

$$s_i = \sum_{j=1}^{N} a_{ij} e_j \tag{3.2}$$

is used to model the achievement of customer needs. Then a strong assumption is made that different ECs have independent influence on the i^{th} customer need and that the influence relationships are of first-order. There are no influences resulting from the interactions between ECs or any other higher-order effects. These simplifications might make the weighting of ECs problematic and finally result in irrational targets and design decisions.

P6. The nature of correlations between ECs can be quite complex (Ramaswamy and Ulrich 1993). Higher achievement of one EC may impact positively or negatively other ECs (see Figure

2.1). The intensity relationship z_{jk} between them may not be constant and it may even change in terms of the signs of impact, because ECs are usually not the independent variables that can be set by engineers directly. They are dependent variables while the design parameters that can be changed directly are independent variables. Z_{jk} can only be modeled appropriately by identifying the common design parameters between EC_j and EC_k. So making design trade-offs among ECs based on correlation matrix is not appropriate and should be extended to include design parameters that are arguments. If an engineering model of performance exists, it is straightforward to combine the value model and the performance model to enable integrated optimization, which optimizes design from controllable design parameters to customer value without concerning to the middle step of setting ECs. However, having performance models sometimes is a luxury, and the situation is more suitable for improving existing products rather than for developing new products. Performing means-ends analysis is an alternative to structure traceable relationships from design parameters to ECs and provides knowledge for trade-offs between ECs.

P7. Setting targets for ECs is an important decision in the house of quality. It is analogue to a resource allocation problem that is intended to maximize customer value under various constraints, e.g. cost, functionality and performance. We think that this process is appropriate when the ECs are design parameters and are directly controllable by the engineers. But ECs normally are not directly controllable as design variables. When ECs are in a high level of system, such as range, payload, maximum take-off weight and minimum landing field length, the achievement of targets will subject to many constraints from low-levels and might not be known at the preliminary design stage. Therefore, it is possible to set unrealistic design targets. Instead of setting targets for ECs, we think it is more useful to establish a value model at every level and then to use the value model for design and optimization. When design alternative is optimized with regards to the value model of the corresponding level, then system is optimized, which is a very desired feature for large and complex system development. Thus the approach will conform to the prospect of VDD.

This list of the methodological problems is the problems existing in the main steps of the house of quality. P1 is about the structuring problem of customer statements. P2, P3 and P4 are about the problems of value measurement. P5, P6 and P7 are about the problems resulting from transforming customer needs into ECs. Theses problems will be resolved by the proposed approach. Before the proposition of the approach, theories and methods for resolving these methodological problems are introduced in Section 3.2.

3.2 Theories and Methods for Resolving Methodological Problems in QFD

After analysis of methodological problems of QFD regarding appropriate establishment of value-based requirements specification, a set of concepts, theories and methods are introduced. The corresponding relationships between problems and solutions are presented in Table 3.3.

The problem P1 is about how to structure customer statements in a logical and traceable way. The concept of "objectives", the methods of "means-ends objectives network" and "fundamental objectives hierarchy" are used to organize the means-ends relationships and part-whole relationships among customer statements. The problems P2, P3 and P4 are about how to quantify value in a meaningful way. The "multi-attribute utility function" is used to establish value model, which will resolve these three methodological problems. The problem P5 is about how to model the relationships between customer attributes and ECs precisely, and "response surface methodology" is introduced to approximate consequent models. The problem P6 is about extending trade-offs between ECs into trade-offs between design parameters, and "means-ends objectives networks" help resolving these concerns partly, if performance models could not be found. The problem P7 is about deriving component value models from the system value model, and the idea of VDD is adopted.

Table 3.3: From problems to solutions

Problems in QFD	Concepts, Methods and Theories
P1, P6	Objectives, means-ends objectives network, fundamental objectives hierarchy
P2, P3, P4	Attributes, multi-attribute utility theory, value model
P5	Response surface methodology, consequence model
P7	Value driven design

3.2.1 Objectives

Objectives are statements of something that one desires to achieve (Keeney 1992) (Bond *et al.* 2008). They are expressed in the form of a verb and a noun. For example, two of the objectives for evaluating commercial aircrafts when customers make their decisions are: maximize quality and minimize cost. Attributes are identified and selected to measure the attainment of objectives. For instance, cost measured in dollars is used to measure the objective "minimize cost".

Three kinds of objectives are necessary to organize sufficiently different types of customer statements: fundamental objectives, means objectives and strategic objectives. Their characteristics are shown in Figure 3.5.

For example, fundamental objectives in the context of purchasing a cordless drill are recognized as the fundamental reasons of interests of purchasing the product, e.g., “maximize comfort”, “maximize usefulness” and “minimize cost”. Means objectives may be design requirements or design parameters e.g., “maximize torque” or “maximize battery life”. Strategic objectives are much more essential and are for all possible contexts, e.g., “maximize quality of life”.

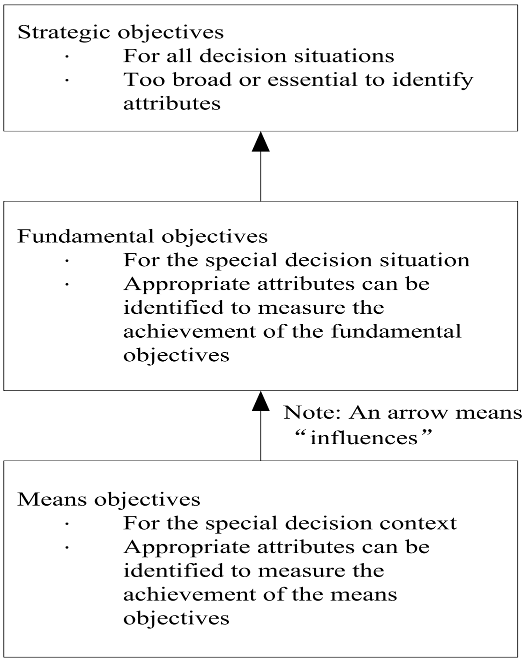


Figure 3.5: Three types of objectives

It is important to determine the current context of decision-making, as identification of fundamental objectives and means objectives depends on the selected context. Fundamental objectives in one context may become means objectives in another context. Means objectives in one context may become fundamental objectives in another context. For example, fundamental objectives, such as “maximize torque” and “maximize battery life” in decision context of “design of cordless drill”, are means objectives in decision context of “customer choice of cordless drills for professional work”. The attainment of “torque”, “battery life” influences the attainment of “usefulness”, “comfort” and other objectives. These relationships are graphically illustrated in Figure 3.6.

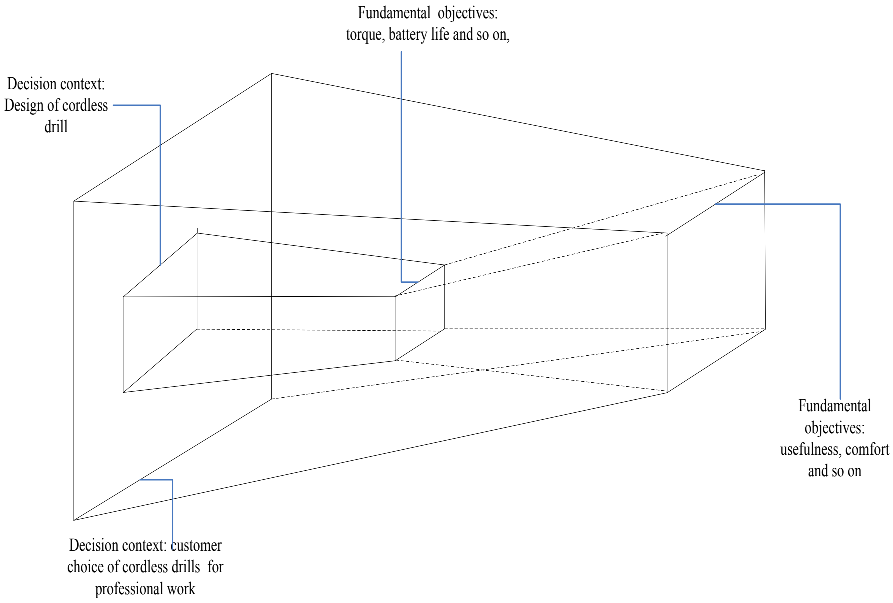


Figure 3.6: Decision contexts and fundamental objectives.

It is critically important to identify fundamental objectives in the identified context of product development or purchasing. It is the fundamental objectives that are the essential reasons of interests for customers. And it is much easier for customers to perceive the value about fundamental objectives. As customer needs are of essential and logical property, and are bound in the problem context, we equate customer needs to fundamental objectives in this thesis but with possibly in different expressions. However, customers need at least two steps to perceive appropriate value of means objectives (Keeney 1992).

A set of desired properties of fundamental objectives is following (Keeney 1992, 2007):

- ***Complete*** *– all of the important consequences of alternatives in a decision context can be adequately described in terms of the set of fundamental objectives.*
- ***Not redundant*** *– the fundamental objectives should not include overlapping concerns.*
- ***Concise*** *–the number of objectives, and sub-objectives, should be kept at a minimum that is appropriate for quality analysis.*
- ***Specific*** *– each objective should be specific enough so that consequences of concern are clear and attributes can be readily selected or defined.*
- ***Understandable*** *– any interested individual knows what is meant by the objectives.*

Compared with goals and constraints, objectives are more suitable for evaluating design alternatives and for the purposes of value-driven design, because in these cases attributes' range information from lowest acceptable level to highest desired level is collected from all possible design alternatives. They are not the same as goals and constraints that are satisfied or not. For instance, if a product development project has a goal of making a profit of $100 million in the coming year, this suggests failure if they make $99 million, and success if they make $101 million. Similarly, this preference does not really represent their real values. Suppose that there were two alternatives. One would guarantee a profit of $101 million and one had a 40/60 chance of a profit of $99 million or a profit of $200 million. Which alternative would the company likely prefer? They would likely prefer the second alternative, and yet the alternative that has a 40 percent chance of failing to meet the target, whereas the first alternative has no chance of failing. Goals that are listed with a target (i.e., the $100 million) are not very useful for evaluating alternatives or thinking about the relative desirability of alternatives (Keeney 2007).

Constraints have another shortcoming for evaluating alternatives (Keeney 2007). Namely, they eliminate alternatives that may end up being very desirable. Suppose a new product was being developed, and a constraint was that the product would need to weigh less than 5 kg. This would naturally eliminate any alternative that would weigh 5.1 kg. But what about the alternative if that alternative performed fantastically well on all the other objectives? It might clearly be the best. By eliminating the constraint, but including an objective such as minimize weight of the product, the relative significance of being 0.1 kg more than 5 kg, or 12 kg more than 5 kg, can be appropriately included in the evaluation of alternatives.

In the optimization process, constraints-based optimization may lead to an "optimized" design solution that is not optimized in customer value. Such examples are discussed in the value-driven design (VDD) community (Collopy 1996, 2009) as shown in Figure 3.7(a). By deploying requirements flexibility, formal optimization and a mathematical value model, it is possible to find a feasible solution that is maximum in value but is out of the scale of constraints as shown in Figure 3.7(b).

The situation can be also alleviated through imposing weaker constraints. For example, the cost constraint of "the cost should be less than $5 million" is extended to the constraint of "the cost should be less than $6 million." This will help exploring broader design space, and including design alternatives that may slightly violate previously given constraints, but yielding higher value for customers. Unfortunately, determining a reasonable degree of relaxation is subject to many considerations, such as the completeness of design space, the time and effort of the search.

Objectives and their attributes try to include the range information of all possible attributes, which enable a complete consequence space and their correspondingly broader design space.

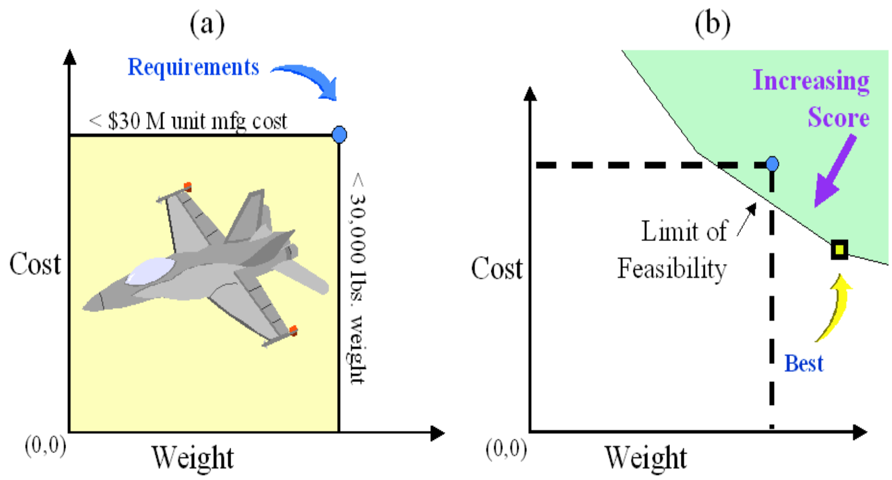


Figure 3.7: Optimization chooses the best design (Collopy 1996) (Cheung *et al.* 2010).

3.2.2 Mean-Ends Objectives Network

Causality is a common existence in the world and it is useful for interpreting the inherent reasons (or rationales) about the customer statements or choices. Means-ends objectives network is one possible way to organize these cause-effect relationships. Other possible techniques are reasoning maps (Nadkarni *et al.* 2004) and influence diagrams (Howard and Matheson 2005) with differently available capabilities of reasoning. In this thesis, means-ends objectives network is selected for the purpose.

Customers may possibly express, for example, the statement of “the battery voltage of the cordless drill should be higher than 12v”. However, battery voltage may not be the essential reason of interest to purchase the coreless drill. We can pursue the essential reasons by asking such questions as “why is the battery voltage important?” The reason may be that it is important because it provides more speed and torque, which further influence positively the usefulness of the cordless drill. Regarding to the question “why is usefulness of the cordless drill important?” the response may be that it is simply important regarding to the current development context. This indicates that the objective concerning usefulness of cordless drill is a fundamental objective in the purchasing context and it is a real customer need. Similarly, we can also ask how questions, for example, “How can that objective be well achieved?” This helps to identify possible means to influence the achievement of the higher-level objective and to discover creative design alternatives. At the same time, one means, such as torque, may influence several customer needs simultaneously. All these questions contribute to establishing a structure of causal network among different levels of objectives, and finding a set of fundamental objectives, which are at the highest level of the network. After this kind of reasoning process, means objectives and fundamental objectives are rationally and logically organized into a means-ends objectives network.

An example of means-ends objectives network is presented in Figure 3.8.

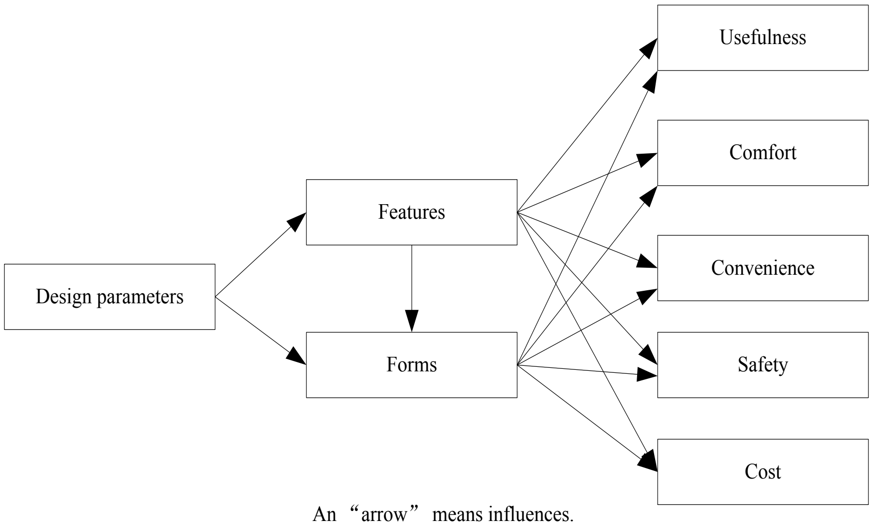


Figure 3.8: Part of means-ends network of cordless drill.

Cordless drill features, e.g., “chuck jaws”, “keyless chuck” and “handle”, are important because they are means to influence the achievement of forms, e.g., “compactness”, and customer needs, e.g., “usefulness” and “cost”. Forms are important because of their implications on customer needs. Customer needs, e.g., “maximum usefulness” and “minimum cost”, are important because customers think they are important in their context. By asking these kinds of why questions, it is possible to identify the customer needs hidden in the initial customer statements.

There are at least four potential benefits of using means-ends objectives network:

1. It helps to organize the objectives with cause-effect relationships. Then the traceability between the objectives are identified and maintained in a network structure. The rationales behind certain needs or expectations are found by pursuing “why” questions.
2. It helps to uncover implicit objectives hidden in the expressed objectives.
3. It helps to enhance understanding of customer value. By performing means-ends analysis, it is possible to identify fundamental objectives that are much easier to be perceived by customers. And thus, it is possible to produce more precise measurements of value. If fundamental objectives are not identified, then decision makers will have to make value trade-offs between means objectives, which are not desired. Assuming customers are provided with two attribute values, such as horsepower and torque, when they want to evaluate available cars, it might be very difficult for them to make beneficial value trade-offs between, say, an additional 20 pound-foot of torque and a reduction of 10 horsepower (Butler *et al.* 2008).
4. It is possible to reduce the possibility of double counting (Keeney 1992). There are usually a set of attributes provided by manufactures, say, torque, horsepower, and acceleration for cars. Means-ends relationships among them are verified after performing an initial means-ends analysis.

Torque and horsepower influence the achievement of acceleration. Therefore, an additive function form as a conjoint measurement to compute value is problematic, resulting in double counting the importance of torque and horsepower. Again, this issue is resolved by identifying fundamental objectives.

3.2.3 Fundamental Objectives Hierarchy

There is another abstraction layer that is commonly used in complex problem solving, that is, part-whole relationship. One kind of the part-whole relationships is parallel decomposition. It decomposes the whole unit in its current level into logical components in a lower level. These components should be mutually exclusive and collectively exhaustive. It is possible to perform part-whole analysis by asking such questions as “what do you mean about maximizing quality?” or “minimizing the mass of the car body is part of which objective?” Clarification of these questions will naturally result in a hierarchy. A hierarchy (or a tree) is a suitable way for clarifying and organizing fundamental objectives. An example of fundamental objective hierarchy is presented in Figure 3.9.

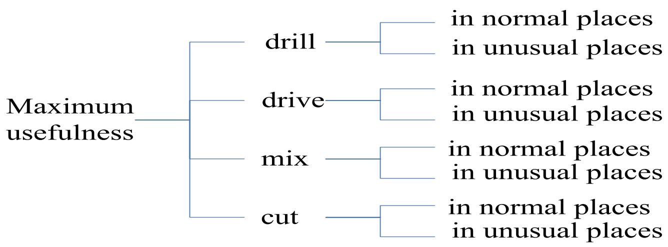


Figure 3.9: Fundamental objective hierarchy of “usefulness”.

The fundamental objective of “maximize usefulness” is in a high level too vague to be measured. Further questions should be pursued to clarify the exact meaning. By asking questions, such as “what do you mean by maximum usefulness?” it is possible to extend the understanding of “maximum usefulness” and to identify missing needs in the initial statements.

Two potential benefits of fundamental objectives hierarchy are:

1. It helps to check the completeness of objectives in certain level by asking “what” questions, and deepens the understanding of fundamental objectives in higher-levels by extending into lower-level objectives. With the same logic, it is possible to identify attributes for measuring the achievement of objectives that are in an appropriate level in the hierarchy.
2. It is easy to ensure mutual exclusion among fundamental objectives in the same level, reducing the possibility of double counting, and it provides a good input for latter verification of preference independence conditions.

A preliminary comparison between means-ends analysis and part-whole analysis is shown in Table 3.4.

Table 3.4: A comparison between means-ends analysis and part-whole analysis.

	Means-ends analysis	Part-whole analysis
Inherent abstraction	Causality	Part-whole
Typical questions to ask	Why the objective is important? (Top)	This objective is a part of what? (Top)
	How the objective can be better achieved? (Down)	What do you mean by that objective? (Down)
When to end asking questions	Why questions: an appropriate set of fundamental objectives is identified	Top questions: A common fundamental objective is identified for all relevant parts
	How questions: the current objective is under direct control of engineers and is measured by independent variants	Down questions: attribute can be identified for fundamental objective as high granularity as possible
Objectives to achieve	Structure and trace objectives in a logical way	Clarify understanding of fundamental objectives
	Find an appropriate set of fundamental objectives	Facilitate identifying attributes for fundamental objectives
Way of organization	Mean-ends objectives network	Fundamental objective hierarchy

3.2.4 Attributes

Attributes clarify the meaning of each objective and are used to measure the degree to which the objectives are attained. They are used to describe the consequences of alternatives in terms of objectives and are necessary to make meaningful value trade-offs between different attainments on objectives. It is important that the attributes be identified in order to enable rational value-informed decision-making. The term performance measure, measurement of effectiveness, criterion, and metrics are often used as synonyms.

A simple example of attributes illustrates this concern. Suppose a mobile phone manufacturer wants to develop a new kind of mobile phone to promote company's competitiveness. Two objectives are "maximize profit from the development program" and "maximize market share", respectively. Attributes for the objectives are "net present value of profit for two years (X_1)" and "percentage of the kind of mobile phone sold in the second year (X_2)", respectively. Then the consequences of the alternatives are represented as (x_1, x_2) where x_1 is a special level of attainment of X_1 and x_2 is a special level of attainment of X_2. Hypothetically, there are two alternatives. One has a \$100 million net present value with 12% market share while the other has a $150 million net present value with 10% market share. Which one is preferred? An evaluation between (100, 12%) and (150, 10%) is needed. Attributes are clarified and listed, as this is necessary to make meaningful value tradeoff between X_1 and X_2, and to enable rational decision-making.

However, identifying attributes is not a trivial task and needs special hard work, especially for some soft or intangible objectives, e.g. "enhance pride" and "maximize comfort". Theory and guidelines are needed to help identifying attributes and regulating this process.

Previous research has identified three different types of attributes: natural attributes, constructed attributes, and proxy attributes (Keeney 1992). Natural attributes are in general use and have a common interpretation. For example, in the context of cordless drill, the objective "minimize cost" has the natural attribute "cost measured in dollars"; the objective "maximize battery life" has the natural attribute "battery life measured in hours". Most natural attributes can be counted or physically measured. Information about alternatives often is collected is terms of natural attributes, so it is readily available or can be gathered without inordinate effort. Natural attributes also have a property that they directly measure the degree to which an objective is met.

Constructed attributes are developed to measure directly the objectives when no natural attribute exists. For example, in the context of aircraft safety, the objective "maximize safety" has a constructed attribute with four levels (Jenkinson *et al.* 1999) as shown in Figure 3.10.

Levels of safety - Categories of effect
(Joint Airworthiness Requirements)

Minor {Nuisance (10^{-2} to 10^{-3} per hour)}
(Concerned with fleet service management and thereby occurring several times in the life of the aircraft)
• Operating limitations, routine changes to flight plan, emergency procedures (10^{-3} to 10^{-5})
• Physical effects but no injury to occupants (less than 10^{-5} per hour)

Major {Remote (10^{-5} to 10^{-7} per hour)}
(Once in the operational life of an aircraft)
• Significant reductions in safety margins
• Difficulty for crew (adverse conditions which impair their efficiency)
• Passenger minor injuries

Hazardous {Extremely remote (10^{-7} to 10^{-9} per hour)}
(e.g. once in 20 years for a fleet)
• Large reductions in safety margins
• Crew extended due to increased workload or poor environment conditions (flight crew unable to perform their tasks accurately or completely)
• Serious injury
• Deaths of small number of occupants

Catastrophic {Extremely improbable (less than 10^{-9} per hour)}
(An unlikely event in the operational life of the aircraft type)
• Multiple deaths
• Usually total loss of aircraft.

Figure 3.10: A constructed attribute for "maximize safety".

This defined-level constructed attribute has four clearly defined levels: minor, major, hazardous and catastrophic. Every level is defined to an extent that will enable you to precisely judge the attainment of objective of different alternatives. This attribute is different from typical Likert five-point or several-point scales (Likert 1932). An example of Likert-scale is shown in Figure 3.11.

Likert-Scale

Use a Likert-scale question when you are trying to determine respondents' attitudes or feeling about something.

Example:
How important do you think SAT scores are to a collage student's success? (Select one):
Not very important O1 O2 O3 O4 O5 extremely important

Figure 3.11: A Likert-scale example.

In this case, the consequences associated with different ratings are ambiguous. It is hard to connect the special consequence to the special rating. For example, with a level of "3", it is hard for us to say the exact meaning, and even different people will have different perception.

A defined-level constructed attribute eliminates much of this ambiguity. The possible consequences of different levels should be chosen so that they cover the range of consequences and the difference in adjacent consequences is significant. To describe the consequences of an alternative of an objective using such an attribute, the judgments of people familiar with that attribute are necessary.

Proxy attributes are used when it is difficult to identify direct attributes to measure the attainment of objectives. For example, in the context of cordless drill, "torque measured in inch-pound" is an attribute used to indirectly measure the usefulness of cordless drill. But, customers care more about the practical usage of cordless drill in different situations rather than the torque itself. Introduction of proxy attribute causes difficulties to decision maker to make meaningful assessment of value. Then relationships between torque and usefulness must be established firstly, explicitly or implicitly, if proxy attributes are utilized.

Keeney proposed a set of desired properties of attributes to be satisfied when selecting of appropriate attributes. The set of five desired properties are following (Keeney 1992, 2005):

- ***Unambiguous*** *– a clear relationship exists between consequences and descriptions of consequences using the attribute.*
- ***Comprehensive*** *– the attribute levels cover the range of possible consequences for corresponding objectives, and value judgments implicit in the attribute are reasonable.*
- ***Direct*** *– the attribute levels directly describe the consequences of interest.*
- ***Operational*** *– in practice, information to describe consequences can be obtained and value trade-offs can reasonable be made.*

- ***Understandable*** *– consequences and value trade-offs made using the attribute can readily be understood and clearly communicated.*

These desired properties act as the objectives of selecting attributes when several attributes are available to measure one objective. Thus identifying and selecting attributes is another decision-making problem. The decision of selecting attributes follows such logic: if a natural attribute can be found that is comprehensive, direct, and operational, it should be selected. When this is not the case, effort should be done to construct an attribute. If there is no time for the effort or if it does not lead to a good constructed attribute, then a proxy attribute should be chosen.

A flowchart for selecting attributes is presented in Figure 3.12 (Keeney 2005).

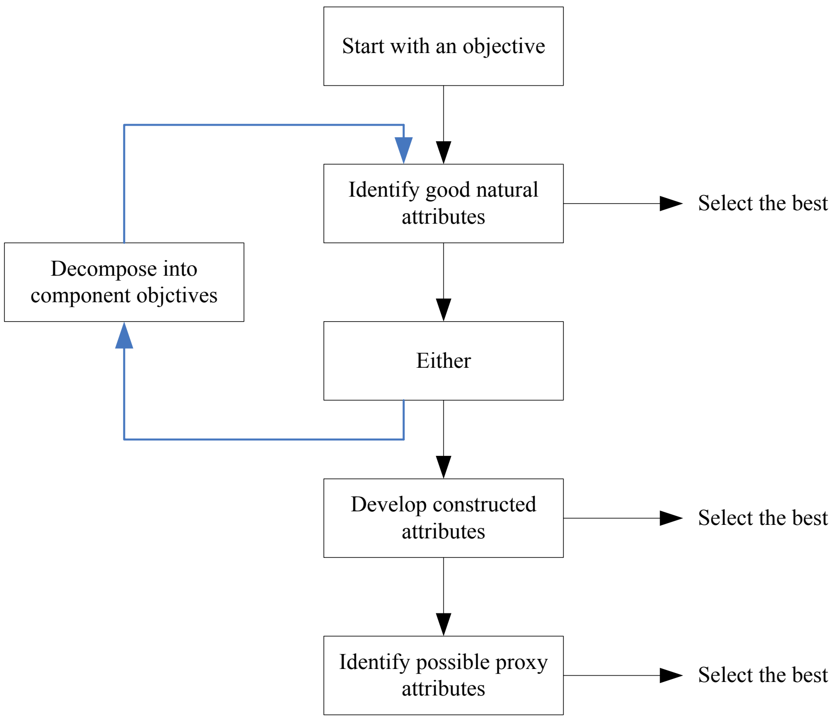


Figure 3.12: A flowchart for selecting attributes.

An important additional aspect is added in Figure 3.12. If a natural attribute is not available for one objective, it is possible that the objective is still in a too high level to be understood. Part-whole analysis is then continually performed towards the objective, and it is decomposed into several component objectives. The selecting process is then iteratively deployed.

3.2.5 Consequence Models and Value Models

In order to make more meaningful design decisions, the consequences of design alternatives must be inferred or observed by referring to output of consequence models first. It is then necessary to utilize the output of consequence models as the input of a value model in order to measure value achievement of the design alternatives. An illustrative example to represent the information flow between consequence models and a value model for aerospace product is presented in Figure 3.13.

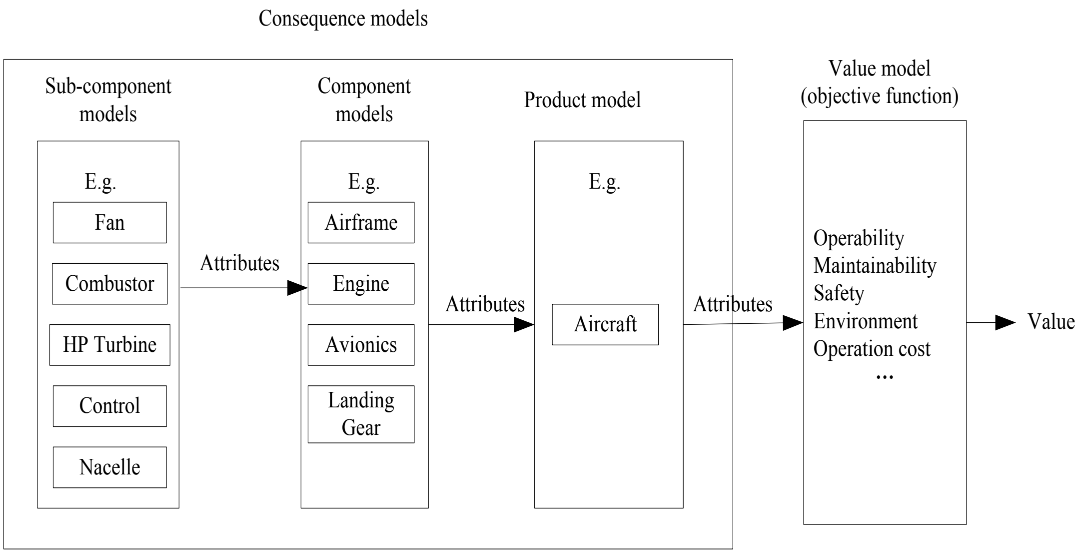


Figure 3.13: Value-informed design decision by combining consequence models and value model.

In traditional engineering design, attention is almost always put on the consequence models, and most of the product development time is spent on developing, modifying and verifying an elaborate simulation model of consequences. Typical examples of consequence models, which are modeled or approximated to reflect the physical mechanism in the underlying problem, are product performance models and cost models. A simplified example of a performance model for empty mass of a commercial aircraft is shown in Figure 3.14. A simplified example of a cost model for commercial aircraft is shown in Figure 3.15.

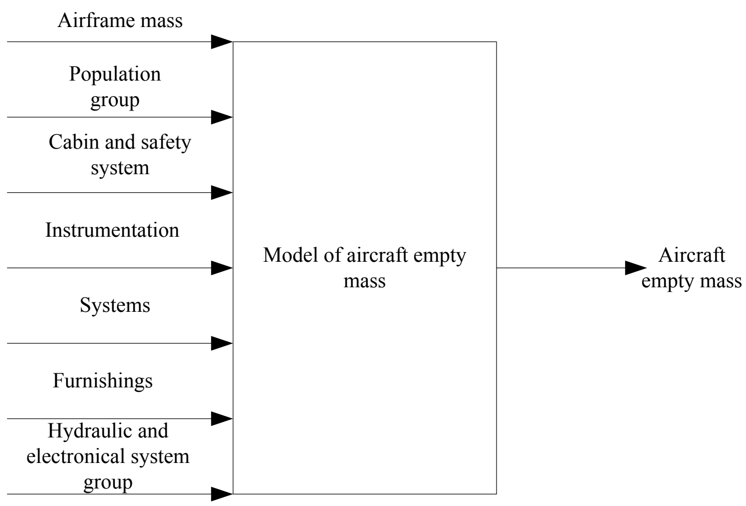


Figure 3.14: A model of aircraft empty mass

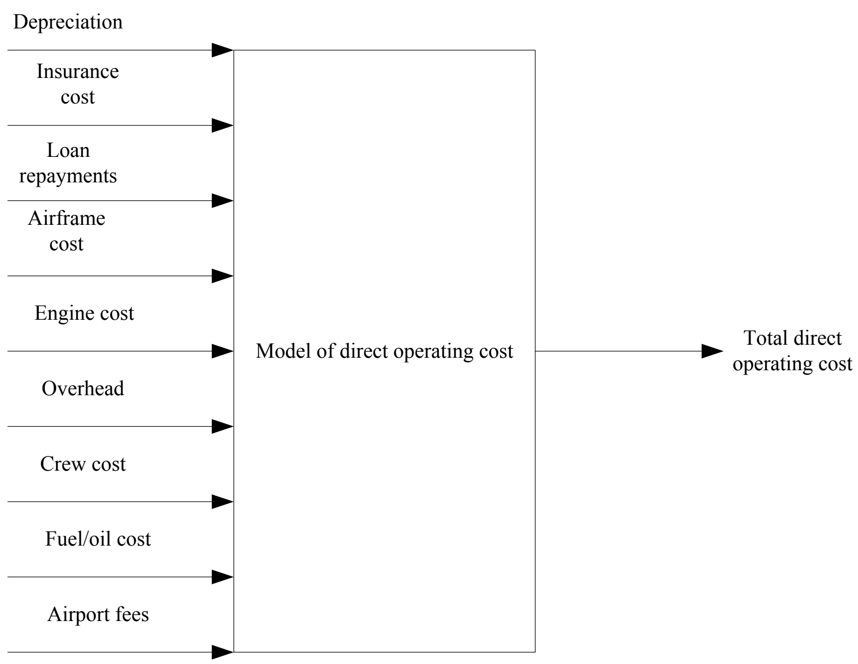


Figure 3.15: A model of direct operating cost

Engineers use many kinds of deterministic or probabilistic approaches to model performance or cost with high fidelity. Engineering expertise, knowledge, and design of experiments data are needed to figure out the parameters in the models. These models are useful for predicting the responses from a set of predictor variables. For example:

- How the fluctuation (or uncertainty) of fuel price influences the direct operation cost (DOC) of airlines?
- How the introduction of natural laminar flow technology improves aircraft drag?
- How the aircraft mass is estimated?
- How to set aircraft parameters to satisfy the takeoff field length of airports?

By considering all relevant consequence models together, it is then possible to reach a Pareto optimal frontier where it is not possible to improve one objective (for example, fuel efficiency) without worsening another (for example, engine cost). Optimization is made possible by maximizing or minimizing certain single desired objective (for example, minimize DOC or mass) with a set of constraints, which might result in suboptimal design solution(s) in terms of value.

However, there are still some new kinds of questions, such as:

- For 10% improvement in fuel efficiency compared with the base case, how much more acquisition cost are you willing to pay that will make you indifferent between them?
- Is the first 10% improvement in terms of SO_2 emission of the same value as the second 10% improvement?

- Which lottery would you prefer if you face with two or more lotteries?
- Which design alternative is of highest value for you?

These questions, instead of the questions concerning the consequence models, can only be answered by concerning to the decision makers who are responsible of making design decisions and to their value model. The necessary information for constructing a value model is all in the mind of the decision maker. It should be properly elicited and assessed through appropriate assessment procedures. Soundness of value model is checked through verifying consistency between identified preference data and constructed value model, while soundness of consequence models is tested or verified by corresponding to the reality, such as experimental data.

Value models are necessary to drive value-informed design decisions. They will necessarily contribute to multi-objective design optimization, evaluation of design alternatives, technology evaluation and others (Keeney 1992) (Collopy 2009). Simply, a value model is constructed to calculate a scalar value if an appropriate set of attributes is inputted. An example of value model is shown in Figure 3.16.

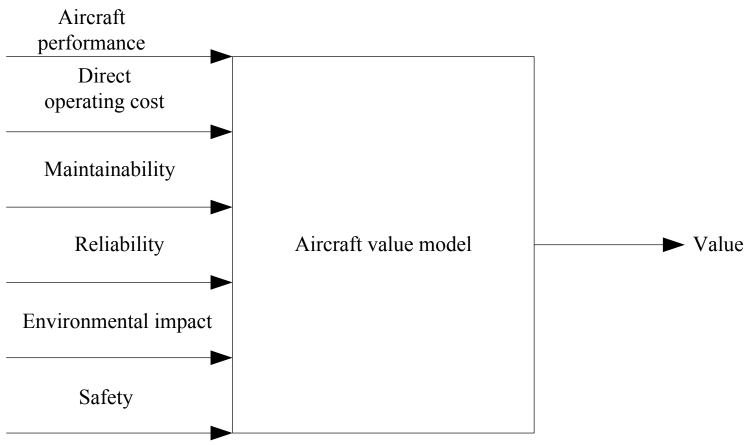


Figure 3.16: A simplified aircraft value model.

There are two types of available value models in the aerospace industry as investigated by (Collopy 2009(a)). Some of them are of one dimension while the others are of multi-dimensions:

- One-dimensional value model

  Surplus value is used as the single criterion to be maximized in VDD (Cheung *et al.* 2009) (Collopy 2001, 2009). As calculation of the surplus value is independent of the pricing and actions of the competitors, it is more stable than profit-based value models that are used in DBD (Wassenaar and Chen 2001) (Hoyle *et al.* 2006, 2007). However, these value models concern only on the economic aspect of the problem.

- Multi-dimensional value model

  There are mainly three types of approaches for modeling multi-dimensional value:

- Cost effectiveness analysis
- Cost benefit analysis (CBA)
- Multi-attribute utility analysis

In cost effectiveness analysis, different benefit measures are listed, but there is no attempt to combine the various benefit measures into a single, composite benefit measure.

CBA estimates and combines equivalent money value of the benefits and costs to make an informed decision on the basis of net present benefit or benefit-cost ratio. Example of application of CBA in aerospace industry can be found in (Collopy 2007). However, applicability of CBA is subject to satisfaction of certain preference independence conditions among attributes and linear functional forms over single attributes. Also, all too often, important benefits may not be included in the list, because it is not clear how a market mechanism may be conjured up to "price out" the particular benefits.

Multi-attribute utility theory is a systematic and mathematically rigorous approach for compositing a set of usually conflicting objectives with different incommensurable units into one common unit, which is called the utility. It helps customers to think hard about various value trade-offs and about the risk attributes towards uncertainty in achieving these objectives (Keeney and Raiffa 1993). Multi-attribute utility function (value model) is the result of performing utility assessment. With a properly constructed value model, it is then possible to calculate the value of different design alternatives, and to perform sensitivity analysis based on changes of weights and attribute values. It has been shown by (Zhang 2011(a), 2011(b)) that multi-attribute utility functions are more general function forms than cost benefit analysis, and the derivation of relationships among different function forms can be established when certain conditions are satisfied, which will be discussed later in this chapter.

3.2.6 Multi-Attribute Utility Theory

3.2.6.1 Utility

In economics, utility is a measure of relative satisfaction. Given this measure, one may speak meaningfully of increasing or decreasing utility, and thereby explain economic behavior in terms of attempts to increase one's utility. Two types of utility are distinguished: cardinal utility and ordinal utility. When cardinal utility is used, the magnitude of *utility differences* is treated as an ethically or behaviorally significant quantity. On the other side, ordinal utility only captures rankings rather than strength of preferences. In this thesis, the discussion of utility focuses on cardinal utility, and strength of preferences can be reasonable quantified and computed.

Based on a set of four axioms (Von Neumann and Morgenstern 1953):

- *Axiom (Completeness): For every A and B either $A < B$, $A > B$ or $A = B$ (this means: A is worse than B, better, or equally good) holds.*

- *Axiom (Transitivity): For every A, B and C with A≥B and B≥C we must have A≥C.*
- *Axiom (Independence): Let A, B, and C be three lotteries with A≥B, and let t ∈ (0,1]; then tA+(1-t)C≥tB+(1-t)C.*
- *Axiom (Continuity): Let A, B and C be lotteries with A > B > C; then there exists a probability p such that B is equally good as pA + (1 − p)C.*

von Neumann and Morgenstern derived the expected utility theorem:

$$E(U) = \sum_i p_i u_i \tag{3.3}$$

where p_i is the possibility of the i^{th} consequence, u_i is the utility of the i^{th} consequence, and consequences are discrete.

Or

$$E(U) = \int pu \tag{3.4}$$

where p is the possibility distribution of consequences, u is the utility function of consequences, and consequences are continuous.

3.2.6.2 Independence Assumptions and Their Verification

Independence assumptions are core concepts of multi-attribute utility theory. They are necessary to infer the function forms of utility functions. There are four main independence assumptions relating to selection of appropriate function forms. They are preferential, weak-difference, utility and additive independence, respectively. Preferential and weak-difference independences relate to situations where there are no uncertainties involved. Utility and additive independences involve preferences for lotteries rather than certain consequences. The definitions of these four independence assumptions are the following:

Preferential Independence

The pair of attributes $\{X_1, X_2\}$ is preferentially independent of the other attributes $\{X_3, \dots, X_N\}$, if the preference order for consequences involving only changes in the levels of X_1 and does X_2 not depend on the levels at which attributes $\{X_3, \dots, X_N\}$ are fixed.

Weak-Difference Independence

Attribute X_1 is weak-difference independent of attributes $\{X_2, \dots, X_N\}$, if the order of preference differences between pairs of X_1 levels does not depend on the levels at which attributes $\{X_2, \dots, X_N\}$ are fixed.

Utility Independence

Attribute X_1 is utility independent of attributes $\{X_2, \dots, X_N\}$, if the preference order for lotteries involving only changes in the level of X_1 does not depend on the levels at which attributes $\{X_2, \dots, X_N\}$ are fixed.

Additive Independence

Attributes $\{X_1, \dots, X_N\}$ are additive independent if the preference order for lotteries does not depend on the joint probability distributions of these lotteries, but depends only on their marginal probability distributions.

To examine appropriateness of any above independence condition, we check whether there are special cases where violation of independence condition are found. For example, to verify whether the attribute pair $\{X_1, X_2\}$ is preferentially independent of other attributes $\{X_3, \dots, X_N\}$, we first identify pairs of attribute levels of $\{X_1, X_2\}$, that is (x_1, x_2), that are indifferent to each other when the levels of other attributes are fixed at a certain level. We then change the levels of other attributes arbitrarily. If the decision maker feels that the pairs of attribute levels of $\{X_1, X_2\}$ are indifferent, then the preferential independence condition holds.

If after careful examination, no independence condition is found, then possibly there are some hidden objectives. Decision maker is referred to figure out and clarify hidden objectives. Also, it is possible that attributes are not appropriately selected. Attributes or part of them then are re-formulated again.

3.2.6.3 Multi-Attribute Utility Function

Different sets of independence assumptions imply different types of function forms. There usually are three robust utility functions that can be used to cover widely different value and decision problems. They are multilinear utility function, multiplicative utility function and additive utility function, respectively. The sets of assumptions and their corresponding function forms are introduced as following:

Result 1. *Given attributes X_1, …, X_N, $N \geq 2$, a multi-linear utility function*

$$u(x_1,\dots,x_N) = \sum_{i=1}^{N} k_i u_i(x_i) + \sum_{i=1}^{N}\sum_{j>i}^{N} k_{ij} u_i(x_i) u_j(x_j) + \sum_{i=1}^{N}\sum_{j>i}^{N}\sum_{h>j}^{N} k_{ijh} u_i(x_i) u_j(x_j) u_h(x_h) + \dots + k_{1\dots N} u_1(x_1)\dots u_N(x_N) \tag{3.5}$$

exists if and only if $X_i, i = 1, \dots, N$, is ***utility independent*** *of the other attributes, where u_i is a utility function over X_i and the k' s are scaling constants.*

To determine u in (3.5), we can assess the individual utility functions u_i on a zero-to-one scale and the scaling constants such that they sum to one.

Result 2. *Given attributes $X_1, \dots, X_N, N \geq 2$, an additive utility function*

$$u(x_1, \dots, x_N) = \sum_{i=1}^{N} k_i u_i(x_i) \tag{3.6}$$

exists if and only if the attributes are ***additive independent****, where u_i is a utility function over X_i and the $k_i{}'$ s are scaling constants.*

Notice that (3.6) is a special case of (3.5) and u can be assessed accordingly.

Result 3. *Given attributes $X_1, \dots, X_N, N \geq 3$, the utility function*

$$u(x_1,\dots,x_N)=\sum_{i=1}^{N}k_iu_i(x_i)+k\sum_{i=1}^{N}\sum_{j>i}^{N}k_ik_ju_i(x_i)u_j(x_j)+$$
$$k^2\sum_{i=1}^{N}\sum_{j>i}^{N}\sum_{h>j}^{N}k_ik_jk_hu_i(x_i)u_j(x_j)u_h(x_h)$$
$$+\dots+k^{N-1}k_1\dots k_Nu_1(x_1)\dots u_N(x_N) \quad (3.7)$$

*exists if and only if $\{X_1, X_2\}, i = 2, \dots, N$, is **preferentially independent** of the other attributes and if X_1 is utility independent of the other attributes.*

As with the other utility functions, we can assess the u_i on a zero-to-one scale and determine the scaling constants k_i to specify u. The additional constant k is calculated from the $k_i, i = 1, \dots, N$.

If $\sum k_i = 1$, then $k = 0$, and if $\sum k_i \neq 1$, then $k \neq 0$. If $k = 0$, then clearly (3.7) reduces to the additive utility function (3.6).

If $k \neq 0$, multiplying each side of (3.7) by k, adding 1, and factoring yields

$$ku(x_1, \dots, x_N) + 1 = \prod_{i=1}^{N}[kk_iu_i(x_i) + 1[\quad (3.8)$$

which is referred to as the multiplicative utility function. It is easy to find out that form (3.8) is a special case of multi-linear utility function (3.6).

Figure 3.17 shows the derivation among different kinds of function forms. The implication is that we should have careful realization of the underlying preference independence conditions when certain function form is finally selected.

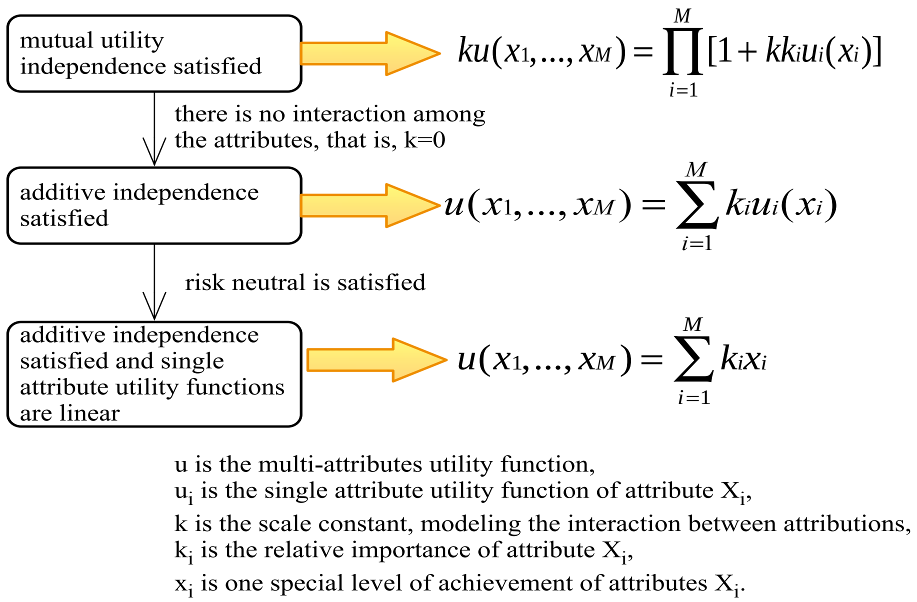


Figure 3.17: The derivation among different function forms

3.2.6.4 Single Attribute Utility Function

Single attribute utility functions $u_i's$ are components in the multi-attribute utility function u. The procedures for assessing single attribute utility functions for natural attributes or proxy attributes are different from those used for constructed attributes. To assess utility functions for natural attributes and proxy attributes, monotonic, risk attitudes towards uncertain attainment of attributes and special value judgments are necessary. To assess utility functions for constructed attributes, defined points or levels of the attributes are directly assessed.

There are attributes, such as profits, for which preferences increase as the attribute level increases. More profits will be preferred to fewer profits. There are also attributes, such as costs, for which preferences decrease as the attribute level increases. Fewer costs will be preferred to more costs. And sometimes, there are some attributes, such as keyboard size of the mobile phone, for which preferences increase up to a certain point when the attribute level increases, say 2 cm for example, and then preferences decrease as the attribute level increases. The point is that simple assumption about monotonic of attributes in a certain domain can always be easily made.

Decision maker's risk attitudes towards uncertainty are important concepts in assessing the single attribute utility function. There are three distinguished risk attitudes: risk aversion, risk neutrality and risk proneness, respectively. The definitions of the three different risk attitudes are following:

Risk Aversion

One is risk averse if and only if the expected consequence of any lottery is preferred to that lottery.

Risk Neutrality

One is risk neutral if and only if the expected consequence of any lottery is indifferent to that lottery.

Risk Proneness

One is risk prone if and only if the expected consequence of any lottery is less preferred than that lottery.

For example, assume there is a lottery $< 10, 0.5, 20 >$, which yields \$10 million operation cost or \$20 million operation cost, each with a half chance. If the decision maker prefers the expected consequence of the lottery ($10 * 0.5 + 20 * 0.5 = 15$) to the lottery, then the decision maker is of risk aversion. If the decision maker is indifferent between lottery and expected consequence of the lottery, then the decision maker is of risk neutrality. Otherwise, the decision maker is of risk proneness. Thus, risk aversion, risk neutrality and risk proneness are mutually exclusive and collectively exhaustive attitudes towards uncertainty.

With the above definitions of risk attitudes, it is possible to lead to determine the class of risk-averse, risk-neutral, and risk-prone utility functions, respectively (Keeney, 1992):

$$u_i(x_i) = a + b(-e^{-cx_i}) \tag{3.9}$$

$$u_i(x_i) = a + b(cx_i) \tag{3.10}$$

$$u_i(x_i) = a + b(e^{cx_i}) \tag{3.11}$$

where a and $b > 0$ are constants to insure that u is scaled from zero to one and c is positive for increasing utility functions and negative for decreasing ones. Examples of increasing and decreasing utility functions are shown in Figure 3.18 and Figure 3.19, respectively. The parameter c in (3.9) and (3.11) indicates the degree of risk aversion. For the linear case (3.10), c is set to 1 for increasing cases, and -1 for decreasing cases, respectively.

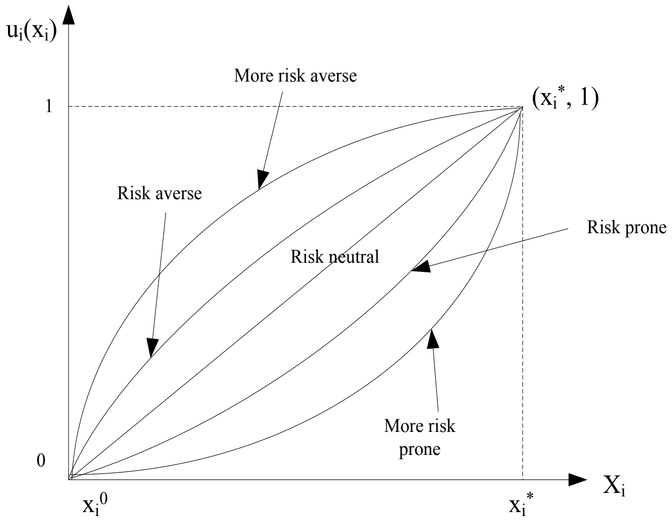


Figure 3.18: Increasing utility functions (Keeney 1992).

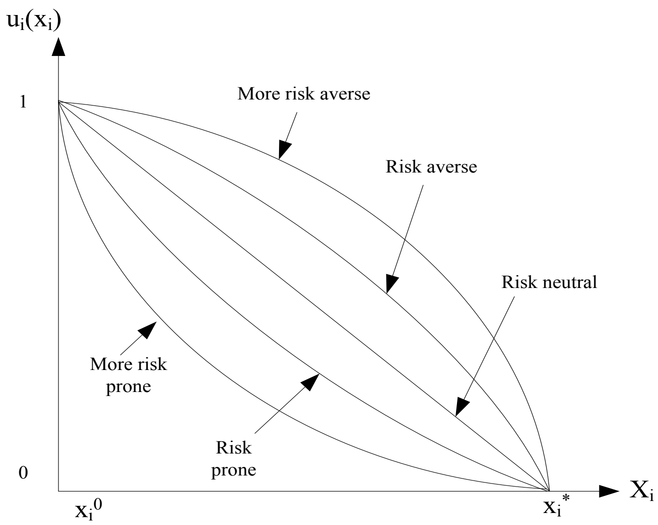


Figure 3.19: Decreasing utility functions (Keeney 1992).

To assess a special single attribute utility function that has three parameters a, b and c, three equations are necessary. If we assume that domain of attribute X_i is range from a minimum acceptable level x_i^0 to a maximum desired level x_i^*, and set $u_i(x_i^0) = 0$, $u_i(x_i^*) = 1$, then two equations are found. It is possible to use certainty equivalent or lottery equivalent to establish another equation. For example, if the decision maker is indifferent between certain achievement of x_i' and the lottery $< x_i^0, p, x_i^* >$, then another equation:

$$u_i(x_i') = (1-p)u_i(x_i^0) + pu_i(x_i^*) = p \qquad (3.12)$$

is found where p is possibility of x_i^*.

With these three equations, the scale constants a, b and c are found and the special single attribute utility function is finally assessed.

It is not an easy process to elicit appropriate certainty equivalence or lottery equivalence. Inconsistencies between elicited preferences and preferences in mind of the decision maker may exist. Thus consistency checks are necessary to ensure real preferences. For example, assume that:

(1) A certain attainment of \$8 unit cost is indifferent to the lottery <5, 0.5, 15>,

(2) A certain attainment of \$6 unit cost is indifferent to the lottery <5, 0.5, 8>, and

(3) A certain attainment of \$10.8 unit cost is indifferent to the lottery <8, 0.5, 15>,

Thus, we naturally expect that a certain attainment of \$8 unit cost is indifferent to the lottery <6, 0.5, 10.8>. If this relationship can finally be verified, we then can ascertain that elicited preferences are consistent. If inconsistencies are found, these inconsistencies are pointed out and referred to the decision maker. The decision maker should think hard about the inconsistencies and their underlying reasons, which contribute to identifying real and consistent preferences.

3.2.6.5 Value Trade-offs

Value trade-offs define how much must be gained in the achievement of one objective (or its attribute) to compensate for a less achievement on a different objective. This will help to find pairs of consequences that are indifferent to decision makers. Value trade-offs are necessary to determine the scale constants $k's$ in the multi-attribute utility functions of (3.5), (3.6), (3.7) and (3.8).

In order to specify value trade-offs formally, assume that there is a set of N objectives $\{O_1, \dots, O_N\}$, where $n \geq 2$, and a set of attributes for the objectives with one-to-one relationships $\{X_1, \dots, X_N\}$. A consequence then can be described as $x = (x_1, \dots, x_N)$, where x_i is a special level of X_i. Conveniently, by determining two consequences that are different in achievement of only two attributes and are indifferent to each other, value trade-offs can be specified. We thus only need two objectives (or two attributes) to specify value trade-offs meaningfully, so we can denote the measures for objectives O_1 and O_2 as X and Y to avoid subscripts. We then represent a consequence as (x, y) where x and y are a special level of attributes X and Y, respectively.

Indifferent pairs should be found by a bounding and converging procedure. This is better illustrated with an example. Suppose a mobile phone company considers designing a particular smart phone. The objectives are to minimize the cost of manufacturing cost per unit and months to market as shown in Figure 3.20. The domain of manufacturing cost per unit ranges from \$150 to \$200, and the domain of months to market ranges from 1 to 5 months. To determine value trade-offs between cost and months to market, one might begin by asking which consequence between A (1 month, $200) and B (5 months, $150) is preferred. Suppose B is preferred. Then one might reduce the cost of A to another consequence C (1 month, $160) and compare it with consequence B. If C would be preferred, then there is one point between A and C being indifferent to B. The same procedure continues from D to E, and finally converges to F (1 month, $180). Since F is (1 month, $180), this means that a reduction of cost from $200 to $180 is compensated by an increase of months to market from 1 month to 5 months. Converging to this indifference requires serious thought by the decision maker whose value is being assessed. And there are no externally correct value trade-offs, although internally consistency among value judgment is necessary.

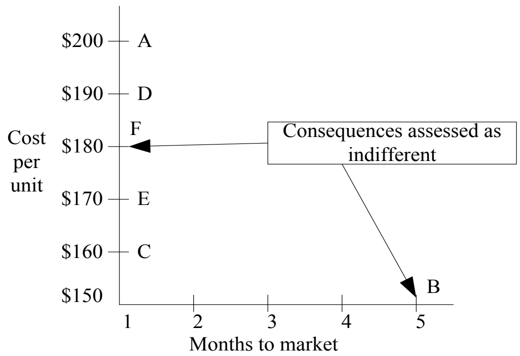


Figure 3.20: a convergence procedure to assess value trade-offs.

However, value trade-offs are one of the most difficult elements in important decisions. It is possible to make twelve common mistakes in making value trade-offs as shown in Table 3.5.

Table 3.5: Twelve common mistakes in making value trade-offs (Keeney 2002)

Mistake 1	Not understanding the decision context
Mistake 2	Not having measures for consequences
Mistake 3	Using inadequate measures
Mistake 4	Not knowing what the measures represent
Mistake 5	Making value trade-offs involving means objectives
Mistake 6	Using willingness to swap as a value trade-offs
Mistake 7	Trying to calculate correct value trade-offs
Mistake 8	Assessing value trade-offs independent of the range of consequences
Mistake 9	Not having value trade-offs depend on where you start
Mistake 10	Proving conservative value trade-offs
Mistake 11	Using screening criteria to imply value judgments
Mistake 12	Failure to use consistency checks in assessing value trade-offs.

A four-step process is presented to focus on substance of making value trade-offs and to avoid any logical mistakes listed in Table 3.5, as shown in Figure 3.21.

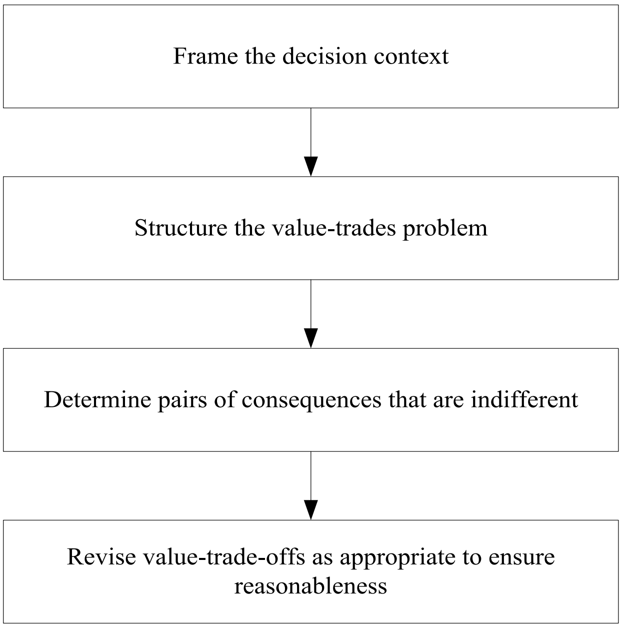


Figure 3.21: A four-step process to make value trade-offs (Keeney 2002)

3.2.6.6 Group Preferences

Product design and development is a group decision-making activity. Several kinds of stakeholders are involved, such as customers, marketing, designers and manufacturers. As they are influential or influenced by relevant decisions, their needs and preferences are necessary for rational decision-makings.

After a set of complete objectives and a set of their corresponding attributes of all stakeholders have been identified, it is time to construct individual utility functions and group utility function. If all the stakeholders agree on a utility function, then that function should be used as a group utility function. This may happen when different stakeholders have different expertise concerning objectives. The more complicated case is when stakeholders disagree on some of value and hence their value must be represented by different utility functions. This is a common case and the differences may not be so significant. In the extreme case where each stakeholder has different values and there is one utility function for each stakeholders. Thus a problem comes whether it is possible to aggregate individual utility functions into a group utility function. This problem is formalized into determining a function f such that

$$P_G = f(P_1, P_2 \ldots, P_K) \tag{3.13}$$

where P_G is group (expected) utility function, and $P_{i,}\ i = 1, \ldots, K,$ is the individual (expected) utility function.

(Hazelrigg 1999) and (Franssen 2005) show impossibility of deriving group preferences according to Arrow's Impossibility Theorem (AIT). But ranking and weights are two different types of preferences as discussed by Keeney (2009):

> *"Arrow's Impossibility Theorem, has been misinterpreted by many (e.g., Hazelrigg, 1999; Franssen, 2005). They make a general conclusion that there is no reasonable or logical way to combine individual preference to obtain a group preference. But Arrow's result is more specific: it is for a specific type of preference, namely rankings, and a specific set of assumptions, namely the assumptions that he chose." (Social choice without interpersonal comparison)*

One can derive group (expected) utilities for group decisions by aggregating the (expected) utilities of different stakeholder as proved by (Harsanyi 1955) and (Keeney 1975, 2009). That is, it is possible to derive a group utility from a set of individual utilities when interpersonal comparisons and strength of preference information are addressed. The assumptions and conclusions of Harsanyi and Keeney are as follows:

Harsanyi's assumptions:

H1: Each $P_k, k = 1, \dots K$, is a utility function u_k over consequences x.

H2: P_G is a utility function u_G over consequences x.

H3: If two alternatives, defined by probability distributions over the consequences x, are indifferent to each individual, then they must be indifferent to the group.

Harsanyi's Result:

$$u_G(x) = \sum_{k=1}^{K} w_k u_k(x) \quad (3.14)$$

where there is K members in the group, and w_k is positive weight for the individual utility function u_k. That is, one can derive group utility function for group decision-making from a set of individual utility functions when H1, H2, and H3 are satisfied.

Keeney's assumptions:

K1: There are at least two individuals in the group, at least two alternatives, and a group utility is specified for all possible individual utilities.

K2: (Positive association of social and individual values): If the group utilities indicate alternative a is preferred to alternative b for a certain set of individual utilities, then the group utilities must imply a is preferred to b if:

- *The individual's utilities of alternatives other than a are not changed*
- *Each individual's utilities between a and any other alternative either remains unchanged or is*

modified in favour of a

K3: (Independence of irrelevant alternatives): If an alternative is eliminated from consideration, the new group utilities for the remaining alternatives should be equivalent to the original group utilities for these same alternatives.

K4: (Individual's sovereignty): For each pair of alternatives a and b, there is some set of individual utilities such that the group prefers a to b.

K5: (Non-dictatorship): There is no individual such that whenever he prefers alternative a to b, the group will also prefer a to b regardless of the other individual's utilities.

Keeney's Result:

$$U = \sum_{k=1}^{K} w_k U_k \tag{3.15}$$

where there is K members in the group, U is group expected utility function, w_k is positive weight for the individual expected utility function U_k. That is, one can derive group expected utility function for group decision-making from a set of individual expected utility functions when $K1, \dots, K5$ are satisfied.

The implications of these results are the following: one can determine the f in equation (3.13) and group (expected) utility function can be aggregated from a set of individual utility functions. This aggregation requires both strength of preference information embedded in the utilities and interpersonal comparisons of preferences addressed by the $w_k, k = 1, \dots, K$.

3.2.7 Response Surface Methodology

In order to model the consequence model between fundamental objectives and ECs, response surface methodology is introduced. Response surface methodology is a collection of statistical and mathematical techniques that are useful for empirical model building and model exploitation (Carley *et al.* 2004). By careful design and analysis of experiments, it seeks to establish a functional relationship between a response (output variables) and several predictors (input variables). It is useful when true response function is unknown, perhaps very complicated and certain laws to determine their relationships have not been found.

Three aspects are included in the field of response surface methodology:

1. Empirical strategy to explore the input variables or the design space,
2. Empirical statistical modeling to develop an approximating relationship between the input variables and output variables,
3. Optimization methods to find the desired values of input variables that produce optimal value of output variable.

On one side, to construct response surface function experimental data must be available to figure out the parameters in the response surface function. On the other side, the form of response surface function will determine the needed data that comes from the designed experiments. Thus, some information about the response surface function is necessary. Assume that we want to figure out the function relationship between one customer need x_i and several ECs $\{y_1, \dots, y_Q\}$.

In general, the relationship is

$$x_i = f_i(y_1, \dots, y_Q) + \theta \tag{3.16}$$

where the form of the true response function f_i is unknown, θ is a term that represents other sources of variability not accounted for in f_i, and $y_k, k = 1, \dots, Q$, is expressed in natural unites of measurement, such as speed and weight. It is convenient to transform natural variable y_k into coded variables y'_k with a common measurement belong to [-1, 1] through

$$y_k^{'} = \frac{y_k - \frac{y_k^0 + y_k^*}{2}}{\frac{y_k^* - y_k^0}{2}} \tag{3.17}$$

thus the response function (3.16) is written as

$$x_i = f_i(y'_1, \dots, y'_Q) + \theta \tag{3.18}$$

Usually, a lower-order polynomial in some relatively small region of input variable space is appropriate to approximate f_i. In many case, either a first-order or a second order model is used. The first-order model is appropriate when the experimenter thinks that only main effects are important and that interaction and higher order effects are indistinguishable. Mathematically, it means that there is little curvature in f_i in a relatively small region of the input variable space. The form of the first-order model is

$$x_i = \beta_{i0} + \sum_{k=1}^{Q} \beta_{ik} y'_{ik} \tag{3.19}$$

where β' s are unknown parameters to be solved.

The equation (3.19) is a linear one and is analogous to the linear equations used for approximating the relationships between customer needs and ECs in traditional QFD. But the latter is based on discrete scales, such as 1-3-9. Thus, the latter is a subset of the former.

The first-order model is inadequate to model curvature in the region of the input variable space. A second-order model will likely be required to approximate this situation. The second-order model is

$$x_i = \beta_{i0} + \sum_{k=1}^{Q} \beta_{ik} y'_{ik} + \sum_{k=1}^{Q} \beta_{ikk} (y'_{ik})^2 + \sum_{k=1}^{Q} \sum_{l>k}^{Q} \beta_{ikl} y'_{ik} y'_{il} \tag{3.20}$$

where β' s are unknown parameters to be solved.

The second-order model is widely used in response surface methodology for several reasons (Carley *et al.* 2004):

1. It is very flexible. It can take on a wide variety of functional forms, so it will often work well as an approximation to the true response surface,
2. It is easy to estimate the parameters (the $\beta's$) in the second-order model. The method of least squares can be used for this purpose,

3. There is considerable practical experience indicating that second-order model works well in solving real response surface problems.

In general, first-order models are useful for screen test when there are many variables, and second-order models are useful for more precise approximations. They can be used for approximating the relationships between customer needs and ECs, which will avoid some potential problems.

3.3 Assumptions Underlying the Approach Development

In this section, we list two assumptions that are made in the forthcoming proposed approach. These two assumptions are made in order to simplify the illustration of the approach, but they will not be the constraints of the approach. The assumptions are:

A1. To derive requirements specification for further system development, it is necessary to consider different stakeholders in the development context. For example, customers, regulators, designers, manufacturers and others. They influence and are influenced by the system development. Therefore, their needs and preferences are important in the development context. We carefully realize the fact, but in the proposed approach we will only consider different customers to avoid possible confusion in illustration. This is especially useful to clearly illustrate our idea. Different customers will have different needs and preferences, although the degree of difference is not so much comparing to that among different stakeholders. To aggregate group customer preferences a group customer utility function is constructed. Similarly, different stakeholder preferences are aggregated and a group stakeholder utility function is constructed. Because of these similarities, we expect the developed approach is also straightforwardly applicable to other stakeholders besides customers.

A2. In decision analysis, preferences include preferences under certainty and preferences under uncertainty. Preferences under certainty means value while preference under uncertainty means utility. Preferences under certainty are modeled with a value function or a measurable value function, while preferences under uncertainty are modeled with a utility function. In the proposed approach, we think of value in a broad sense, including preference under certainty and uncertainty, so value in this thesis equates to preferences in general sense. And we only adopt utility and utility function to measure value, which is practical for two reasons:

a. Most engineering design problems involve uncertainties and these uncertainties should be explicitly modeled, and

b. If the approach is developed on the basis of utility functions, then analogue results can be expected with regards to value functions.

As utility and utility functions are used for measuring value, the underlying assumptions and axioms for utility and utility function are implicitly included.

As can be seen from these two assumptions, they will not limit the applicability of the approach and the approach can be straightforwardly extended through eliminating these two assumptions. But they are beneficial as they are introduced for convenience of presentation of the approach. In next section, we will list the desired effects to-be achieved about the approach development.

3.4 Desired Effects to-be Achieved about Approach Development

Regarding to approach development, a value-centric QFD is proposed to help deriving a value-based requirements specification from initial customer statements. In detail, it should satisfy the following set of properties:

1. It should be consistent with engineering practice, e.g. adopting system engineering standards in industry,
2. It should help understanding customer needs in detail,
3. Value becomes explicit construct that can be modeled and simulated,
4. The process and its supporting methods should be based on sound theory and methods, and should simultaneously consider the cognitive limitation of human judgments and the typical abstractions used by humans to solve complex problems,
5. It is based on traditional QFD principles, but it should resolve methodological problems underlying in the traditional QFD approach, and
6. It should promote progression of VDD from economic-based value model to multi-dimensional value model.

3.5 Conclusions

Firstly, this chapter gives a brief introduction to QFD in Section 3.1.1. The nature, process and quantification in traditional QFD are discussed. Section 3.1.2 presents QFD's seven methodological problems, including missing of structure to logically organize customer statements, missing of attributes to measure customer needs, confusion of weighting and ranking and other aspects. These methodological problems hinder appropriate understanding of customer needs and derivation of value-based requirements specification. In order to mitigate these methodological problems, a set of theories methods and concepts are introduced in Section 3.2, including concepts of objective, attribute, consequence model and value model, methods of means-ends objectives networks, fundamental objectives hierarchy and response surface methodology, and theory of multi-attribute utility theory. Two assumptions underlying the approach are also listed in Section 3.3. After that, desired effects to-be achieved about approach development are presented in Section 3.4, which guides the development efforts to be presented in Chapter 4. In the next chapter, the solution approach is proposed based on QFD, means-ends objectives network, fundamental objectives hierarchy, multi-attribute utility theory and others, aiming to drive value-based requirements specification and mitigate the methodological problems of the QFD.

4 Approach Development and Application

In this chapter, the value-centric quality function deployment (QFD) is proposed, which includes qualification and quantification of value. The approach supports three levels of specification, that is, qualitative relation, function form and numerical calculation. It is a prescriptive approach, which is different from normative and descriptive approaches (Edwards *et al.* 2007). It helps customers or engineers to think systematically about customer needs and value by using normative theory with careful awareness of the typical ways they use in problem solving. Thus, a set of theories and methods, such as multi-attribute utility theory, means-ends objectives network, fundamental objectives hierarchy and response surface methodology, are introduced and integrated into traditional QFD method, which enables the proposed approach to satisfy the desired properties in Section 3.4.

The reminder of this chapter is organized into two sections. In Section 4.1, the approach is proposed, which is a four-step process with the support from a set of theories and methods. In Section 4.2, a case study is deployed to illustrate the applicability and usefulness of the developed approach.

4.1 Approach Development

In Chapter 3, we have discussed about the underlying process in traditional QFD. To facilitate illustration and comparison, the original process, underlying methodological problems and the proposed process of the approach are presented in Table 4.1.

In our proposed approach, it is a four-step process. The 1st and 2nd steps are about the part of the voice of the customer. The 1st step helps to structure logically customer objectives while the 2nd step quantifies customer objectives with a value model. Customers' fundamental objectives then are transformed into ECs in the 3rd step, and simultaneously customer value model is transformed into system value model. These first three steps are necessary for deriving system-level requirements specification. Finally, component value models are derived from system value model through sensitivity analysis, which is complementary for component-level requirements specification. Therefore, the 5th step and 6th in the original process are eliminated and the underlying methodological problems P6 and P7 are avoided in our process. But we do not intend to replace the traditional QFD, at least in this beginning stage. The approach proposed here is recognized as a potential alternative for rationalizing the process of requirements establishment in terms of value.

Table 4.1: The original process, underlying methodological problems and the proposed process

Original process	Methodological problems	Proposed new process
1. Identify and structure customer needs	P1	1. Identify and structure objectives
2. Assign relative weights to customer needs	P2, P3 and P4	2. Specifying attributes and constructing customer value model
3. Incorporate customer perceptions with perception map	P2, P3 and P4	
4. Transform customer needs into ECs with a relationship matrix	P5	3. Transform fundamental objective (customer value model) into ECs (system value model) 4. Derive component value models
5. Make trade-offs between ECs with a correlation matrix	P6	
6. Set targets of ECs for maximizing customer satisfaction	P7	

The high-level process is presented in an IDEF0 diagram. The graphical language of IDEF0 uses boxes to represent activities and lines with arrows to link the activities where the arrows indicate the direction of flow. The flow lines, such as "initial customer statements", "fundamental objective hierarchy" and "attributes", represent real objects or information needed or produced by the activities. The side of the activity box to which a flow line may enter or leave objects depicts the meaning of the activity, such as 'A1: identify and structure objectives', as shown in Figure 4.1. Inputs enter an activity box on its left side, with outputs leaving from the right hand side. Therefore, the activity may be said to transform the received input into a produced output. The flow lines that enter the top of an activity box represent a control or a constraint. A control describes the conditions and/or circumstances that govern the transformation, such as "concepts of objectives" and "concepts of value model". The flow line that enters the bottom of an activity box is known as a mechanism. This is the means by which an activity is carried out, such as the methods "means-ends analysis", "part-whole analysis" and "multi-attribute utility function".

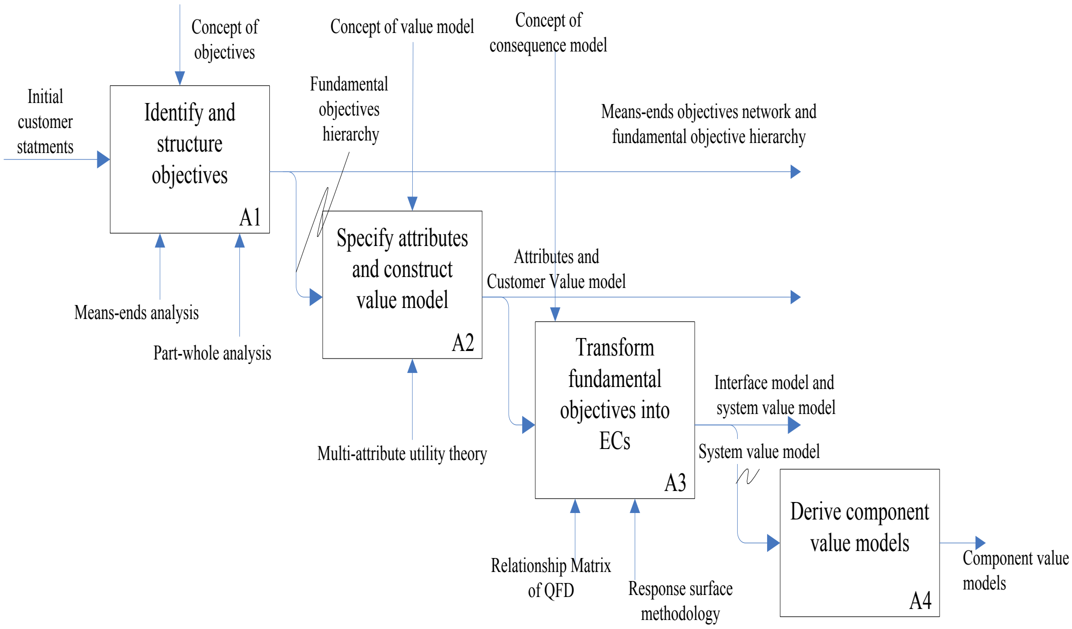


Figure 4.1: Four steps of the value-centric QFD.

4.1.1 Identify and Structure Objectives

The process of identifying and structuring objectives is represented in Figure 4.2.

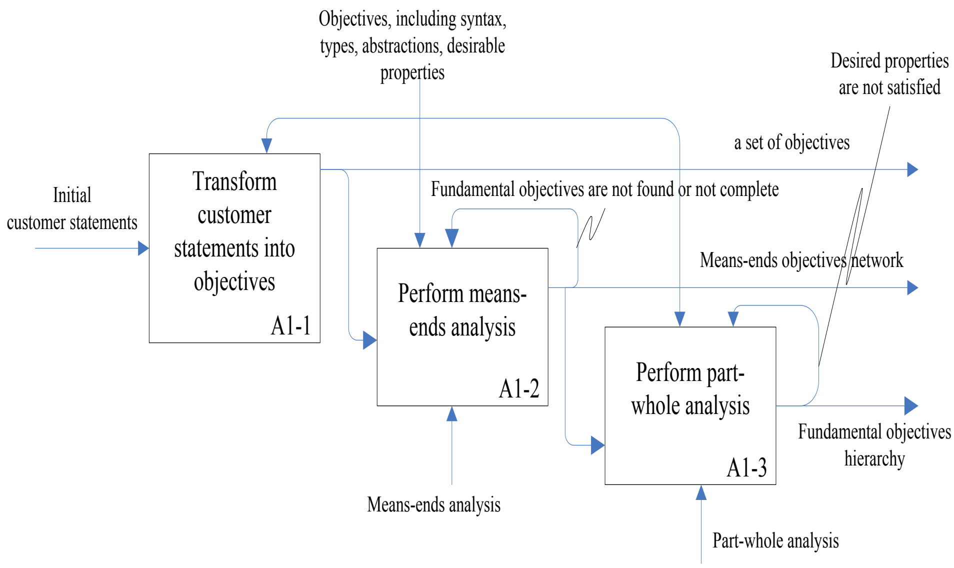


Figure 4.2: The process of identifying and structuring objectives.

It begins with identification of customers and ends with establishment of a hierarchy of fundamental objectives. An obvious fact in the process is that customers try to express customer statements in different levels and granularities. The customer statements may be in the form of customer needs, goals, objectives, constraints, ECs, or design parameters, and the statements have several different expressions. This phenomenon causes difficulties in understanding customer needs. It is straightforward to transform initial statements into objectives. These transformations help to form a common expression of a verb plus a noun and facilitate the process of structuring. Also this transformation is useful to reduce or eliminate possible redundancies. For example, if different customers wrote "make money", "meet our profit goal", "earn a fair profit", "profit", and "maximize profits", these could all be combined under the objective "maximize profits".

Three kinds of objectives, including fundamental objectives, means objectives and strategic objectives, are used for characterizing the transformed customer objectives. Fundamental objectives are used for representing the objectives that are transformed from customer needs. Means objectives may be objectives transformed from ECs or design parameters. This categorization is appropriate as there are causal relationships implied among customer needs, ECs and design parameters.

After the transformation of customer statements into objectives, means-ends analysis is then performed on the transformed objectives, which tries to trace their causal relationships and pursues fundamental objectives in the current context. "Why" and "how" questions are usually asked to explore implicit means and ends in the transformed objectives. Pursuing "why" questions leads to discover the reasons (ends) behind certain objectives and finally the fundamental reasons of interest. Implicit fundamental objectives underlying means objectives are then identified. Asking "how" questions helps to discover the possible means to influence the achievement of current objective. After this kind of a reasoning process, means objectives and fundamental objectives can be rationally and logically organized into a means-ends objectives network.

But there is a danger to ask questions too far, because it is always possible to ask "why" and "how" questions. Care must be given to check whether the identified "fundamental objectives" are related to the current decision context or broader contexts that are not under the control of available solutions. If strategic objectives are found, it is then necessary to return back by asking "how" questions.

It is then necessary to perform part-whole analysis on fundamental objectives, which helps to clarify understanding of fundamental objectives in higher levels into lower levels with part-whole relationships. "What" questions are typically asked, such as "what do you mean by that objective", which give much more details for understanding the fundamental objectives.

However, care should also be given about how long to continue to ask "what" questions. Objectives in the lowest level of fundamental objectives hierarchy are desired when we reach at a special level where reasonable attributes can be identified to measure the attainment of the objectives and there is a minimum demand on information collection. As deeper the hierarchy gets the more objectives and their attributes are found, and more information is needed to be collected for attributes. When the set of fundamental objectives satisfy a set of desired properties, including complete, non-redundant, concise, specific and understandable (Keeney 1992, 2005), it is time to quantify fundamental objective in terms of value.

4.1.2 Specify Attributes and Construct Value model

The process of specifying attributes and constructing a value model is shown in Figure 4.3. In this process, it represents how the initial set of qualitative fundamental objectives is transformed into a quantitative value model. To enable this transformation, attributes needed to be identified to measure achievement of fundamental objectives.

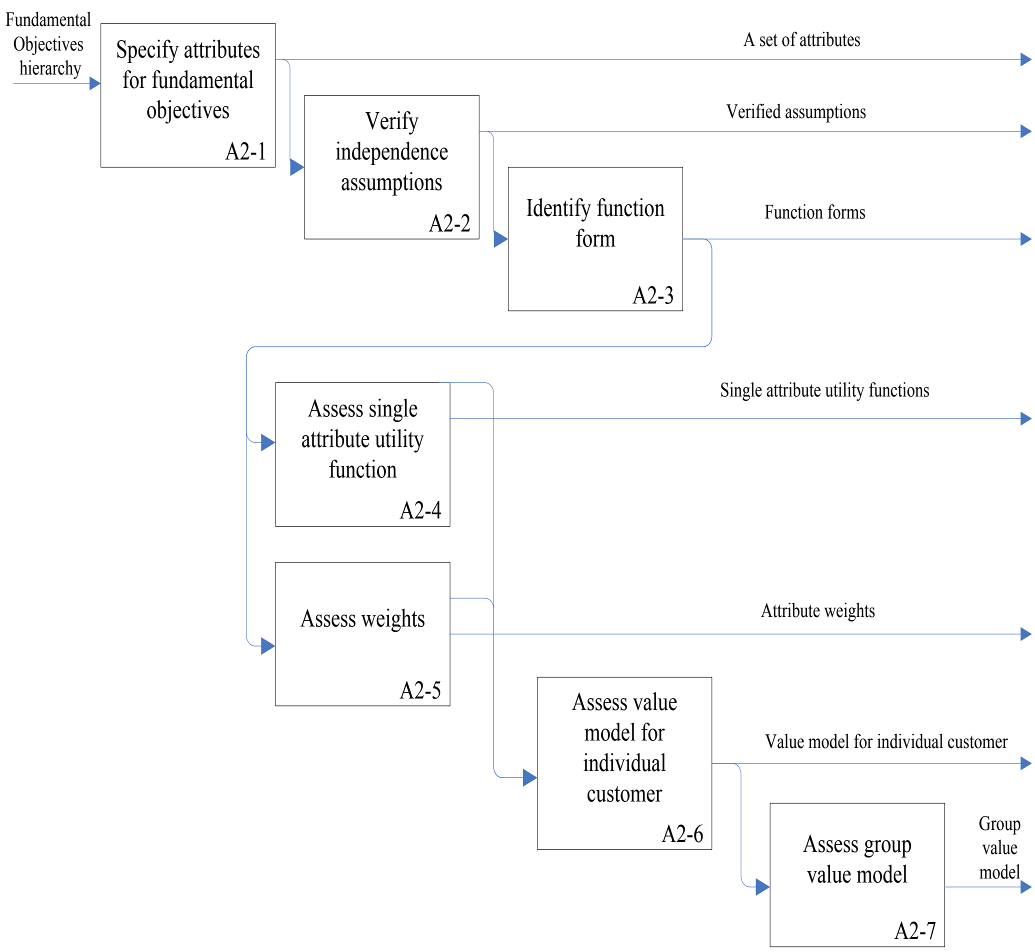


Figure 4.3: The process of specifying attributes and constructing value model.

Selecting appropriate attributes for the corresponding fundamental objectives, however, is not a trivial task, especially for intangible or soft objectives, e.g. comfort, pride or fashion. If they are at a too high level to be measured, the type of “what do you mean by that objective” questions should be pursued to clarify understanding. Different customers may have different meaning about comfort. By continually asking such kind of questions, the ideas underlying the ambiguous fundamental objectives are elicited. And there is more possibility to identify measurable attributes for low-level fundamental objectives. Thus identifying appropriate attributes is strongly relevant to part-whole analysis.

Three kinds of attributes have been discussed in the previous section, including natural attributes, constructed attributes and proxy attributes. These attributes are also useful in field of engineering design. Selecting appropriate attributes for measuring customer needs is a sophisticated and intricate challenge. That is possibly the reason why there are no available attributes in the voice of the customer. But design decisions have to be made in a rational way. Then how to identify and select attributes for customer needs is a serious decision-making problem, which deserves time and hard work. The procedures to specify attributes are the same as that in the flowchart of selecting attributes in Figure 3.12. A sufficient set of properties for good attributes are already discussed in previous sections: unambiguous, comprehensive, direct, operational and understandable (Keeney 1992, 2005). They are used as the criteria to stimulate the creation and selection of attributes.

The output of "specify attributes for fundamental objectives" is a set of attributes. For example, the set of attributes may be represented as $X = \{X_1, \dots, X_M\}$, and a special level of X will be $x = \{x_1, \dots, x_M\}$ with x_i as a special level of the attribute X_i. We assume there is only one attribute for one fundamental objective, that is, there is a mapping relationship from the fundamental objective O_i to the $X_i, i = 1, \dots M$. This assumption is reasonable and can be illustrated with a simple example in Figure 4.4.

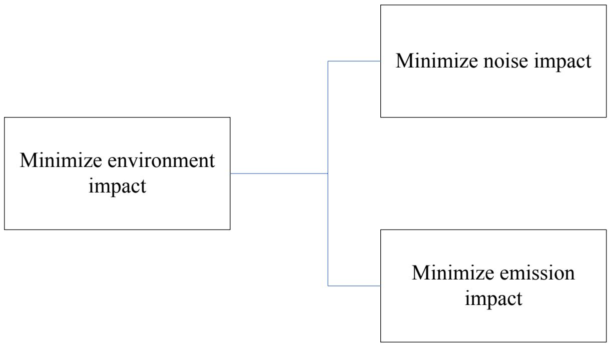


Figure 4.4: Composing two attributes into one attribute.

In this example, for the fundamental objective "minimize environment impact", there are two parts: "minimize noise impact" and "minimize emission impact". One composed attribute can be identified for measuring noise impact, and the same case applies to emission impact. A first look is that there are two attributes for "minimize environment impact" and the assumption is not reasonable. However, these two attributes can be composed in a certain way, say by multi-attribute utility function, into a common attribute, which may scale from zero to one and means utility. Then for every fundamental objective there is one corresponding attribute for meaningful measurement.

With a set of attributes, relationships among the attributes needed to be checked in terms of independence assumptions in order to compose the set of incommensurable units into a multi-attribute value model. This process is analogous to the process used for constructing other kinds of models, such as performance models. The analyst decides on the variables (attributes) to use in constructing the value model, selects and/or verifies the relationships among those variables to get a mathematical representation of interest (preferences in this case), and then quantifies the parameters for the model using information that is available and/or can be gathered (Keeney 1992).

However, independence assumptions to be verified in the context of mathematical representation of value (preferences) are different from the normal concept of "independence". The former concerns to the independence of preferences that reside in human mind while the latter is checked only though the physical design artifact in the external world (Thurston 2001).

There are several sets of preference independence assumptions, such as preference independence, utility independence and additive independence, which will imply different function forms of the value model, e.g., multiplicative or additive function from. If mutual preference independence among the set of attributes and utility independence of X_i regarding to the other attributes are finally verified, the value model is of multiplicative form. If additive independence among the attributes is verified, then the value model is of a special form of multiplicative form, that is, additive form.

Practically, as identified by (Keeney 2007), it is appropriate to determine an additive function form when the set of objectives are fundamental objectives and the objectives satisfy the set of desired properties of fundamental objectives. He also finds several situations where linear single attribute value models are appropriate. If the linear additive form is finally used in QFD, those properties or requirements then have to be satisfied.

To assess single attribute value model, attribute information and customer risk attitudes towards uncertain achievement of attribute are then used. Single attribute value model may be of concave, convex or linear form, corresponding to risk aversion, risk proneness or risk neutrality of customer attitude, respectively. The detail procedures to assess single attribute value model and to select certain function forms have been detailed in Section 3.2.6.

With determined function form of multi-attribute value model and single attribute value model, weights of customer attributes are then assessed through value trade-offs. Value trade-offs are usually performed between pairs of two possible hypothetical alternatives with the same utilities to customers but differ only in levels of achievement of two attributes. Two indifferent consequences are modeled through:

$$u(x_1, \dots, x_i, \dots, x_j, \dots, x_M) = u(x_1, \dots, x^*{}_i, \dots, x^*{}_j, \dots, x_M) \tag{4.1}$$

For M attributes, a set of at least M equations (M pairs) has to be constructed to determine the M $k_i's$ in the additive function form. Sometimes iterations may be necessary when the equations are not independent from each other. If the number of the set attributes is large, it makes verification of independence conditions and value trade-offs a difficult job. Then some work to categorize the fundamental objectives is necessary to manage the complexity of assessment. After all, the $k_i's$ have been assessed, the value model of an individual customer is finally constructed.

However, different customers may have different preferences about attributes and their importance. In most applications of the voice of the customer, an assumption is made that customers could finally achieve compromise and reach consensus about importance of customer needs. But if consensus cannot be achieved, group preferences have always to be modeled. Customers then may have different value models, although the same set of fundamental objectives and attributes is used for assessment as presented in Figure 4.5. Some attributes may be assigned a higher weight by a certain customer while others assign them a lower weight. Customers may even have different perceptions about single attribute achievement.

(Harsanyi 1953) and (Keeney 1975, 1993, 2009) proved that one could derive group (expected) utility function from individual (expected) utility functions given that a set of reasonable assumptions is satisfied, which is shown in Section 3.2.6. Therefore, multi-attribute utility theory is appropriate for aggregating group utility from individual utilities.

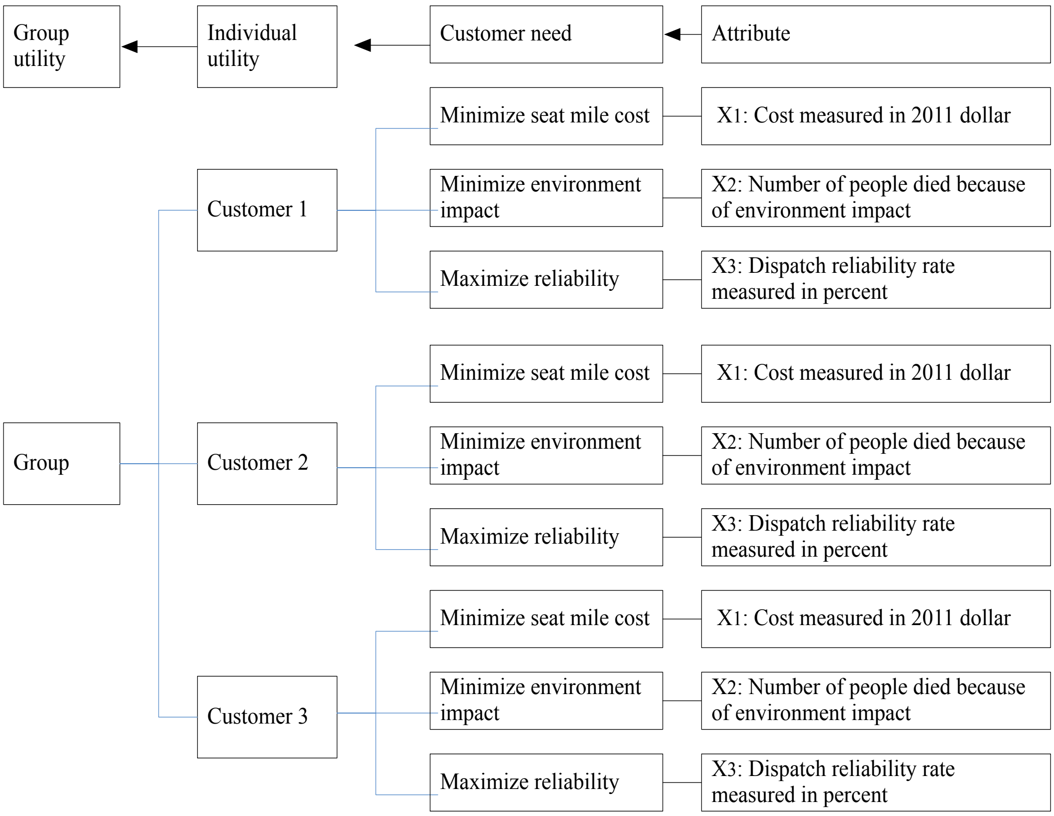


Figure 4.5: Derivation of group utility from individual utility.

A formulation of the group utility problem in Figure 4.5, which is a simple problem of three customers with three attributes, is given Table 4.2, assuming the set of assumptions defined by Harsanyi or Keeney is satisfied.

If $u_i(x), i = 1, 2, 3$, is assessed of additive function form for customers, and $u_{1j} = u_{2j} = u_{3j}, j = 1, 2, 3$, for attributes, the group weight of attribute X_i is assessed as:

$$A_j = \sum_{s=1}^{3} w_s k_{sj} \quad (4.2)$$

where A_j is the group weight of attribute $j, j = 1, 2, 3$. This equation is commonly used to calculate group weights of customer needs in practice, but little effort is spent in the underlying assumptions.

Table 4.2: A formulation of group utility problem for three customers with three attributes.

	Individual	Importance of individual	Attribute	Importance of attribute	Single attribute utility function	Value model
Group $u = \sum_{s=1}^{3} w_s u_s(x)$	Customer 1	w_1	X_1	k_{11}	$u_{11}(x_1)$	$u_1(x)$
			X_2	k_{12}	$u_{12}(x_2)$	
			X_3	k_{13}	$u_{13}(x_3)$	
	Customer 2	w_2	X_1	k_{21}	$u_{21}(x_1)$	$u_2(x)$
			X_2	k_{22}	$u_{22}(x_2)$	
			X_3	k_{23}	$u_{23}(x_3)$	
	Customer 3	w_3	X_1	k_{31}	$u_{31}(x_1)$	$u_3(x)$
			X_2	k_{32}	$u_{32}(x_2)$	
			X_3	k_{33}	$u_{33}(x_3)$	

The three customers and three attributes group preferences can be easily extended to N customers with M attributes:

$$u = \sum_{s=1}^{N} w_s u_s(x) \tag{4.3}$$

If there are a large number of customers, it takes time to assessment value models for every customer. It is then more reasonable to aggregate or category customers into several types with the help of other methods and tools. If uncertain achievement of attributes is important, group expected utility could also be derived straightforwardly.

4.1.3 Transform Fundamental Objectives into Engineering Characteristics

Fundamental objectives are customers' fundamental reasons of interests in the decision context and they indicate what customer values. They should be derived into ECs that are means to influence the achievement of fundamental objectives. The relationships are expressed in a two-level means-ends objectives network. Traditionally, this network is modeled in the house of quality with a two-dimensional matrix as shown in Table 4.3.

Table 4.3: A two-dimensional matrix between customer needs and ECs.

	EC 1	EC 2	…	EC Q
Customer need 1	1			9
Customer need 2		3		
…				
Customer needs M		3		

The entries of the relationship matrix are usually filled with, for example, 1-3-9 scales or qualitative symbols. These scales provide a primitive way to measure the influence relationships, but they are not precise enough when the product to be developed is of high monetary or value influence. They is a simplification of this function form:

$$x_i = f_i(y_1, \dots, y_Q), i = 1, \dots, M \tag{4.4}$$

where $y_j, j = 1, \dots, Q$, is a special level of the j^{th} EC, f_i maps the achievement of ECs to the achievement of X_i. This type of model, called consequence model in decision analysis, is different from value model that incorporates the value or value trade-offs and risk tolerances to evaluate consequences. The construction of consequence model should collect data in the external world rather than in human mind in order to assign parameters in the function form of (4.4).

However, it is sometimes difficult to identify function forms between x_i and $y_i's$, partly because of the missing attributes for measuring the customer needs. Even if reasonable attributes could be identified, exact mathematical functions may be a luxury. Approximation techniques are also acceptable and well adopted in practice. Some attempts have been made to approximate the mapping relationships, but first-order linear relationships are always assumed (De Poel 2007). A reasonable approximation that is supported by the robustness of a linear model (Butler *et al.* 2006) is

$$S_i = \sum_{j=1}^{Q} k_{ij} f_{ij}(y_j) \tag{4.5}$$

where $k_{ij} \in [-1, 1[$ corresponding to a_{ij} in Table 3.1 is the impact weight of the j^{th} EC Y_j on the i^{th} customer need X_i, and k_{ij} may be positive, negative or zero, corresponding to the fact that Y_j may have a positive, negative or no impact on the X_i; f_{ij} is a function mapping Y_j onto [0,1], being linear or non-linear, representing the attainment of Y_j when the j^{th} EC is a level of y_j.

In order to model the interactions between ECs and second-order effects, a second-order model is introduced as a sufficient approximation to equation (4.4), which is very flexible and works well in solving real response surface problems (Carley *et al.* 2004). For the case of Q numbers of ECs, the second-order model is

$$x_i = \beta_{i0} + \sum_{j=1}^{Q} \beta_{ij} y'_{ij} + \sum_{j=1}^{Q} \beta_{ijj} (y'_{ij})^2 + \sum_{j=1}^{Q} \sum_{l>j}^{Q} \beta_{ijl} y'_{ij} y'_{il} \tag{4.6}$$

where β_{ij} are regression coefficients for the first degree terms, β_{ijj} are coefficients for the quadratic terms, and β_{ijl} are coefficients for the cross-product terms, and β_{i0} is the intercept term. If β_{ijj} are set to zero, then the second-order model reduces to first-order model with interactions. If β_{ijj} and β_{ijl} are set to zero, then the model reduces to main effects model that is similar to the equation used in traditional QFD.

To solve coefficients in the equation (4.6), design of experiment needs to be deployed to collect necessary data. When the set of ECs is large, the number of experiments will be large and it is necessary to select main impact factors. Relationship matrix in QFD is a useful tool to recognize appearance of the relationships between ECs and customer attributes. Thus in the proposed approach, it eliminates usage of 1-3-9 scales and only be used for recognizing qualitative relationships, which will facilitate deployment of design of experiments.

With the established equation (4.6), it is then possible to calculate the utility of a design alternative with a vector of Y using:

$$u_Y(y_1, \ldots, y_Q) = u(x_1, \ldots, x_M) = \sum_{i=1}^{M} k_i u_i\left(f_i(y_1, \ldots, y_Q)\right) \qquad (4.7)$$

The underlying fact in equation (4.7) is that it is a two-step modeling process as shown in Figure 4.6. In the first step the value model of customers is modeled and it is subjective, reflecting customer preferences. On the other hand, the consequence model from $y_i's$ to x_i is modeled though response surface methodology by considering the influences from ECs to customer attributes. It is different from the one-step process that models directly the relationships from EC to value without identifying the implicit fundamental objectives (Scanlan *et al.* 2011). The equation (4.7) is called the system value model.

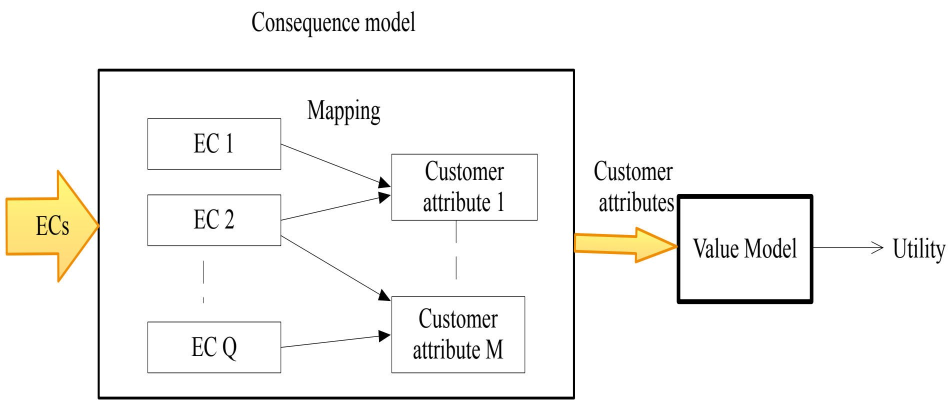


Figure 4.6: Consequence model and value model.

4.1.4 Derive component value models

In the systems engineering practice, component requirements typically are derived from system requirements through a process of decomposition within a hierarchy. This can be illustrated with an example in Figure 4.7.

In some cases, the top-level requirements are allocated directly to the next level (part-whole relationships), such as aircraft weight and unit cost. And the other cases, the top-level requirements are allocated using analytical relationships between the levels (means-ends relationships). For example, a top-level acoustic requirement may be translated into vibration requirement at the engine system level. For means-ends relationships between two adjacent levels of requirements, their characteristics of requirements changed, such as a change from acoustic requirement to vibration requirement. In this process, it is critical that requirements flow down is carried out carefully and consistently, but this process unavoidably introduces further problems.

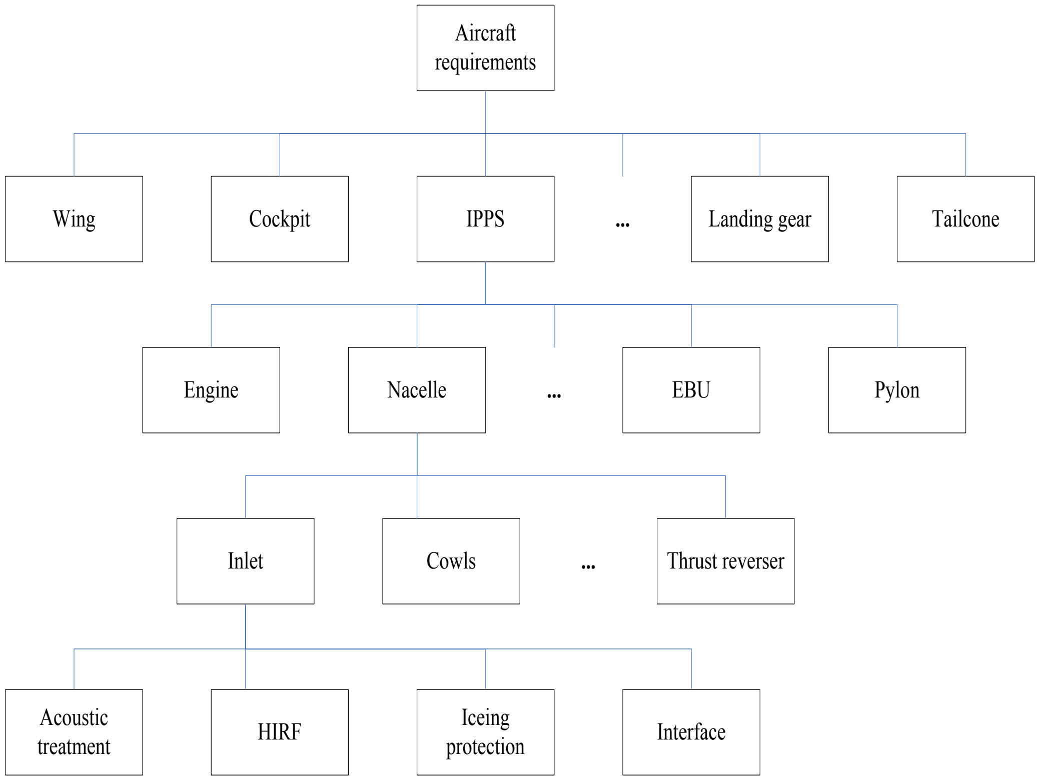


Figure 4.7: Requirements flow down in commercial aircraft domain (INCOSE 2000).

A hypothetical example can illustrate the problem. For example, an originally allocated wing requirement with regards to cost and weight is (x_1, y_1) and an originally allocated landing gear requirement with regards to cost and weight is (x_2, y_2). After design activities, the designed wing has attained the level of (x_1+10, y_1-20) and the designed landing gear has attained level of (x_2-20, y_2+3). Thus the two designs all are not desired as they are beyond the limit of allocated requirements, although the two together (x_1+x_2-10, y_1+y_2-17) satisfy the requirements constraints (x_1+x_2, y_1+y_2). In order to improve the design of wing, a new design solution is proposed that reduce the cost to x_1-1 with an addition of weight to y_1-15. In order to improve the design of landing gear, a new design solution is proposed that reduce the cost to x_2-5 with an addition of weight to y_2-1. Then the two improved design solutions will all satisfy the requirements constraints and they together attain the level of (x_1+x_2-6, y_1+y_2-14). But after a check, the improved attainment in the two components with regards to cost and weight are worse than the first design (x_1+x_2-10, y_1+y_2-17). Through this example, the problem is much clear:

- Flowing down of top-level requirements to component requirements sets constraints to the development of components. When these constraints are used, the design space is constrained. And the final design which satisfies the requirement constraints might not be optimized in terms of value. This problem results from different nature in components' design. That is, in different components' design, to achieve the same level of improvement in one attribute, there are different compensations in other attributes.

In order to resolve this problem, instead of setting targets for ECs and then flowing down these targets to components requirements, component value models are derived from system value models through sensitivity analysis. The component value models then are used for design optimization. When the component designs are maximized with regards to component value models, the system is optimized (Castagne *et al.* 2009) (Collopy 1996, 2001, 2008).

Given:

- The system has a set of ECs $\{y_1, \dots, y_Q\}$, expressed as a vector $\mathbf{y}$,
- A system value model $u_y(y_1, \dots, y_Q)$ is derived from customer value model $u(x_1, \dots, x_M)$,
- The system has a set of P components,
- The p^{th} component p has a set of m_p attributes, $p = 1, \dots, P$, expressed as a vector $\boldsymbol{z_p}$,
- All component attributes are concatenated into a vector $\mathbf{z}$,
- There is a vector function h such that $\boldsymbol{y} = h(\boldsymbol{z})$,
- The objective is to maximize $u_y(\boldsymbol{y}) = u_y(h(\boldsymbol{z}))$,

Distributed optimization can be achieved if, for every component p, a component value model u_{cp} can de defined such that if the design for every component z_p maximizes u_{cp}, then the resulting system $\boldsymbol{y}$ will maximize $u_y(y_1, \dots, y_Q)$.

Because attribute spaces tend to be smooth, $u_y(h(\boldsymbol{z}))$ can be linearized by a Taylor's series expansion in the vicinity of the preliminary design $\boldsymbol{y}'$, corresponding to component design attributes $\boldsymbol{z}'$. Component value model for the component p can de approximated by:

$$u_{cp} \approx \sum_{k=1}^{m_p} \left(\sum_{j=1}^{Q} \frac{du_y}{dy_j} |y_j' \cdot \frac{dy_j}{dz_{pk}} |z_{pk}'\right) \cdot z_{pk} \tag{4.8}$$

Similar result is given in (Collopy 2001).

Through this formalization, we obtain component value models (component requirements specification) from system value model (system requirements specification), and they can be used directly for optimization of component designs.

These four steps represent a systematic process from initial customer statements to component value models. It can be used for establishing value-based requirements specification for system level and also for component levels. A case study application the approach is deployed in the next section, which focuses on the first-two steps and transforms initial airline statements to airline group value model.

4.2 Case Study

In this section, we apply the proposed approach to a test case of requirements establishment for a commercial aircraft. In detail, a formulation of the problem in the commercial aircraft development context is described in sub-section 4.2.1; the refined project context and test case are illustrated in sub-section 4.2.2; and the application of developed approach is presented in sub-section 4.2.3.

4.2.1 Formulation of the problem

In the past management practice of new airplane development projects, the design process usually began when the top-level aircraft requirements (TLAR) were defined. An example of the TLAR is given in Table 4.4, which shows three configurations of short-range to medium-range, narrow body commercial aircraft.

Table 4.4: An example of TLAR (CRESCENDO 2010).

Requirements	Unit	Central configuration	Long configuration	Short configuration
Range (2-class, 120kg/pax for opsitems+payload)	[nm]	3500	3800	3000
Passager Capacity (2-class)	[-]	160	130	190
Design Mach Number Vmo/Mmo	[-] [kt/-]	0.76 330/0.81	0.76 330/0.81	0.76 330/0.81
Initial Cruise Altitude Capability (300fpm)	[ft]	≥ 33000	≥ 35000	≥ 33000
Maximum Cruise Altitude (300fpm)	[ft]	≥ 37000	≥ 37000	≥ 37000
Time To Climb to 33000ft	[min]	≤ 25	≤ 20	≤ 30
Take-Off Field Length		TOFL 3200m at MTOW 1200ft, ISA+33°	TOFL 3000m at MTOW 1200ft, ISA+33°	TOFL3400m at MTOW 1200ft, ISA+33°
		TOFL 1700m at MTOW SL, ISA+15°	TOFL 1500m at MTOW SL, ISA+15°	TOFL 2000m at MTOW SL, ISA+15°
One engine out ceiling (0.97*MTOW, ISA+10)	[ft]	≥ 16000	≥ 16000	≥ 16000
Vapp (MLW, SL, ISA)	[kt]	≤ 137	≤ 130	≤ 140

The development teams always focus on satisfying and improving well-defined TLAR or technological performances, such as low-speed and high-speed performance, stability, range, payload and safety on the basis of previous technological best practices. Design optimizations are always based on one dimension, such as weight or direct operation cost, under a set of constraints. No value trade-offs are performed among these multiple dimensions, and generally stakeholder value is not maximized in this development practice.

More recently, because of the higher competition levels and evolution of the market needs, the program managers aim to supervising the projects from the perspectives of value creation to the stakeholders: the internal stakeholders, the airlines, the airports, the passengers and the certification organizations. Then the purpose is to build commercial aircrafts that do provide a higher value to relevant stakeholders, such the example shown in Figure 4.8. The left part of the Figure 4.8 shows that cheap flight tickets are perceived of high value by passengers of easyJet, which demands to develop commercial aircraft with low acquisition cost and operation cost. The right part of the Figure 4.8 shows that passenger experience is important, which demands to develop commercial aircraft with comfort cabin for resting or working. There are other value dimensions besides cost and comfort, such as safety, reliability and others. All these value dimensions are perceived as valuable to relevant stakeholders and should be provided during the delivery of commercial aircrafts.

The problem in this development context is then how to identify these value dimensions as complete as possible, how to use this identified value dimensions to construct a value model, and how to connect the constructed value model to the TLAR.

Figure 4.8: Creating value for relevant stakeholders.

4.2.2 Case study context

This development of the proposed approach to support value-focused RE builds on a current research conducted within the European Commission's seventh framework (FP7) research project

CRESCENDO in the domain of European aerospace industry in collaboration with mainly European universities and manufacturers (CRESCENDO 2011). The test case of "Requirements Establishment and Value Generation" provides a beneficial link to main manufacturers (i.e., aircraft, engine, sub-systems and others) in the European aerospace industry and useful input during the development of the approach. A schematic illustration of value-driven design among different levels of aerospace product is shown in Figure 4.9 (Cheung *et al.* 2010).

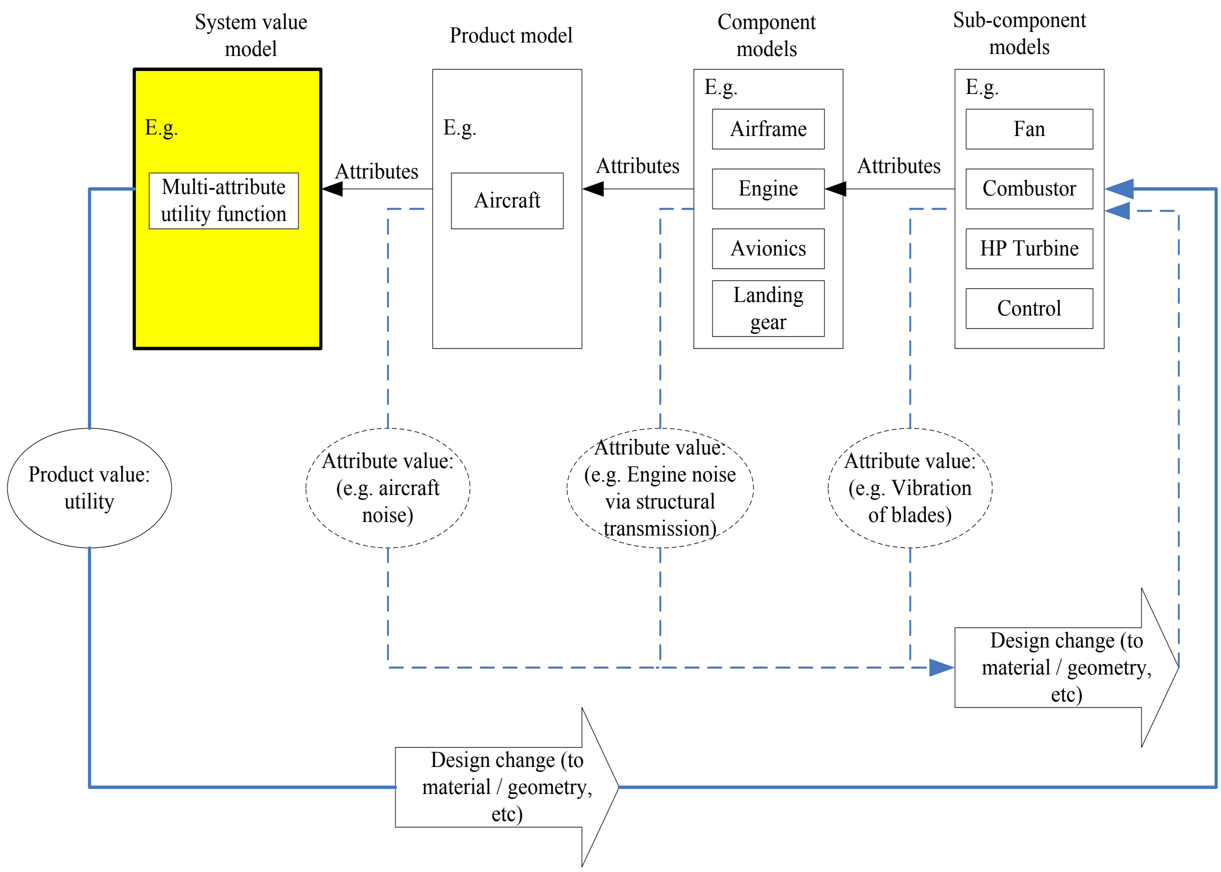


Figure 4.9: A schematic illustration of VDD in context of CRESCENDO.

One innovative aspect of this test case is to build a value model based on airliners needs, expectations and other statements paralleling with traditional RE process, which ensures the developed airplane reflecting customer value. This is shown as the system value model in the left yellow part of Figure 4.9. In this framework, system value model is a multi-attribute utility function rather than the originally surplus value based value model deployed in initial investigation. It is a combination of customer value model and interface model which models the functional relationships between customer needs and top-level aircraft requirements. With the system value model it is straightforward to calculate the utility of special inputs of aircraft attributes that are outputs of aircraft product model. Then evaluation of different alternatives and design optimizations is enabled in terms of customer value. This capability is attributed to single attribute utility information and value trade-offs information contained in the value model. This VDD cycle in the Figure 4.9 is from sub-component models through component models, product model, and system value model back to sub-component models. This cycle is actually very flexible and models can be added to extend sub-component models to further finer models, such as sub-sub-component models. Models can also been deleted from the cycle from sub-component models to component models. For example, deletion of the part of "sub-component model" will create an evaluation and optimization cycle from component models back to component models.

The problems in the processes are how value model can be built, which includes:

- How to construct airline value model,
- How to construct aircraft value model,
- How to construct component value models and sub-component value models.

Besides above concerns, discussions with industrial partners also help identify their expectations about approach development and test case application:

E1. Establish value-driven traceability from customer statements to requirements,

E2. Enable value-driven trade-off capability at requirements level and design solution level,

E3. Pay more attention on intangible value dimensions rather than only on cost aspect (or surplus value), and

E4. Foresee prototypes in place that can be integrated into industrial environments.

We have proposed the approach of value-centric QFD aiming to resolve these concerns. But we realize difficulties from application itself. For the aircraft design and manufacturing process, it is intuitively attractive for the manufacturer to transform airlines' fundamental objectives to top-level aircraft requirements, such as range, payload, maximum take-off weight, and take-off field length, and use these relationships for design and optimization. However, these transformation relationships have not be established and typically, cost or weight based optimization is used in current aircraft design practice. More fundamental research is needed to model their qualitative relationships and functional forms, which is outside of the scope of our current work. But the implications of the approach are clear: to model appropriately the value of ECs, a two-level modeling process is necessary. Also, because of this limit, we will not derive component value models from aircraft value model, although the methods are available. We show in next section how the approach help to derive airlines' value model from initial airline statements.

It is also well recognized that a commercial aircraft is a class of very complex products. Its development demands the application of systematic processes, such as the system engineering processes in general and RE processes for establishing requirements specifications. After investigations within major aircraft manufacturers, several processes and methods used for requirements establishment have been identified. These are called "Working Together Groups" in Boeing and "Customer Focus Groups" in Airbus (De Chazelles *et al.* 2004), which significantly help to understand customer needs. As our intention is to focus on value at RE stage and not to depart from available best practices, a parallel process is used as shown in Figure 4.10. That is, besides the traditional process of requirements cascade, there is a novel process of value cascade. System value model is constructed through value cascade while traditional requirements specification is established through requirements cascade. The combination of system value model and traditional requirements specification results in value-based requirements specification. We also assume that the initial customer statements have been identified through the activities of traditional RE process.

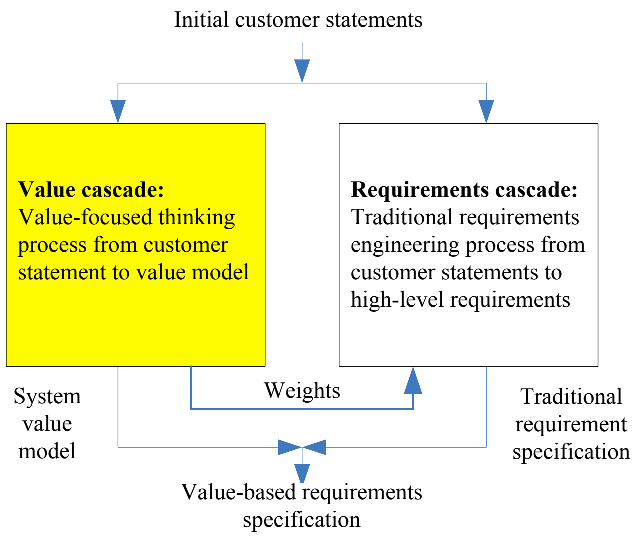


Figure 4.10: Value and requirements - a parallel process.

4.2.3 Application of the approach

As discussed in Section 4.1, we have developed a four-steps process to transform initial customer statements through customer value model through system value model into component value models. However, in view of the complexity from the test case itself, the application of approach focuses on the first two-steps: (1) identifying and structuring objectives, and (2) specifying attributes and constructing value model.

Step 1: Identifying and Structuring Objectives

The initial customer statements in the Table 4.4 are used as the starting point for deriving requirements specification. Although they are incomplete, they are sufficient for the illustration of the approach.

The types and examples of initial airline statements are partly given in the first two-column of Table 4.4. An obvious fact regarding to the statements is that airlines try to express statements in different levels and granularities. The airline statements may be in the form of needs, goals, objectives, constraints, ECs, or design parameters. It is straightforward to transform the initial statements into objectives as shown in the third column of Table 4.4.

Table 4.4: Part of initial customer statements, their transformed objectives

Types of statements	Examples	Transformed objectives	Types of objectives
Customer need	Minimize operating cost	Minimize operating cost	Fundamental
Customer need	Reduce environmental impact	Minimize environmental impact	Fundamental
Others	Minimize fuel consumption	Minimize fuel consumption	Means
Others	Standardization and commonality is desired	Provide standardization and commonality	Means
Goal	Range is expected to achieve 9000 nm	Maximize range	Means
Constraint	Approach speed must lower than 150 kts	Optimize approach speed	Means
Proposed technology	The natural laminar flow has important potential to reduce drag	Utilize natural laminar flow when design the wing	Means
Others	Fleet rationalization	Rationalize fleet	Strategic

Some of these transformed objectives may be fundamental objectives. The objective of "minimize operating cost" is a fundamental objective for chosen airlines, as they think it is one of the fundamental reasons to select a commercial aircraft. It is possible to ask why "minimize operating cost is important", and the answer may be that it directly influences profit levels. On the other hand, profit is also influenced by other means, such as pricing, marketing and strategy, which are not under the control of the current decision context of aircraft development.

Some of these transformed objectives may be means objectives. "Minimize fuel consumption" is a means objective, although there is a high frequency of mentions by airlines. The underlying reasons are that it influences positively the achievement of "minimize operating cost" and "minimize environment impact", which are fundamental objectives. "Provide commonality" is also a means objective, which influence positively "minimize operating cost" and "maximize maintainability", and it may influence negatively "maximize performance", such as the range and the maximum take-off weight of the aircraft. The overall performance as a means influences several objectives, such as operating cost and usability to route operation. "Maximize maintainability" is uncovered as a missed fundamental objective in Table 4.4. Through means-ends analysis on "provide commonality", it is found that it is difficult to make sensible decisions when commonality is considered directly. The decisions of how much commonality to realize should all depend on its influence on operating cost, maintainability and usability. Then value trade-offs should be made among operating cost, maintainability and usability to determine the degree of commonality. A reckless combination of commonality, operating cost, maintainability, performance and usability without distinguishing the underlying means-ends relationships will result in double counting the importance of commonality. This simply highlights the importance of identifying fundamental objectives.

Transformed objectives may be strategic objectives, such as "rationalize fleet". They are at a too high level to be controlled by decisions under aircraft development. "How" questions should be pursued to explore its relationship with aircraft development. The outcome may be that current fleet is in a certain situation in which longer range and more fuel-efficient aircrafts are needed. This will help to find the underlying fundamental objectives. However, these transformations do not eliminate those original customer statements that are also useful for design. For example, the imposed constraints are usually to be utilized to check the technical feasibility and economic viability of the design alternatives.

After a complete means-ends analysis on the objectives in Table 4.4, a means-ends objectives network is established and a set of fundamental objectives is identified. Those uncovered fundamental objectives from the transformed objectives are presented in Table 4.5.

Table 4.5: Transformed objective and their fundamental objectives

Transformed objectives	Types of objectives	Uncovered fundamental objectives
Minimize operating cost	Fundamental	
Minimize environmental impact	Fundamental	
Minimize fuel consumption	Means	Minimize operating cost, minimize environment impact
Provide standardization and commonality	Means	Minimize operating cost, *maximize usability*, *maximize maintainability*
Maximize range	Means	Part of "Maximize performance" (means), which influences operating cost, usability
Optimize approach speed	Means	
Utilize natural laminar flow when design the wing	Means	Minimize operating cost, minimize environment impact, maximize usability, *maximize safety*, *maximize reliability*
Rationalize fleet	Strategic	Minimize operating cost, minimize environment impact, maximize usability, maximize maintainability

It is then necessary to perform part-whole analysis on the fundamental objectives in Figure 4.11, which helps to clarify the understanding of fundamental objectives of high levels and granularities.

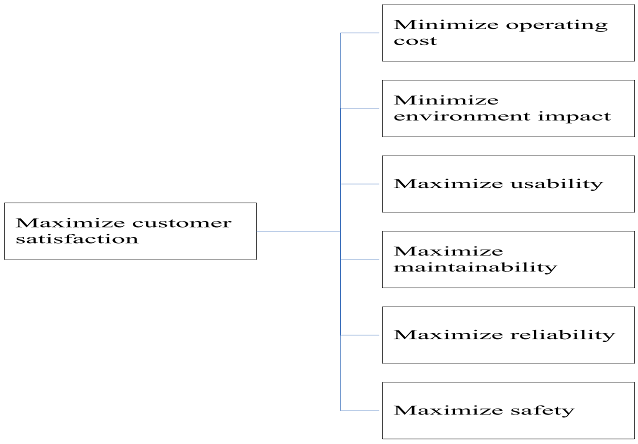


Figure 4.11: The fundamental objectives established from transformed objectives.

A fundamental objectives hierarchy for the objectives of "Minimize environmental impact" is given in Figure 4.12, which is a sub-hierarchy in the Figure 4.11. In this figure, a narrow perspective is adopted and environmental impact is limited to noise and emission impact that will be sufficient to illustrate the process and methods. In this hierarchy, the objective of minimizing environmental impact is decomposed into a degree at which appropriate attributes for measurement can be selected.

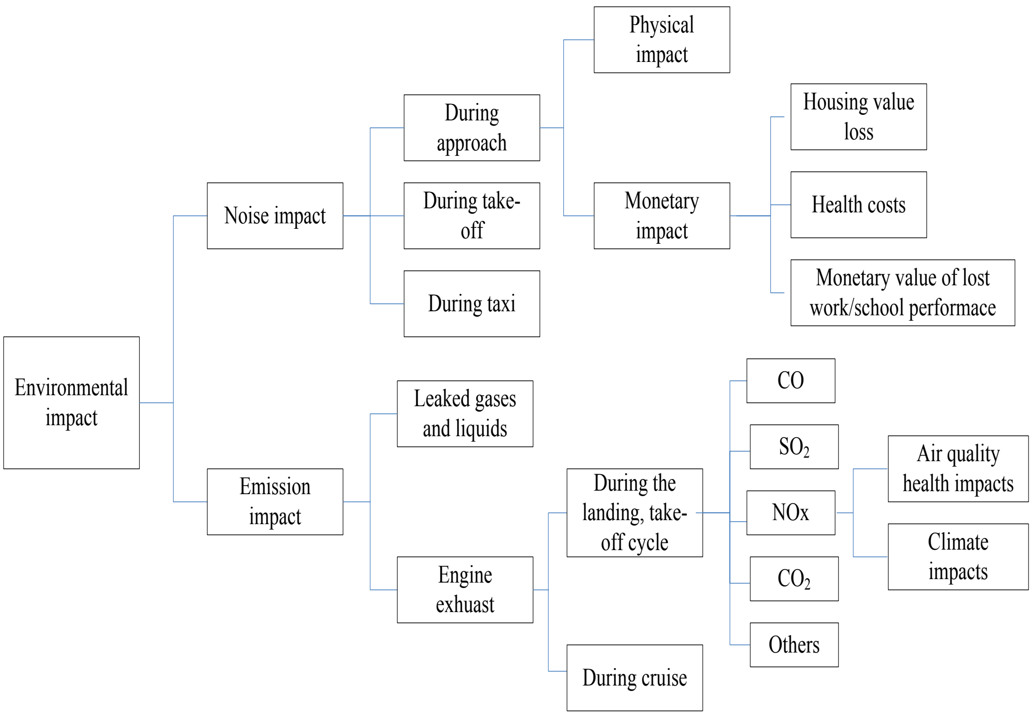


Figure 4.12: A hierarchy of fundamental objectives of minimizing environmental impact.

The same procedures are performed in other fundamental objectives, such as "Minimize operating cost". The first attempt of asking questions leads to a decomposition into direct operating cost and indirect operating cost. Asking further what questions lead to a fundamental objectives hierarchy of operating cost in Figure 4.13. This hierarchy is useful to understand the meaning of the "minimize operating cost" and to collect necessary information to measure "minimize operating cost". Finally, a complete hierarchy of all the fundamental objectives is established.

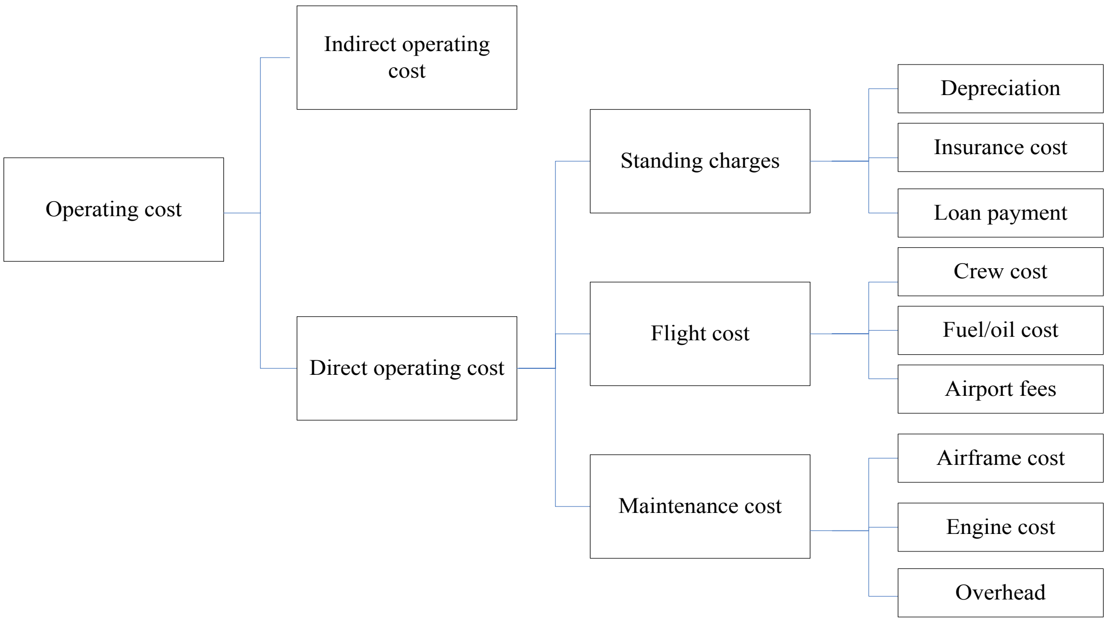


Figure 4.13: A hierarchy of the fundamental objective "minimize operating cost".

Through means-ends and part-whole analysis, hard work and creative thinking on these objectives, confidence is established that the set of fundamental objectives satisfies the desired properties of fundamental objectives specified by (Keeney 1992). Thus the procedure facilitates further quantification and value measurements.

Step 2: Specifying Attributes and Constructing Value model

A hierarchy of airlines' fundamental objectives provides well-structured forms of input for the quantification process. In order to enable transformation from qualification to quantification, certain attributes or metrics are needed to measure the achievement of each of the fundamental objectives in the leaves of the hierarchy, which is necessary to assign meaningful weights to fundamental objectives.

Seat mile cost measured in 2011 dollars is a natural attribute regarding to operational cost. A constructed attribute with four levels is used for safety measurement in Joint Airworthiness Requirements: Minor, Major, Hazardous and Catastrophic. Every level is given clear clarification in value so that customers or designers can easily find the safety level of a special aircraft. "Mean maintenance man-hours per flight hour" is selected as an attribute for "Maximize maintainability".

"Dispatch reliability rate measured in %" is an attribute for "Maximize reliability". For usability of airplane, one attribute is identified for each function in appropriate levels and for airplane's capability to commit certain route, and these attributes are expressed as elements of a vector.

However, for some objectives, it may be too difficult to identify direct measurements or collect the information for the direct measurements. For example, the overall health cost resulting from noise impact is hard to collect. Proxy attributes are then used as indirect measurements for fundamental objectives, which may be the direct measurement of some means objectives. For example, attribute X_1 effective perceived noise in decibels (EPNdB) is a proxy attribute for noise impact that maybe more appropriately measured by health impact (X_2), noise depreciation index and monetary impact (Jenkinson *et al.* 1999) (Mahashabde 2009) (Mahashabde *et al.* 2011). However, introducing of proxy attributes, e.g. EPNdB and NOx emission, causes difficulty of verifying independence assumptions and assessing value models at later stages. For example, to assess value model of attribute X_1 in terms of "health impact X_2)," meaningfully, a two-level process is implied as shown in Figure 4.14(a). The function between x_1 and x_2 is necessary to be found firstly. Possibly, it is modelled with a conditional probability function $p(x_2/x_1)$. Then single attribute utility function over X_2 is assessed. These together give single attribute utility function over X_1. It is also possible to assess this value model directly from proxy attribute X_1 to utility as shown in Figure 4.14(b), but it demands more cognitive complexity to assess reasonable utilities of levels of proxy attribute X_1, which is normally error-prone. Without clear consciousness of the relationships between noise levels and health impact, it is difficult to assess the utilities of different noise levels. While the difference, say between 108 EPNdB and 90 EPNdB, is obvious, the difference of their utility cannot be obtained directly.

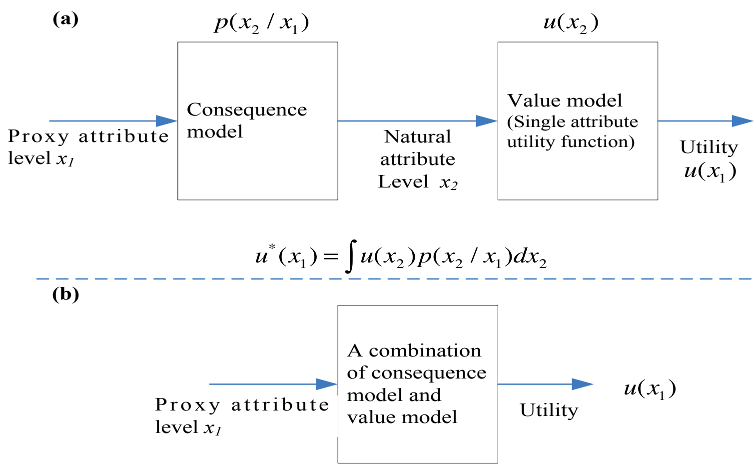
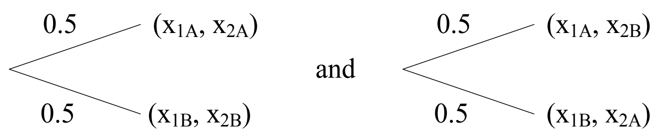


Figure 4.14: Proxy attribute and its assessment of value.

It is desirable that the set of selected attributes satisfies desired properties of attributes, e.g. measurable, operational, direct and unambiguous. And, there are one-to-one relationships rather than multiple-to-multiple relationships between objectives and attributes. In order to facilitate latter illustration, we assume that there is a set of M objectives $\{O_1, \ldots, O_M\}$ in the leaves of the fundamental objectives hierarchy of airlines with a set of M attributes $\{X_1, \ldots, X_M\}$, that is, one attribute for one objective. We also assume that the selected attributes are all direct attributes and there is a transformation process from these direct attributes to ECs that are proxy attributes for fundamental objectives. These assumptions are reasonable, although they introduce the difficulty of modeling or approximating the relationships between direct customer attributes and proxy attributes.

After specifying attributes, it is time to verify possible preference independence assumptions among attributes, which help finding function forms of the value model, e.g., multiplicative or additive function forms. For example, to verify the relationships between seat-mile cost (X_1) and man-hours per flight hour (X_2), a test as in Figure 4.15 is deployed. Actually, for all values of X_1 and X_2, the customer is indifferent between the two lotteries, which imply existence of additive independence between X_1 and X_2. When additive independence is verified, an additive function form can be used for compose together X_1 and X_2. For M attributes, the same procedures are used, although it is time-consuming when M is large.

If the decision maker is indifferent between the lottries



for all values of x_1 and x_2, then x_1 and x_2 are additive independence.

Figure 4.15: Verification of independence assumptions.

Empirically, Keeney shows that it is appropriate to determine an additive function form when the set of objectives are fundamental objectives and the objectives satisfy the set of desired properties of fundamental objectives (Keeney 1992). After carefully performing means-ends and part-whole analysis, we have confidence that additive function form

$$u(x_1, \ldots, x_M) = \sum_{i=1}^{M} k_i u_i(x_i) \tag{4.9}$$

is a reasonable approximation of customer preferences. Therefore, it is a reasonable form for representing airline preferences.

Single attribute utility functions for attributes are then assessed. Necessary information for assessing one single attribute utility function includes: 1) range information of the attribute, 2) the monotonicity of the utility function, 3) risk attitude of the customer towards the uncertainty attainment of the attribute, and 4) certainty equivalence (or lottery equivalence). One hypothetical single attribute utility function over seat-mile cost is modeled and illustrated in Figure 4.16.

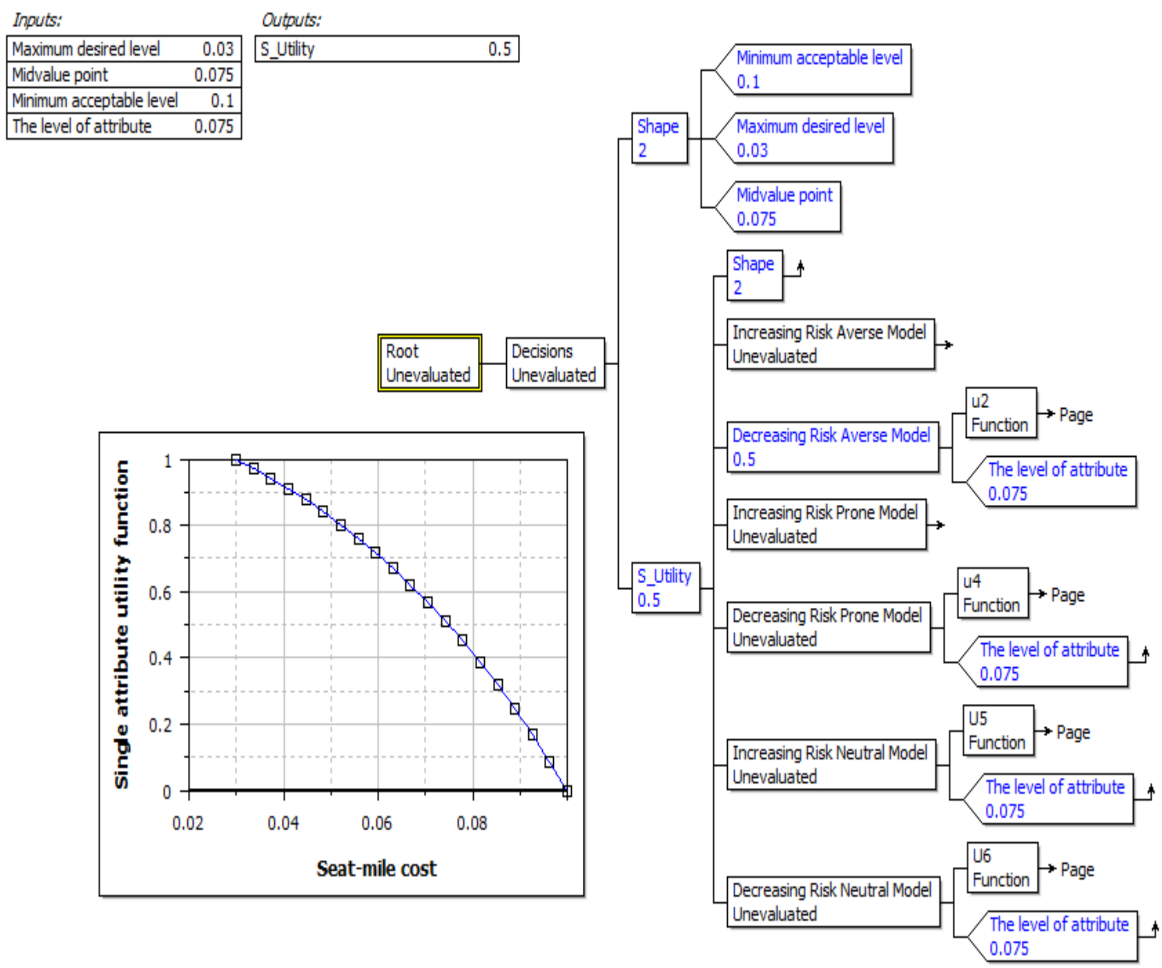


Figure 4.16: Single attribute utility function: seat-mile cost.

For single attribute utility function over seat-mile cost, the underlying process to determine it reasonably is following: (1) Collect range information of attribute, that is from 0.03 to 0.1 dollar every seat-mile cost, (2) Ascertain the direction of increasing preferences and monotonically decreasing preferences is verified, (3) Verify airline risk attitudes towards uncertain attainment of seat-mile cost and risk averse is found as airline would prefer expected consequence to the lottery, (4) Select the class of risk averse utility functions (Keeney 1992):

$$u_i(x_i) = a + b(-e^{-cx_i}) \tag{4.10}$$

where a and b>0 are constants and are selected to ensure u_i being scaled from zero to one, constant c<0 indicates monotonically decreasing preferences, and the value of c indicates the degree of airline's risk averse, (5) Assess certainty equivalence (or) lottery equivalence, and 0.075 dollar is determined as indifferent to the lottery <0.03, 0.5, 0.1> which yields either a 0.03 dollar or a 0.1 dollar seat-mile cost, each with a one-half chance, and (6) Solve a, b and c in equation (2) for determining single attribute utility function over seat-mile cost using available information.

The single attribute utility function over man-hours per flight hour is assessed of risk neutrality as shown in Figure 4.17, which is a linear form.

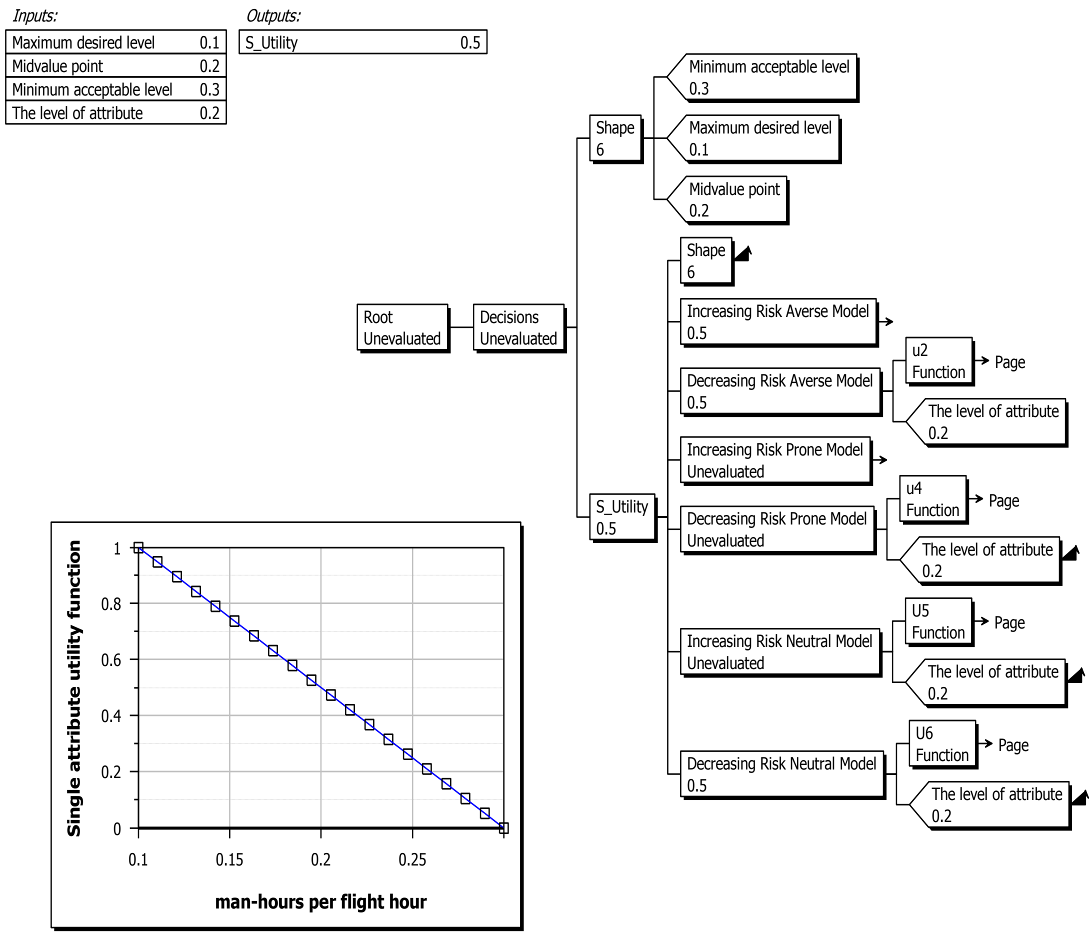


Figure 4.17: Single attribute utility function: man-hours per flight hour.

These assessments of single attribute utility functions are implemented in the Vanguard Studio, which is one of business software for decision analysis and has a wide range of applications in industries and by our partners. A Vanguard Studio model has been developed for the assessment, which includes six possible sub-models:

- Increasing risk averseness model,
- Increasing risk neutrality model,
- Increasing risk proneness model,
- Decreasing risk averseness model,
- Decreasing risk neutrality model,
- Decreasing risk proneness model.

The inputs of the model are following (when monotonicity is verified):

- The most desired level of the attribute x_i',
- The minimum acceptable level of the attribute x_i'',
- The mid-value point in the attribute range x_i'''.

Then the model can judge the direction of increasing preferences, customer's risk attitudes and assess the single attribute utility automatically. The underlying rational is that when there are the inputs of x_i', x_i'' and x_i''', three equations can be found. For example, if $x_i' > x_i'''$ could be found, then the single attribute utility function is increasing; if $x_i'' < \frac{x_i' + x_i'''}{2}$ could be further found, then the customer is risk averse over the attribute, which gives the following equations:

$$u_i(x_i') = a + b\left(-e^{-cx_i'}\right) = 1 \quad (4.11)$$

$$u_i(x_i'') = a + b\left(-e^{-cx_i''}\right) = 0.5 \quad (4.12)$$

$$u_i(x_i''') = a + b\left(-e^{-cx_i'''}\right) = 0 \quad (4.13)$$

These three equations have three parameters and can be easily solved in some mathematical software, such as Maple. But it poses problems to the Vanguard Studio, as there are no available functions for solving nonlinear equations. Actually, after some transformation, these equations can be transformed into three single-variable equations that could be solved in Vanguard Studio.

$$2e^{-cx_i''} = e^{-cx_i'} + e^{-cx_i'''} \quad (4.14)$$

$$b = \frac{1}{e^{-cx_i'''} - e^{-cx_i'}} \quad (4.15)$$

$$a = be^{-cx_i'''} \quad (4.16)$$

Then another problem comes. In order to solve (4.14) in Vanguard Studio, some initial guess about the parameter c is necessary for the function $\boldsymbol{root}\ (\boldsymbol{f(x), x, x_1, x_2})$. If the initial guess is not in a reasonable range, it will risk of not finding the root for the (4.14). For the case of seat-mile cost, the initial guess of c could be solved by a simple plotting function as shown in Figure 4.18.

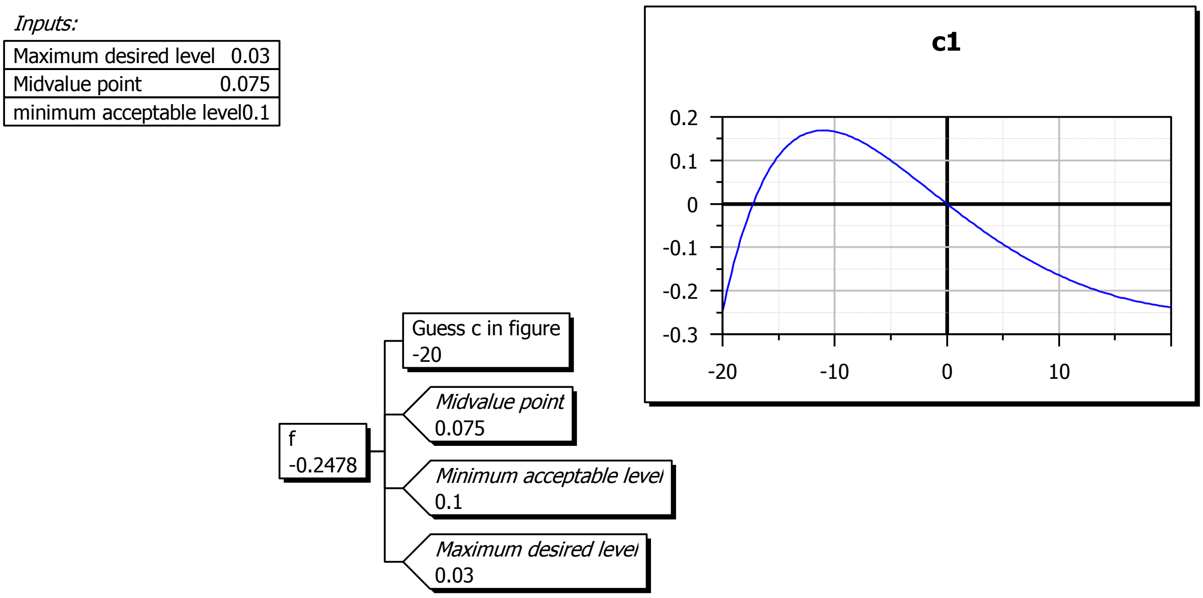


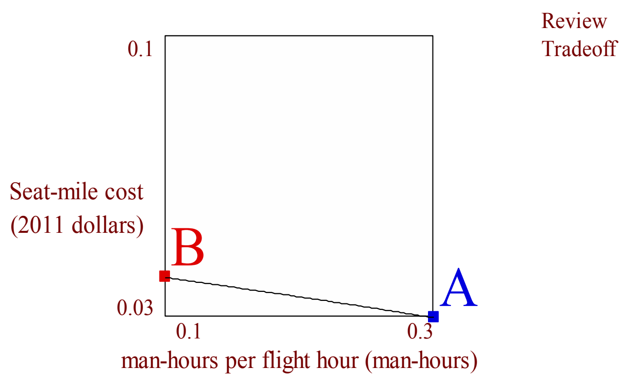
Figure 4.18: Initial guess of the parameter c.

This solution is feasible when the model is used separately, but it fails when the model used as a component in other larger models. Thus another solution is explored to avoid the initial guess of parameter c. In the case of seat-mile cost, it can be ascertained that the parameter c is smaller than zero. We then set the c to be a value smaller than zero and very near to zero, such as -0.00000001. If for this value, the root could be found, then the parameter c is found. If the root could not be found, some adjustments are made to help finding the parameter c. This solution has proved its effectiveness and is used in our model.

Scale constants (or relative importance) k_i's are assessed through making value trade-offs. For example, with two hypothetical alternatives of the same utilities for airlines differing only in achievement of two attributes: seat-mile cost (X_i) and man-hours per flight hour (X_j). If an airline would like to pay 0.01 dollar more in seat-mile cost in order to exchange a reduction of 0.2 man-hours per flight hour, then

$$u(x_1, \dots, 0.03, \dots, 0.3, \dots, x_M) = u(x_1, \dots, 0.04, \dots, 0.1, \dots, x_M) \qquad (4.17)$$

is satisfied, which is visually displayed in Figure 4.19. Weight ratio between k_j and k_i is shown at the bottom of the figure, which shows one equation with k_i's as unknown.



	A	B	A-B
man-hours per flight hour (man-hours):	0.3	0.1	0.2
Seat-mile cost (2011 dollars):	0.03	0.04	-0.01

man-hours per flight hour Measure Weight:Seat-mile cost Measure Weight = 0.0801682:1

Figure 4.19: Value trade-off between two attributes to determine relative weights.

For M attributes, a set of at least M equations is constructed to determine the M k_i's in the additive function form. These equations are linear and can be easily solved in Vanguard Studio. The roots of these equations are the k_i's. After assessing function form for the multiple attributes, single attribute utility functions and k_i's, a multi-attribute value model for individual airline is established.

However, different airlines may have different preferences about attributes and their importance. They then may have different value models, although the same set of fundamental objectives and attributes is used for assessment. Some attributes may be assigned a higher weight by a certain airline while others may assign them a lower weight. Airlines may even have different perceptions about single attribute achievement. If consensus cannot be achieved, group preferences have always to be derived.

In order to simplify the illustration, let' s consider a case of two airlines. One airline is a low-cost carrier and the other is a flagship carrier. They have the same set of fundamental objectives that are narrowed to three in our context. This example is demonstrated in Table 4.6. However, they have different preferences about relative weights and attainment of objectives.

Table 4.6: A group utility problem.

	Customer	Fundamental objectives	Attributes
Group	Flagship airline 1	Minimize operating cost	X_1: Seat-mile cost measured in 2011 dollars
		Maximize maintainability	X_2: Man-hours maintain per flight hour
		Maximize reliability	X_3: Dispatch reliability rate measured in %
	Low-cost airline 2	Minimize operating cost	X_1: Seat-mile cost measured in 2011 dollars
		Maximize maintainability	X_2: Man-hours maintain per flight hour
		Maximize reliability	X_3: Dispatch reliability rate measured in %

A formulation of the group utility problem in Table 4.6 is given in Table 4.7.

Table 4.7: A formulation of group utility problem.

Group	Customer	Importance of customer	Attribute	Weight of attribute	Single attribute utility function
$\boldsymbol{u_G} = \sum_{s=1}^{2} \boldsymbol{w_s u^{(s)}}$	Flagship airline 1	0.35	X_1	0.7531	$u_{11}(x_1) = 1.05184 + 0.01427(-e^{43.00272x_1})$
			X_2	0.02098	$u_{12}(x_2) = 1.5 - 5x_2$
			X_3	0.22593	$u_{13}(x_3) = 1.30902 + 2.2534e^{13}(-e^{-32.08079x_3})$
	Low-cost airline 2	0.65	X_1	0.78115	$u_{21}(x_1) = 1.42477 + 0.25287(-e^{17.28891x_1})$
			X_2	0.06262	$u_{22}(x_2) = 1.5 - 5x_2$
			X_3	0.15623	$u_{23}(x_3) = 1.06002 + 2.2422e^{36}(-e^{-63.80672x_3})$

In this case, the Supra Decision Maker (Keeney 1993) is the aircraft manufacturer who verifies the assumptions and assesses the scaling constants w_s that address interpersonal comparison of utility. In order for aircraft manufacturer to meaningfully assign relative weights of airlines, a sophisticated assessment process is necessary, which is another decision-making problem of multiple objectives. The weights are influenced by percentage of orders, market potential, political considerations and others.

The two airlines with three attributes can be easily extended to N customers with M attributes

$$u_G = \sum_{s=1}^{N} w_s u^{(s)}(x), i = 1, \ldots, M \tag{4.18}$$

With a quantified group value model and several individual value models, it is then possible to do various kinds of visual analysis, sensitivity analysis, Monte Carlo simulations and optimization. These modeling and simulation have been also implemented in the software of Vanguard Studio. Figure 4.20 represents the implemented model of group utility function and a color-based sensitivity analysis, which shows the degree of relevance between customer attributes and group utility. Differences between airlines can be identified: different relative weights of airlines, different perception of attribute attainment and different relative weights of attributes. Individual utilities are assessed and aggregated meaningfully into group utility without making compromise between airlines.

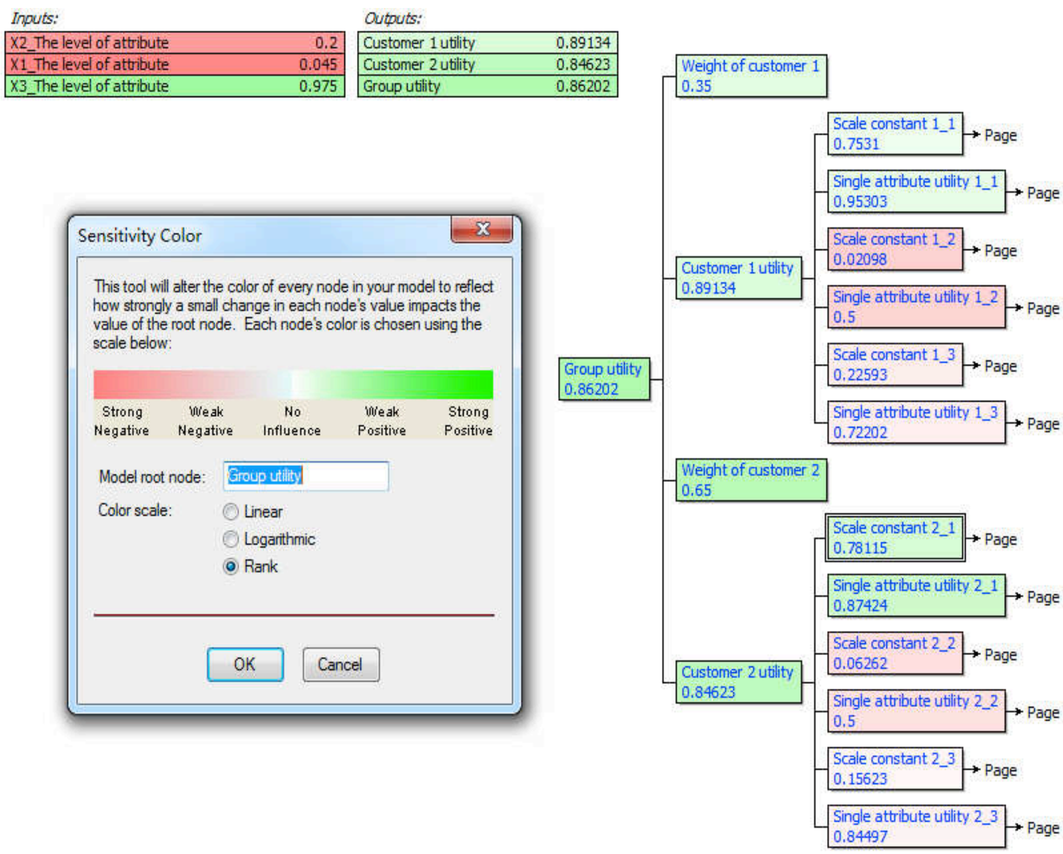


Figure 4.20: Group utility and color-based sensitivity analysis.

Other capabilities of value modeling and simulation are also implemented, such as component-based modeling and internet-based simulation, which supports distributional design and development. Parts of them are shown in Figures 4.21. This value model can be conveniently integrated into existing engineering models in an Isight simulation process workflow when the interface between top-level aircraft requirements and customer attributes are available.

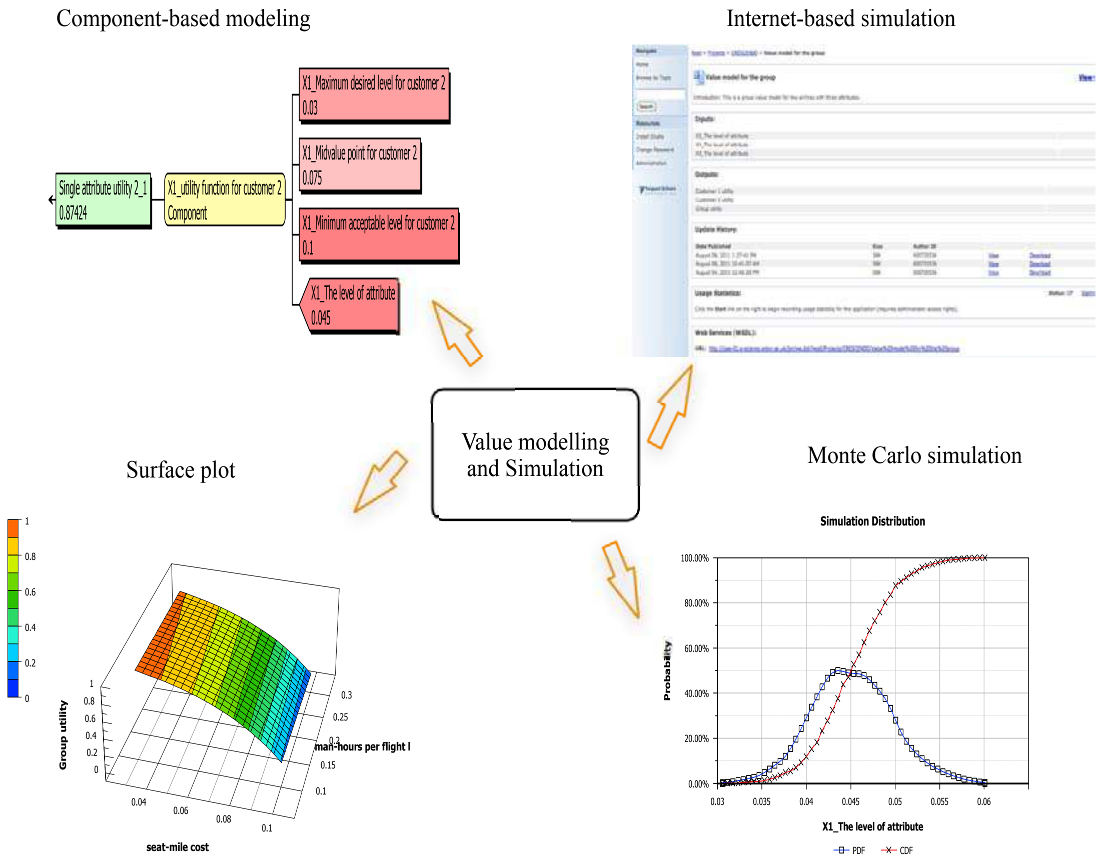


Figure 4.21: Value modeling and simulation.

From this case study, we show how an initial set of airline statements can be used for developing an airlines' group value model. The step-by-step procedures are illustrated clearly. Firstly, the initial airline statements are transformed into objectives with common expression. Then means-ends analysis is performed on these objectives, which tries to identify and discover the airlines' fundamental objectives in the commercial aircraft development context. In order to promote an in-depth and common understanding of the fundamental objectives, part-whole analysis is performed. Attributes are then carefully identified and selected for further clarifying the meaning and measuring the attainment of the fundamental objectives. With verification of the independence assumptions among the attributes, additive function form is selected as an appropriately approximation to model individual airline's preferences. Single attribute utility functions and relative weights of attributes are then assessed with the theoretical support from multi-attribute utility theory. Finally, the individual airline's preferences are composed into a group value model. These assessments of value model have been implemented in Vanguard Studio, which enables simulation and integration with existing aircraft engineering models.

This application shows some attractive features and can answer the following two questions: (1) what are perceived as valuable by airlines with regards to commercial aircraft development, and (2) how this airlines' value can be reasonably quantified. Therefore, the approach is considered as a potential alternative by industrial partners in the CRESCENDO projects to support value-based requirements establishment.

In the application process, we also recognize some limitations of the approach concerning the complexity. While the approach is logical and based on sound theory, it demands more subjective inputs about their value judgments and it is more time-consuming. It is more sophisticated than some other approaches, such as the QFD and the KANO models. Especially, when the number of objectives and attributes in the development context are large, more time and hard work are needed to verify assumptions, make value trade-offs and assess single attribute utility functions. This could make the applicability of the approach questionable in practice.

However, we have to consider one remarkable fact as mentioned by (Keeney 1992):

> *The only reason for an interest in such problems (complex decisions) is because some consequences may be much better than others, and some alternatives may be much better than others. And yet the amount of time devoted to careful study of the appropriate values is minuscule relative to the time used to address other aspects of the decision situation. The "objective function" (value model) may be chosen in an hour with very little thought, while several person-years of effort and millions of dollars may be used to model the relationships between the alternatives and the consequences and to gather information about those relationships. Since values are the entire reason for caring about the problem, it would seem reasonable to use a portion of those resources to structure, quantify, and understand the relevant values. Such an effort should be used to build a value model.*

Therefore, it is reasonable and valuable to spent time and resources to build the value model, especially in the complex decisions with high impact to customers.

4.3 Conclusions

Aiming to mitigate those methodological problems and rationalize the requirements establishment process, this chapter presents a prescriptive approach to support value-based requirements engineering.

It is a four-step process, including (1) identify and structure objectives, (2) specify attributes and construct value model, (3) transform fundamental objectives into ECs and (4) derive component value models. The process is supported by a set of theories and methods, which includes usage of objectives, attributes, means-ends objectives network, fundamental objectives hierarchy, multi-attribute utility theory, response surface methodology and VDD. We claim the approach does provide a prescriptive and logical way to understand customer needs in terms of value. The main contribution of this research is to derive value model(s) from initial customer statements, which enables a progression of VDD from economic based value model to multi-dimensional value model, and some methodological problems underlying QFD are resolved.

One application of the proposed approach in a business case of requirements engineering for commercial aircraft is deployed. It focuses on the first aspect of deriving airlines' value model from initial airlines' statements, and the aircraft value model and component value models are not established in current work because of some limits in application itself. The value models are implemented in business software Vanguard Studio can be simulated and integrated into existing engineering models. The initial responses from the partners about the approach and the test case are positive, and the approach is listed as a potential alternative for establishing value-based requirements specification among the industrial partners.

5 Conclusions and Recommendations

It is a never-ending job to satisfy customers. Traditionally, products were designed and produced from the viewpoints of manufacturers that try to maximize product performance or minimize cost under a set of constraints. Customers almost accept whatever products manufacturers supply in the market. And they are generally happy about the situation as they can use or enjoy the functions of product to improve their work and life. But, as time elapses, they recently become more demanding. They propose their needs and expectations about the existing products or the products to-be developed. These needs and expectations are then transformed and used by engineers for design and development. This is a great change for customers and a great challenge for manufacturers. In order to satisfy customers, manufacturers have to pay more attention to customers and their needs, which means to change their focus from performance-oriented to customer-oriented design and development. Great success about customer-oriented design and development has been achieved, and many of these kinds of examples can be found in industries. However, this traditional customer-oriented paradigm of design and development fails to answer what are perceived as valuable by customer and how much. The correspondences between customer needs and customer value have not been established. Therefore, while the products developed according to this paradigm can satisfy the customer needs, this paradigm can not answer how much value have been realized by the products.

The intention of this thesis is to propose a prescriptive approach to derive value-based requirements specification, which can help clarify two critical questions during the requirements establishment stage. The first one is about how to identify as completely as possible and logically structure customer value while the second one is about how customer value can be reasonably modeled and simulated for deriving value-based requirements specification. The context, problems, and objective of this approach development have been discussed in the Chapter 1.

While our approach development is essentially based on state of theory and is expected to be applicable to industrial practice, an extensive review of state of theory and state of practice is deployed in Chapter 2. The review of state of theory concerns theories, processes, methods and tools of requirements establishment and value modeling. The review of state of practice concerns processes, methods and tools that are being used in requirements establishment practice of CRESCENDO industrial partners. One innovative aspect of this review is to combine together requirements establishment and value modeling as value is always a missing element in traditional requirements establishment. This review helps selecting the QFD as the methodological foundation for further development. And it helps identifying possible value modeling methods, e.g. multi-attribute utility theory.

Although QFD is a systematic method to transform customer needs into requirements specification, it suffers from seven methodological problems with regards to establishing appropriate value-based requirements specification. These methodological problems are listed with illustrative examples in Section 3.1.2. Some of these problems have already been identified in the literature, such as P3 and P4, but there is no given solution in the context of QFD. Others, such as P1 and P2, are newly proposed. It is critical attractive to display the problems and their examples in such a clear way, which help identifying potential traps to avoid and promoting the idea of developing more rigorous approach for value-based requirements establishment. Following QFD's methodological problems, a set of concepts, theories and methods are also introduced for resolving these methodological problems in Section 3.2. These concepts, theory and methods are introduced in a way in which there are close correspondence between problems and solutions. For example, means-ends objectives network is used for organizing means-ends relationships among transformed customer objectives, while fundamental objectives hierarchy is used for organizing the part-whole relationships. To resolve the possible traps of "weighting" and "additive linear measurement", multi-attribute utility function is used. To model more precisely the functional relationships between fundamental objectives and ECs (interface model), response surface methodology is introduced.

After discussing the foundations of approach development, the procedures of proposed approach are discussed in detail in Chapter 4, which is a four-steps process: (1) identify and structure objectives, (2) specify attributes and construct value model, (3) transform fundamental objectives into ECs to establish a interface model between customer attributes and ECs, and (4) derive component value models. The set of concepts, theories and methods discussed in Chapter 3 has been integrated into different steps of this process. Customer value model, system value model and component value models can be established through performing this four-steps process, and can be used to derive value-based requirements specification. With proposition of the approach, application of the first two-steps of the approach has also been deployed together with industrial partners in the requirements engineering stage of commercial aircraft. This application is under project context of CRESCENDO and in the test case of "Requirements Establishment and Value Generation", which helps providing useful inputs to carry out the approach. The development of value models also been implemented in a business software Vanguard Studio. This development enables customer value can be modeled, simulated and finally integrated into existing engineering models.

When we develop the approach, we realize the importance of developing approach that are based on sound theory and can be applicable to industrial practice. Therefore, we believe that the proposed approach and the value-based requirements specification derived from this approach can bring at least 3 benefits to the academics and industries with regards to value-based requirements establishment and value driven design. We replicate the benefits that were introduced in Chapter 1: (1) value becomes an explicit construct that can be qualified and quantified to some extent enabling value modeling and simulation, (2) value-based requirements specification is used for evaluating of design alternatives, which helps selecting one or a subset of design alternatives with high value to customers. It is a kind of reactive way of using value-based requirements specification, and (3) value-based requirements specification can be used for designing for value in the life cycle of products. Important value dimensions and value drivers are identified as pointers for designing. It is a kind of proactive way of using value-based requirements specification.

We also realize limitations of the proposed approach in terms of complexity when it is compared with the traditional approaches. It is obvious in traditional requirements practice, customer needs and requirements are usually expressed in textual form and there is little available quantitation. However, the proposed approach demands more subjective and measurable judgments from customers in order to quantify customer value appropriately, which requires customer to work hard to figure out complete and consistent value judgments. The proposed approach also demands to identify and select attributes to measure the attainment of customer needs. While it is a missing aspect in traditional approaches and an innovative aspect of the proposed approach, it is not so straightforward to identify attribute for some customer needs. All these demand more work and creative thinking from customers. This is not an easy transformation. Because of these complexity, it is more time-consuming than traditional approaches, which is a not an attractive feature. But from the viewpoint of investing more time and resources in the requirements establishment stage, it is fully deserved in order to develop value-added products.

We think the approach should be refined in terms of the following aspects: (1) for some cases, it is necessary to use proxy attributes to indirectly measure fundamental objectives, but this usage introduces problems to construct value model and assign appropriate weights to attributes. Some research papers are available to discuss their effects in decision-making (Butler *et al.* 2006) (Keeney 1992), but their implications in requirements establishment should be understood appropriately, (2) in the development of approach it avoids to use targets for customer attributes or ECs, but target-based product development is widely used in development practice and is especially attractive for certain context. Although it might cause problems, e.g. the selected design alternatives being inconsistent with maximized expected utility theory, it would be useful to develop approach to use target-based product development and it is still consistent with maximized expected utility theory, and (3) some practical consideration that may simplify value assessment is desired to-be explored. This could reduce the resources and time dispensed during this stage and could promote it application in industrial practice.

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Abstract

Specialty: Industrial Engineering
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Thesis delivered at: LAAS, INSA Toulouse

Title: A prescriptive approach to derive value-based requirements specification: application to the requirements engineering of commercial aircraft

Recently customer-based product development is becoming a popular paradigm. Customer needs and expectations are identified and transformed into requirements in systematic processes for product design with the help of various methods and tools. However, in many cases, these approaches fail to focus on the perceived value that is crucially important when customers make the decision of purchasing a product. The requirements specification derived from these approaches are typically value-implicit.

In this thesis, a prescriptive approach to derive value-based requirements specification is proposed by integrating the concept of value into the house of quality of quality function deployment. An integrated set of theories, methods and concepts is introduced in order to mitigate the seven methodological problems of house of quality regarding to establishing appropriate value-based requirements specification. The foundations of the approach include *concepts* of objective, value model and consequence model, *methods* of means-ends objectives network, fundamental objectives hierarchy, response surface methodology and value-driven design, and *theory* of multi-attribute utility theory. The procedure of the approach is a four-step process: (1) identify and structure objectives from initial customer statements of expectations, (2) specify attributes and construct customer value model, (3) transform fundamental objectives into engineering characteristics to construct system value model, and (4) derive component value models from system value model. Through this procedure, initial customer statements can be reasonably derived into customer value model, system value model and component value model. The benefits of the approach are that it enables (1) reasonably qualifying and quantifying customer value, and performing value modeling and simulation, (2) perceived customer value being subsequently used reactively for design evaluation, and proactively for value-driven design.

The approach is applied in the context of a European Community's R&D project CRESCENDO to help constructing airlines' group value model for commercial aircraft development. This application focuses on the first two-steps of the approach, and the value models are implemented in business software Vanguard Studio.

Key words: customer value, value model, requirements engineering, quality function deployment, multi-attribute utility theory and commercial aircraft.

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Thèse effectuée au : LAAS, INSA Toulouse

Titre de la thèse en française : Prise en compte de la valeur ajoutée client dans la spécification des exigences.

Ces dernières années, la conception de produit vise de plus en plus à remettre le client au centre du processus de développement. De nouvelles méthodes et outils ont permis de formaliser non seulement l'identification des besoins et des attentes du client mais également leur transformation en exigences. Cependant, malgré les progrès récemment apparus dans ce domaine, la notion de valeur perçue par le client qui est associée au produit reste faiblement considérée durant le développement du produit alors que la perception de cette valeur par le client va jouer un rôle clé au moment du choix du produit.

Dans cette thèse, nous proposons une approche normative visant l'intégration de la notion de valeur du produit dans le processus d'établissement des exigences. Un état de l'art présente les concepts et les pratiques impliqués dans le déploiement de la fonction de qualité, étroitement liée au processus de spécification des exigences basé sur la valeur. Ces concepts sont relatifs aux notions d'objectifs, de modèles de la valeur, de fonctions d'utilité multi attributs et de hiérarchie et de réseaux d'objectifs.

Notre approche se déroule en 4 étapes : (1) identifier et structurer les objectifs à partir de l'expression des attentes du client, (2) spécifier les attributs de la valeur perçue par le client et construire un modèle de la valeur client, (3) transformer les objectifs en exigences pour construire un modèle global de la valeur produit et (4) dériver ce modèle global en un modèle de la valeur pour chaque composant du produit. Cette approche permet ainsi de prendre en compte explicitement la valeur produit perçue par le client en l'intégrant dans les phases de développement, ce qui favorise une conception proactive dirigée par la valeur.

Nous l'illustrons sur un exemple d'avion de ligne développé en Vanguard Studio. Cet exemple a été élaboré par l'ensemble des partenaires au cours du projet Européen IST CRESCENDO et sert de cas-test pour ce projet.

Mots-clés : modèle de la valeur, ingénierie des exigences, fonction qualité, théorie de l'utilité multi-attributs

Résume

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1 Introduction

Afin d'atteindre des niveaux plus élevés de satisfaction des clients, il y a au moins deux aspects importants à prendre en considération. La première porte sur ce que les valeurs des clients et l'autre sont sur le point de conception produits à valeur ajoutée. Il y a une abondance de définitions de la valeur client avec leur consensus et de divergence (Zeithaml 1988, Keeney 1992, Keeney 2004, Woodruff 1997). La définition de (Woodruff 1997) est utilisée dans cette thèse, qui est, la valeur du client est la préférence perçue d'un client pour les attributs des produits, des spectacles d'attributs, les conséquences de l'utilisation, les objectifs et les buts énoncés dans la situation d'utilisation. Naturellement, la valeur du client doit être identifié et utilisé pour entraîner les activités de conception et développement de produits. Il est plus sur un processus subjectif et axée sur l'humain, et pourtant il y a seulement une poignée de processus et de méthodes analytiques disponibles pour permettre la modélisation et la simulation en termes de valeur (Agouridas et al. 2006, 2008, Bayus 2007, Griffin et Hauser 1993, Pahl et Beitz 2007, Ulrich et Eppinger 2007). Certains travaux préliminaires ont été faits pour distinguer ou de mesurer les niveaux de rendement différents de la satisfaction du client (valeur), comme le modèle de Kano et de déploiement de la fonction qualité (QFD) (Bayus 2007, Hauser et Clausing 1988, Bode et Fung 1998). Cependant, ils ont certaines lacunes quand il s'agit de permettre un examen systémique de la valeur client.

Cette thèse porte sur la clarification des valeurs des clients. Son intention est de fournir une approche normative pour soutenir basée sur la valeur d'ingénierie des exigences (RE). Notre approche est basée sur un ensemble de méthodes et de la théorie: moyens et des fins d'analyse, partie-tout l'analyse, et théorie de l'utilité multi-attributs. Ils sont intégrés ensemble pour résoudre les problèmes découlant de différentes valeurs la compréhension du client. Techniquement, cette approche permet d'identifier la valeur implicite, la structuration des déclarations de clients logiquement collectées, la modélisation et l'exécution de valeur et de simulation à partir de besoins des clients à des paramètres de conception et vice-versa. En outre, il aide à établir la dérivation à partir de l'approche proposée pour la mesure de satisfaction des clients traditionnels, en offrant différents types de formes fonctionnelles pour mesurer les niveaux de satisfaction des clients.

2 Approches pour RE dans le contexte du développement des produits

Il existe déjà des ensembles d'approches utilisées pour comprendre les attentes et besoins des clients, par exemple:

(1) Les processus et les méthodes décrites par (Pahl et Beitz 2007) et par (Ulrich et Eppinger 2007), respectivement, pour l'établissement des exigences du produit des documents,

(2) Les processus décrits dans les normes RE ingénierie système, telles que (EIA 632 1998), la norme ISO 15288 et IEEE 1220,

(3) Modèle de Kano pour faire de distinction entre les différents degrés de satisfaction de la clientèle sur les différents types de besoins des clients (Bayus 2007),

(4) Diagramme d'affinité et des algorithmes de cluster pour les états catégorisation des clients semblables ou pertinents en catégories (Pahl et Beitz 2007), et

(5) QFD pour transformer les besoins des clients en caractéristiques techniques (ECS) et pour le calcul de la satisfaction du client (Hauser et Clausing 1988).

Cependant, ces approches ne parviennent pas à clarifier suffisamment compte des préoccupations de valeur qui sont d'une importance cruciale au cours de la prise de décision des clients et la conception des processus décisionnels. Il y a quelques lacunes évidentes de ces approches, qui peuvent nuire à l'optimisation de la conception basée sur la valeur client:

P1. Différents niveaux de déclarations de clients ne sont pas structurés avec une saine logique.

P2. Les besoins des clients sont presque toujours donnés poids indépendants à partir d'informations gamme d'attributs qui est utilisé pour mesurer la réalisation des besoins des clients (Zhang et al. 2011).

P3. Il y a une inclination profonde dans la pratique de confondre les classements ordinaux avec des pondérations cardinaux.

P4. Forme linéaire additive est directement utilisé pour mesurer l'atteinte des niveaux de satisfaction de la clientèle.

3 Contexte de développement de l'approche

Ce développement de la stratégie d'assistance axée sur la valeur RE s'appuie sur une recherche en cours menée au sein du programme de la Commission européenne septième programme-cadre (7e PC) CRESCENDO projet de recherche dans le domaine de l'industrie aérospatiale européenne, en collaboration avec les universités, principalement européens, et les fabricants. Le cas de test d'établissement des exigences et la génération de valeur fournissent un lien bénéfique pour les fabricants principaux (c.-à-aéronefs, de moteurs, sous-systèmes et d'autres) dans l'industrie aérospatiale européenne et une contribution utile au cours du développement de l'approche. Une représentation schématique de la valeur axée sur la conception entre les différents niveaux de produits aérospatiaux est illustrée à la Figure 1 (Cheung et al. 2012). Modèle de la valeur du système est normalement utilisé dans le processus pour permettre l'évaluation de conception et d'optimisation en termes de valeur ainsi que d'autres attributs de performance physiques, tels que la gamme, la poussée, la consommation spécifique de carburant, etc et les attributs économiques, tels que le coût de fabrication, les coûts d'exploitation, coût d'entretien, etc L'accent dans cette thèse porte sur la façon de construire un modèle de la valeur client à partir des besoins des avions de ligne, les attentes et autres déclarations en parallèle avec le processus de RE traditionnelle et sur la façon de tirer le modèle de la valeur client dans le modèle de système de valeurs.

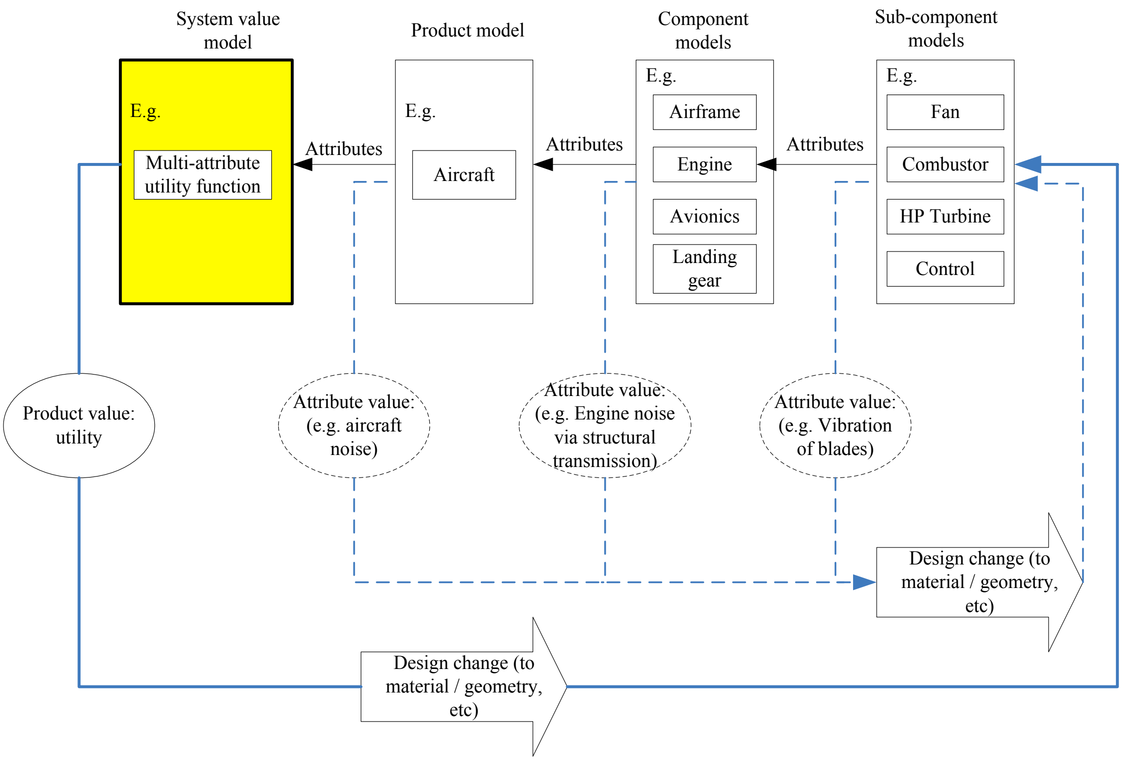


Figure 1: A schematic illustration of value-driven design in context of CRESCENDO.

Certaines attentes sur le modèle de la valeur de l'avionneur en ce qui concerne l'approche de développement et son application sont les suivantes:

E1. Établir la valeur axée sur la traçabilité à partir des attentes des clients aux exigences.

E2. Activer axée sur la valeur compromis la capacité au niveau des exigences et le niveau de solution de conception.

E3. Accorder plus d'attention sur les dimensions de valeur incorporelle plutôt que seulement sur un aspect particulier des coûts (plus-value, par exemple).

Il est alors utile d'introduire des techniques qui peuvent résoudre ou au moins atténuer les problèmes mentionnés ci-dessus dans la Section 2 et les attentes des avionneurs. Une approche normative est introduit ici comme une solution potentielle.

4 L'approche

Dans cette section, l'approche normative est proposée de développer des modèles de valeur. Une procédure en trois étapes de l'approche est présenté dans la Figure 2, qui relie le processus avec des fondations identifiées, la transformation des déclarations de clients initiaux dans le modèle d'un des clients la valeur du groupe et un modèle de la valeur du système. Le modèle des clients la valeur du groupe et le modèle le système de valeurs sont ensuite utilisées pour aider traditionnelle spécification des exigences pour la conception axée sur la valeur. La procédure en trois étapes de la démarche est la suivante: (1) Identifier et objectifs de la structure, (2) Préciser les attributs et de construire le modèle de valeur, et (3) Transformer les objectifs fondamentaux dans les CE.

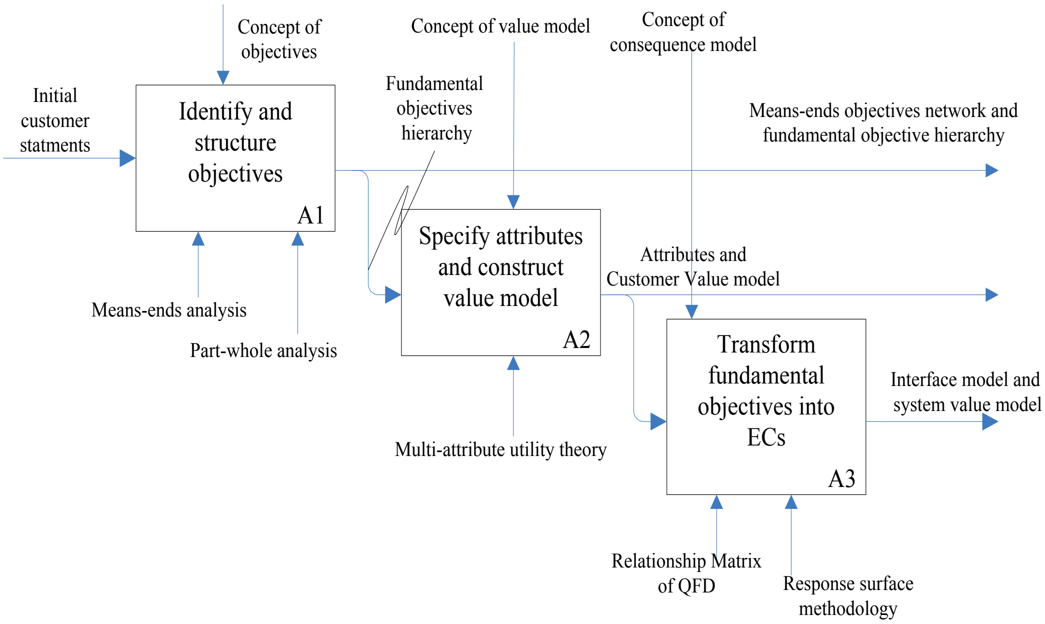


Figure 2: A three-step procedure of the approach.

4.1 Identifier les objectifs et la structure

Le processus d'identification et de structuration des objectifs est donné à la Figure 3. Il commence par des déclarations de clients initiaux et se termine par l'établissement d'une hiérarchie des objectifs fondamentaux.

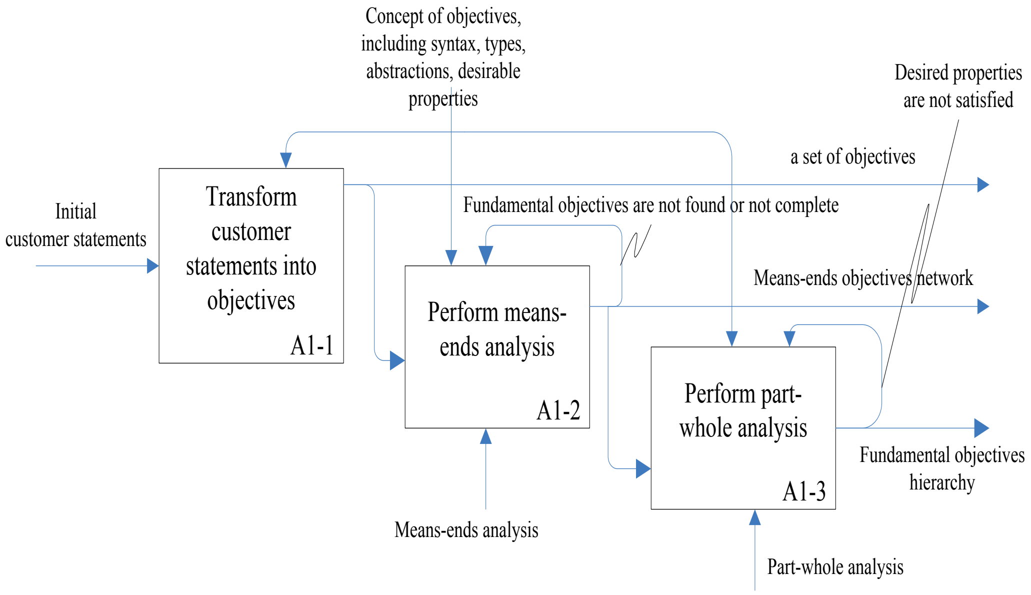


Figure 3: The process of identifying and structuring objectives.

Un fait évident dans le processus est que les clients essaient d'exprimer les états à différents niveaux et granularité avec une combinaison de signifier-ends et les relations partie-tout des relations. Habituellement, ces déclarations sont des expressions différentes qui entravent la compréhension profonde de la valeur client. Avant de structuration, les relevés des clients initiaux sont transformés en objectifs avec une expression commune. Moyens et des fins d'analyse est ensuite effectuée sur ces objectifs transformés en différents niveaux pour découvrir les objectifs fondamentaux. Lorsque tous les objectifs fondamentaux dans le contexte actuel se trouvent qui sont dans le même niveau, partie-tout analyse est effectuée pour identifier les partie-tout des relations d'objectifs fondamentaux. Après ces activités, une hiérarchie des objectifs fondamentaux est établie, qui prévoit une forme bien structurée d'entrée pour le processus de quantification. Cette étape permettra de résoudre le problème méthodologique de P1.

4.2 Spécifier des attributs et de construire le modèle de valeur

Les procédures de la deuxième étape sont données dans la Figure 4. Théorie de l'utilité multi-attribut est utilisé pour soutenir cette étape. Afin de permettre la transformation de la qualification à la quantification, certains attributs où paramètres sont nécessaires pour mesurer l'atteinte de chacun des objectifs fondamentaux dans les feuilles de la hiérarchie. Les attributs sont nécessaires pour attribuer des pondérations significatives aux objectifs fondamentaux et aidera à résoudre le problème méthodologique de P2. L'ensemble de X attributs identifiés est ensuite utilisé comme entrée pour construire le modèle de la valeur.

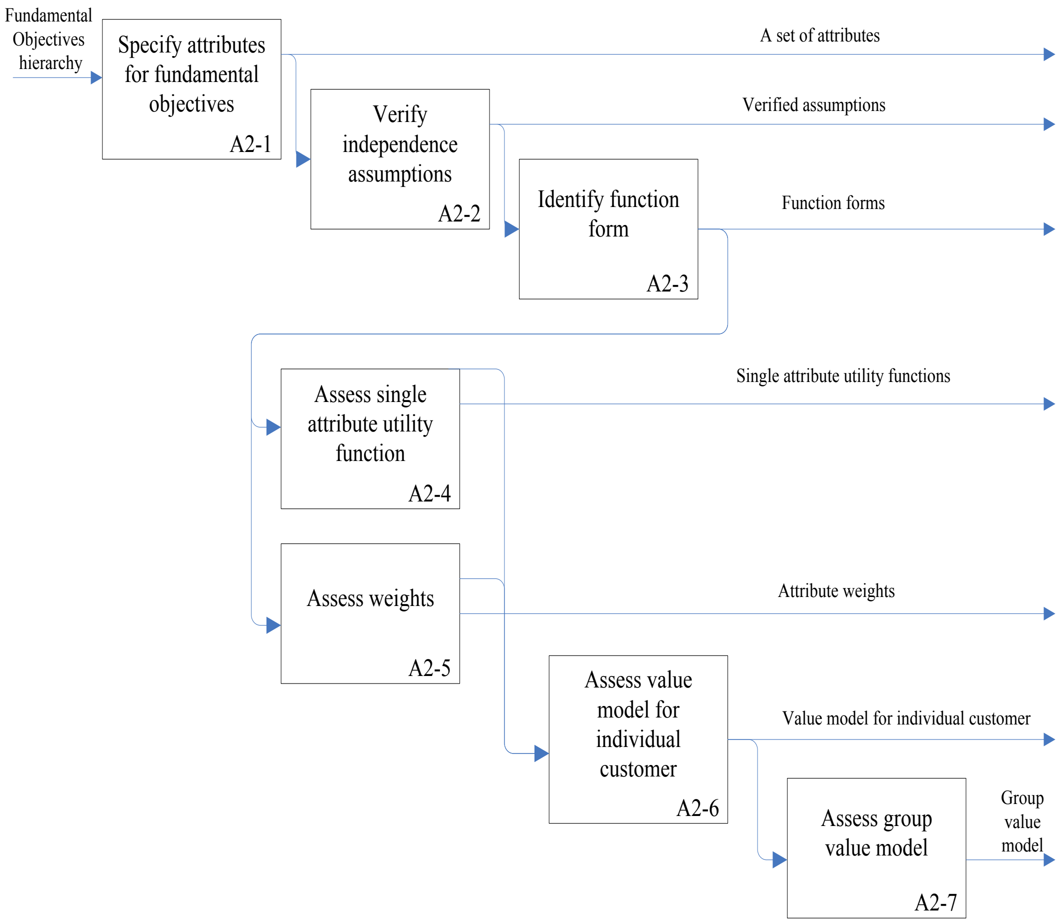


Figure 4: The process of specifying attributes and constructing value model.

Hypothèses d'indépendance tels que l'indépendance additive parmi ces attributs sont vérifiées afin d'identifier une forme de fonction pour composer les attributs ensemble. Si l'indépendance mutuelle entre préférence l'ensemble des attributs et l'indépendance d'utilité de Xi concernant les autres attributs sont finalement vérifié, la valeur du modèle multiplicatif est de forme. Si l'indépendance additive parmi les attributs est vérifiée, alors le modèle de la valeur est d'une forme particulière de la forme multiplicative, sous forme additive ie.

Empiriquement, Keeney montre qu'il est approprié pour déterminer une forme de fonction d'additifs lorsque l'ensemble des objectifs sont des objectifs fondamentaux et les objectifs de satisfaire l'ensemble des propriétés souhaitées des objectifs fondamentaux (Keeney 1992). Après avoir soigneusement effectuer moyens-fins et partie-tout d'analyse, nous avons confiance que la forme de fonction d'additifs.

$$u(x_1, \dots, x_M) = \sum_{i=1}^{M} k_i u_i\,(x_i) \quad (1)$$

est une approximation raisonnable des préférences des clients.

Simple fonctions d'utilité des attributs pour les attributs sont ensuite évaluées. Informations nécessaires pour évaluer une seule fonction d'utilité d'attribut inclut: l'information de distance (1) de l'attribut, (2) de la monotonie de la fonction d'utilité, attitude face au risque (3) du client vers la réalisation d'incertitude de l'attribut, et (4) certitude l'équivalence (ou de la loterie d'équivalence).

Constantes échelle (ou poids) k_i sont évalués en rendant la valeur des arbitrages. Valeur compromise définit combien doit être améliorée dans la réalisation d'un attribut pour compenser une moindre réalisation dans un autre attribut. Ils sont généralement effectués en utilisant des paires de deux possibles solutions alternatives hypothétiques avec les mêmes services aux clients, mais ne diffèrent que par les niveaux de réalisation des deux attributs. Deux conséquences indifférents sont modélisés par:

$$u\left(x_1, \dots, x_i, \dots, x_j, \dots, x_M\right) = u(x_1, \dots, x^*{}_i, \dots, x^*{}_j, \dots, x_M) \quad (2)$$

Pour les attributs M, un ensemble d'équations d'au moins M doit être construite pour déterminer l'M k_i sous la forme de fonction d'additifs. Parfois itérations peut être nécessaire lorsque les équations ne sont pas indépendants les uns des autres. Après avoir évalué les $k_i's$, le modèle de la valeur d'un client individuel est finalement construit par la forme fonction combinant identifiés, évalués simples fonctions utilitaires d'attributs et de poids.

Toutefois, les clients différents peuvent avoir des préférences différentes sur les attributs et leur importance. Dans la plupart des applications de la méthode QFD, une hypothèse est faite que les clients pourraient enfin parvenir à un compromis et parvenir à un consensus sur l'importance des besoins des clients. Toutefois, si le consensus ne peut être atteint, les préférences de groupe doivent toujours être modélisé. Les clients peuvent ensuite avoir des modèles de valeurs différentes, même si le même jeu de ses objectifs fondamentaux et les attributs est utilisé pour l'évaluation. Certains attributs peuvent être affectés un poids plus élevé par un certain client tandis que d'autres peut leur assigner un poids inférieur. Les clients peuvent même avoir des perceptions différentes sur la réalisation d'attribut unique.

On peut tirer utilitaires du groupe pour les décisions du groupe en agrégeant les utilités des différentes compagnies aériennes, prouvés par Harsanyi (1955), Sen (1970), et Keeney (2009). Autrement dit, il est possible de dériver un utilitaire groupe à partir d'un ensemble de N utilités individuelles abordé. Ainsi, l'évaluation de la fonction d'utilité du groupe peut résoudre le problème méthodologique de P3. Un modèle de la valeur du groupe pour N clients avec des attributs M est la suivante:

$$u_G = \sum_{s=1}^{N} w_s u^{(s)}(x),\ i = 1, \ldots, M \qquad (3)$$

4.3 Transformer les objectifs fondamentaux dans EC

Objectifs fondamentaux devrait être transformé en EC qui ont les moyens d'influencer l'atteinte des objectifs fondamentaux. Les procédures de la troisième étape sont présentées dans la Figure 5.

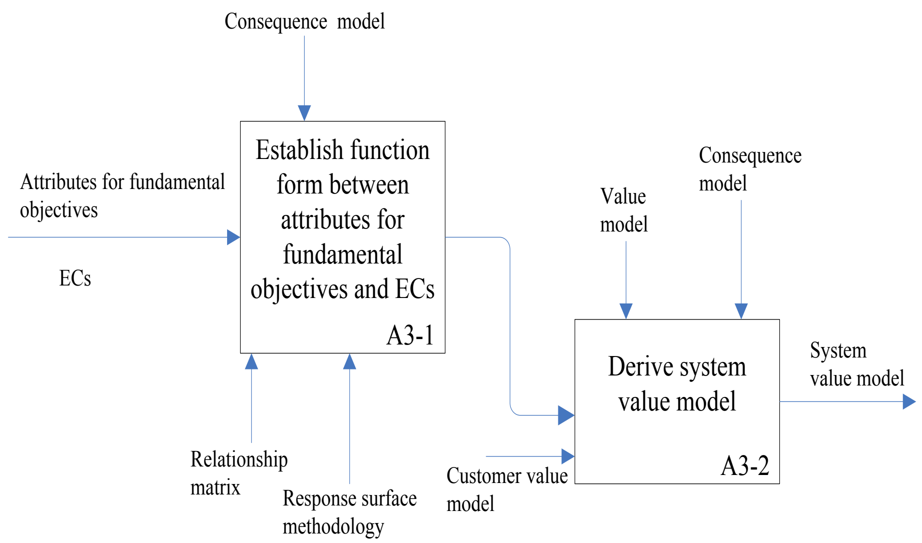


Figure 5: The process of transforming fundamental objectives into ECs

Les relations entre les attributs pour objectifs fondamentaux et ECs sont d'abord exprimées en deux niveaux d'un réseau de moyens et des fins des objectifs. Ce réseau est modélisé dans la maison de qualité avec une matrice à deux dimensions. La matrice est habituellement relation remplie avec, par exemple, 1-3-9 échelles. Ces échelles constituent un moyen pratique pour mesurer les relations d'influence, mais ils ne sont pas précis. Il y a d'autres approximations, comme les équations de surface de réponse. Ils sont la simplification de cette forme de la fonction:

$$x_i = f_i(y_1, \ldots, y_Q),\ i = 1, \ldots, M \qquad (4)$$

Il est alors possible de calculer l'utilité d'une conception de rechange avec un vecteur de Y en combinant le modèle de la valeur client avec la forme de la fonction (4):

$$u_Y(y_1, \ldots, y_Q) = u(x_1, \ldots, x_M) = \sum_{i=1}^{M} k_i u_i\,(f_i(y_1, \ldots, y_Q)) \qquad (5)$$

Équation (5) est un modèle de système valeurs modèles l'utilitaire de EC du système. Le fait sous-jacent dans cette équation est ce qu'il s'agit d'un processus de modélisation en deux étapes, tel que présenté dans la figure 7. Dans la première étape, le modèle conséquence d'ECS à des attributs pour objectifs fondamentaux est modélisé en considérant fin et les moyens des relations. Il est ensuite combiné avec le modèle de la valeur client d'obtenir un modèle le système de valeurs qui reflète l'influence des contraceptifs d'urgence sur la valeur du système. Il est différent du processus en une étape qui modélise directement les relations à ECS à la valeur sans l'identification des objectifs implicites fondamentales (Scanlan et al. 2011).

5 La demande

Dans cette section, l'approche proposée est appliquée afin d'aider l'ingénierie des exigences du développement des avions commerciaux. En raison de certaines limitations, le cas d'application se concentre sur les deux premiers étapes de l'approche, et le modèle des compagnies aériennes groupe de valeurs est construit dans ce processus.

Etape 1 : Identifier les objectifs et la structure

Les déclarations des compagnies aériennes initiales »dans le tableau 3 sont utilisés comme point de départ pour dériver modèle de la valeur. Bien qu'ils soient incomplets, elles sont suffisantes pour l'illustration de l'approche.

Les types et des exemples de déclarations initiales des compagnies aériennes sont en partie donnés dans les deux premières colonnes du Tableau 1. Il est facile de transformer les déclarations initiales dans les objectifs comme indiqués dans la troisième colonne du Tableau 1.

Table 1: Part of initial customer statements, their transformed objectives.

Types of statements	Examples	Transformed objectives	Types of objectives
Customer need	Minimize operating cost	Minimize operating cost	Fundamental
Customer need	Reduce environmental impact	Minimize environmental impact	Fundamental
Others	Minimize fuel consumption	Minimize fuel consumption	Means
Others	Standardization and commonality is desired	Provide standardization and commonality	Means
Goal	Range is expected to achieve 9000 nm	Maximize range	Means
Constraint	Approach speed must lower than 150 kts	Optimize approach speed	Means
Proposed	The natural laminar flow has	Utilize natural laminar	Means

technology	important potential to reduce drag	flow when design the wing	
Others	Fleet rationalization	Rationalize fleet	Strategic

Ces objectifs peuvent être transformées objectifs fondamentaux, les moyens ou stratégique. Après un complet moyen et des fins d'analyse sur les objectifs figurant dans le Tableau 1, un réseau des moyens et des fins des objectifs est établi et un ensemble d'objectifs fondamentaux est identifié. Ces objectifs fondamentaux non couverts par rapport aux objectifs transformés sont présentés dans le Tableau 2.

Table 2: Transformed objective and their fundamental objectives.

Transformed objectives	Types of objectives	Uncovered fundamental objectives
Minimize operating cost	Fundamental	
Minimize environmental impact	Fundamental	
Minimize fuel consumption	Means	Minimize operating cost, minimize environment impact
Provide standardization and commonality	Means	Minimize operating cost, *maximize usability*, *maximize maintainability*
Maximize range	Means	Part of "Maximize performance" (means), which influences operating cost, usability
Optimize approach speed	Means	
Utilize natural laminar flow when design the wing	Means	Minimize operating cost, minimize environment impact, maximize usability, *maximize safety, maximize reliability*
Rationalize fleet	Strategic	Minimize operating cost, minimize environment impact, maximize usability, maximize maintainability

Il est alors nécessaire pour effectuer une partie-totalité des analyses sur les objectifs fondamentaux de la Figure 6, ce qui contribue à clarifier la compréhension des objectifs fondamentaux de niveaux élevés et granularité.

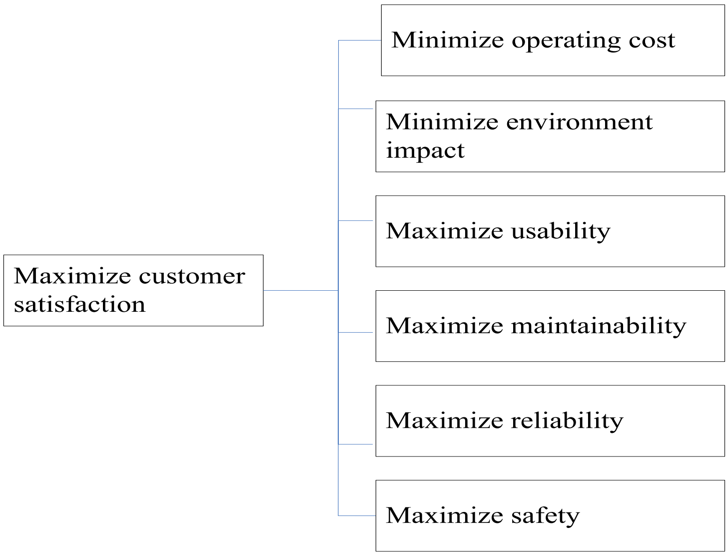


Figure 6: The fundamental objectives established from transformed objectives.

Une hiérarchie fondamentale des objectifs pour les objectifs de "minimiser l'impact environnemental» est donnée dans la Figure 7, qui est une hiérarchie de sous-Figure 6. Les mêmes procédures sont effectuées dans d'autres objectifs fondamentaux, tels que «Réduire les coûts d'exploitation". Enfin, une hiérarchie complète de tous les objectifs fondamentaux est établie.

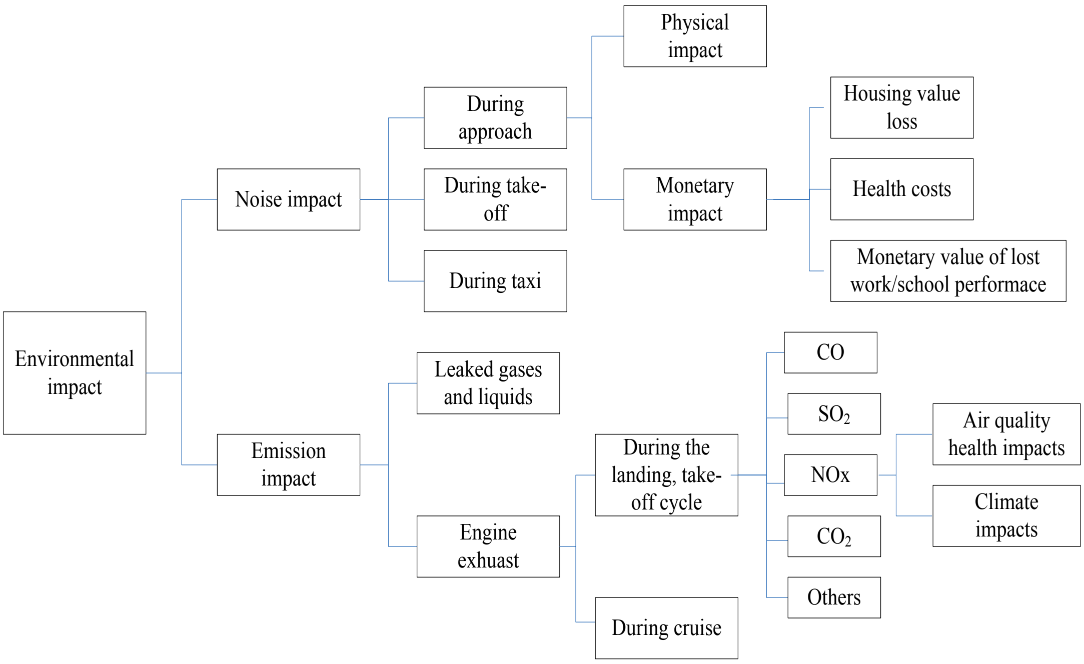


Figure 7: A hierarchy of fundamental objective of "minimizing environmental impact".

Grâce à des moyens et des extrémités et partie-tout d'analyse, le travail acharné et la pensée créatrice de ces objectifs, la confiance est établi que l'ensemble des objectifs fondamentaux satisfait les propriétés désirées des objectifs fondamentaux prévus par Keeney (1992). Ainsi, la procédure facilite la quantification des mesures de plus en valeur.

Étape 2: Spécifier les attributs et construire modèle de la valeur

Les attributs sont définis pour mesurer les objectifs fondamentaux dans la hiérarchie des objectifs fondamentaux des compagnies aériennes. Coût mile siège mesuré en 2011 dollars est un attribut naturel en ce qui concerne le coût opérationnel. Un attribut construit avec quatre niveaux est utilisé pour la mesure de la sécurité dans les Exigences de navigabilité communes: mineure, majeure, dangereux et onéreux. Chaque niveau est donné des précisions claires en valeur afin que les clients ou les concepteurs peuvent facilement trouver le niveau de sécurité d'un avion spécial. "Moyenne entretien d'heures de travail par heure de vol" est sélectionné comme un attribut de "Maximiser la maintenabilité". "Taux de fiabilité de répartition mesurée en %" est un attribut de "Maximiser la fiabilité". Pour la facilité d'utilisation de l'avion, un attribut est identifié pour chaque fonction dans les niveaux appropriés et pour la capacité d'avion pour commettre certain itinéraire, et ces attributs sont exprimés comme des éléments d'un vecteur.

Après avoir spécifié les attributs, il est temps de vérifier les hypothèses possibles de l'indépendance de préférence parmi les attributs, qui aident à trouver des formes de la fonction du modèle de valeur, par exemple multiplicatif ou formes de fonction d'additifs. Après avoir soigneusement effectuer moyens-fins et partie-tout d'analyse, nous avons confiance que la forme de fonction d'additifs est une approximation raisonnable des préférences des compagnies aériennes.

Simple fonctions d'utilité des attributs pour les attributs sont ensuite évaluées. Par exemple, une seule fonction d'utilité hypothétique attribut sur le siège-mile coût est modélisé et illustré à la Figure 8, qui est une fonction décroissante du risque d'utilité aversion à la forme concave. La fonction d'utilité sur un seul attribut d'heures de travail par heure de vol est évaluée de neutralité face au risque, qui a une forme linéaire.

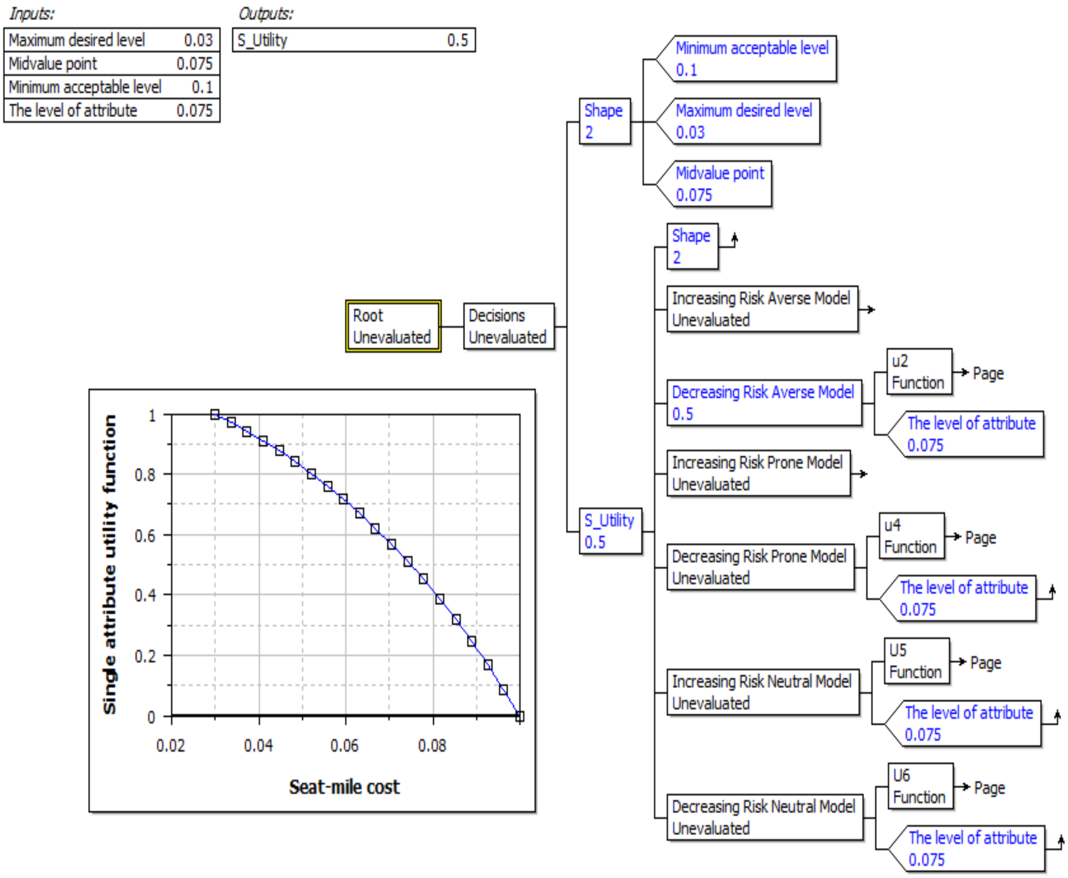


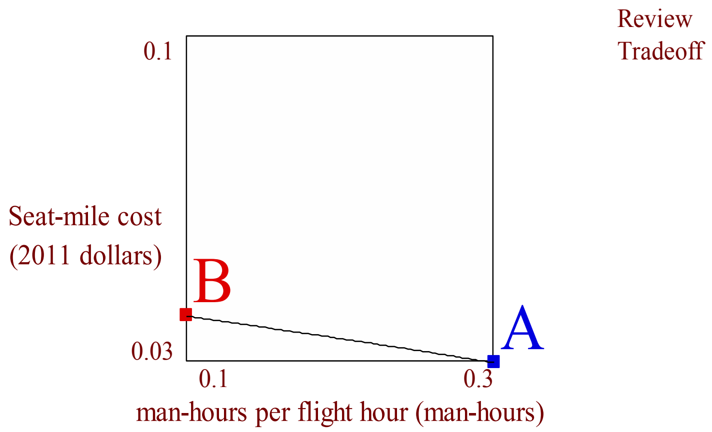
Figure 8: Single attribute utility function: seat-mile cost.

Ces évaluations de simples fonctions utilitaires d'attributs sont mises en œuvre dans l'outil de modélisation Vanguard Studio, qui est l'un des logiciels de gestion pour l'analyse des décisions et dispose d'un large éventail d'applications dans les industries et par nos partenaires. Un modèle Vanguard Studio a été développé pour l'évaluation, qui comprend six possibles des sous-modèles et peut être trouvée dans (Zhang et al. 2012).

Constantes d'échelle (ou l'importance relative) k_i's sont ensuite évaluées. Par exemple, avec deux alternatives hypothétiques des mêmes services pour les compagnies aériennes qui ne diffèrent que dans la réalisation de deux attributs: le siège-mile de coûts (X_i) et d'heures de travail d'entretien par heure de vol (X_j). Si une compagnie aérienne tiens à rendre 0,01 dollar de plus dans le siège-mile coût en vue d'échanger une réduction de 0,2 heures de travail d'entretien par heure de vol, puis

$$u(x_1, \ldots, 0.03, \ldots, 0.3, \ldots, x_M) = u(x_1, \ldots, 0.04, \ldots, 0.1, \ldots, x_M) \qquad (6)$$

est satisfaite, qui est affiché visuellement dans la Figure 9. Rapport de poids entre kj et k_i est indiqué au bas de la figure, ce qui montre une équation avec k_i’s comme inconnue.



	A	B	A-B
man-hours per flight hour (man-hours):	0.3	0.1	0.2
Seat-mile cost (2011 dollars):	0.03	0.04	-0.01

man-hours per flight hour Measure Weight:Seat-mile cost Measure Weight = 0.0801682:1

Figure 9: Value trade-off to determine relative weights.

M équations sont construites de manière à déterminer le M k_i’s dans ce formulaire de fonction d'additifs. Ces équations sont linéaires et peut être facilement résolu à Vanguard Studio. Les racines de ces équations sont celles de k_i’s. Après avoir évalué sous forme de fonction pour les attributs multiples, simples fonctions utilitaires d'attributs et k_i’s, un modèle multi-attributs de valeur pour la compagnie individuel est établi.

Cependant, les différentes compagnies aériennes ont des préférences différentes sur les attributs et leur importance. Ils ont alors des modèles de valeurs différents, bien que le même ensemble d'objectifs fondamentaux et les attributs sont utilisés pour l'évaluation. Certains attributs peuvent être affectés un poids plus élevé par une certaine compagnie aérienne tandis que d'autres peut leur assigner un poids inférieur. Les compagnies aériennes peuvent même avoir des perceptions différentes sur la réalisation d'attribut unique. Si un consensus ne peut être atteint, les préférences de groupe doivent toujours être dérivée.

Afin de simplifier l'illustration, nous devrions envisager le cas de deux compagnies aériennes. Une compagnie aérienne est un transporteur à faible coût et l'autre est un transporteur phare. Ils ont le même ensemble d'objectifs fondamentaux qui sont réduite à trois, dans notre contexte. Cet exemple est montré dans le Tableau 3. Cependant, ils ont des préférences différentes sur les poids relatifs et la réalisation des objectifs.

Table 3: A group utility problem.

	Customer	Fundamental objectives	Attributes
Group	Flagship airline 1	Minimize operating cost	X_1: Seat-mile cost measured in 2011 dollars
		Maximize maintainability	X_2: Man-hours maintenance per flight hour
		Maximize reliability	X_3: Dispatch reliability rate measured in %
	Low-cost airline 2	Minimize operating cost	X_1: Seat-mile cost measured in 2011 dollars
		Maximize maintainability	X_2: Man-hours maintenance per flight hour
		Maximize reliability	X_3: Dispatch reliability rate measured in %

Une formulation du problème utilitaire groupe dans le Tableau 3 est donnée dans le Tableau 4. Dans ce cas, le décideur Supra (Keeney 1993) est le constructeur de l'avion qui vérifie les hypothèses et évalue la mise à l'échelle $w's$ constantes de comparaison d'adresse que interpersonnelles d'utilité.

Table 4: A formulation of group utility problem.

Group	Customer	Importance of customer	Attribute	Weight of attribute	Single attribute utility function
$\boldsymbol{u_G} = \sum_{s=1}^{2} \boldsymbol{w_s u^{(s)}(x)}$	Flagship airline 1	0.35	X_1	0.7531	$u_{11}(x_1) = 1.05184 + 0.01427(-e^{43.00272x_1})$
			X_2	0.02098	$u_{12}(x_2) = 1.5 - 5x_2$
			X_3	0.22593	$u_{13}(x_3) = 1.30902 + 2.2534e^{13}(-e^{-32.08079x_3})$
	Low-cost airline 2	0.65	X_1	0.78115	$u_{21}(x_1) = 1.42477 + 0.25287(-e^{17.28891x_1})$
			X_2	0.06262	$u_{22}(x_2) = 1.5 - 5x_2$
			X_3	0.15623	$u_{23}(x_3) = 1.06002 + 2.2422e^{36}(-e^{-63.80672x_3})$

Avec un modèle de la valeur du groupe quantifiés et plusieurs modèles de valeurs individuelles, il est alors possible d'effectuer différents types d'analyse visuelle, analyse de sensibilité et d'optimisation. La Figure 10 représente le modèle mis en œuvre de la fonction d'utilité du groupe et une analyse de sensibilité basé sur la couleur, ce qui montre le degré de pertinence entre les attributs des clients et utilitaires du groupe. Les différences entre les compagnies aériennes peuvent être identifiés: un poids relatif différent de compagnies aériennes, la perception différente de la réalisation d'attribut et des poids relatifs différents des attributs. Services publics individuels sont évalués et regroupés de façon significative dans l'utilité du groupe sans faire un compromis entre les compagnies aériennes.

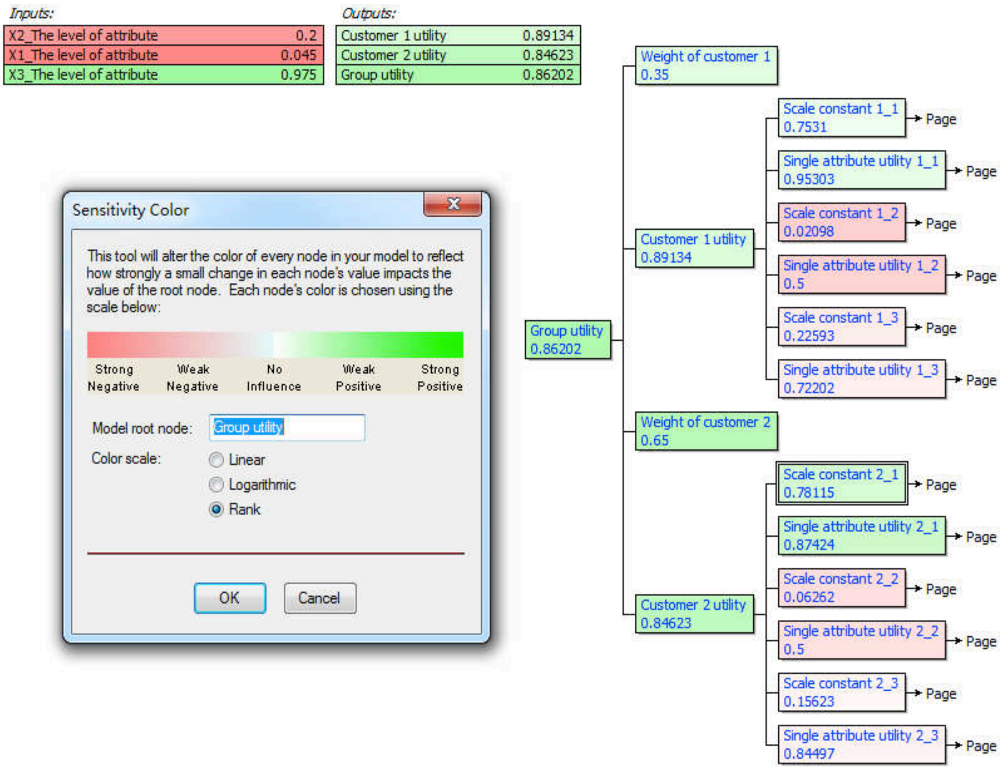


Figure 10. Group utility and color-based sensitivity analysis

D'autres fonctionnalités de modélisation et de simulation de valeur sont également mis en œuvre. Pièces d'entre eux sont présentés dans la Figure 11.

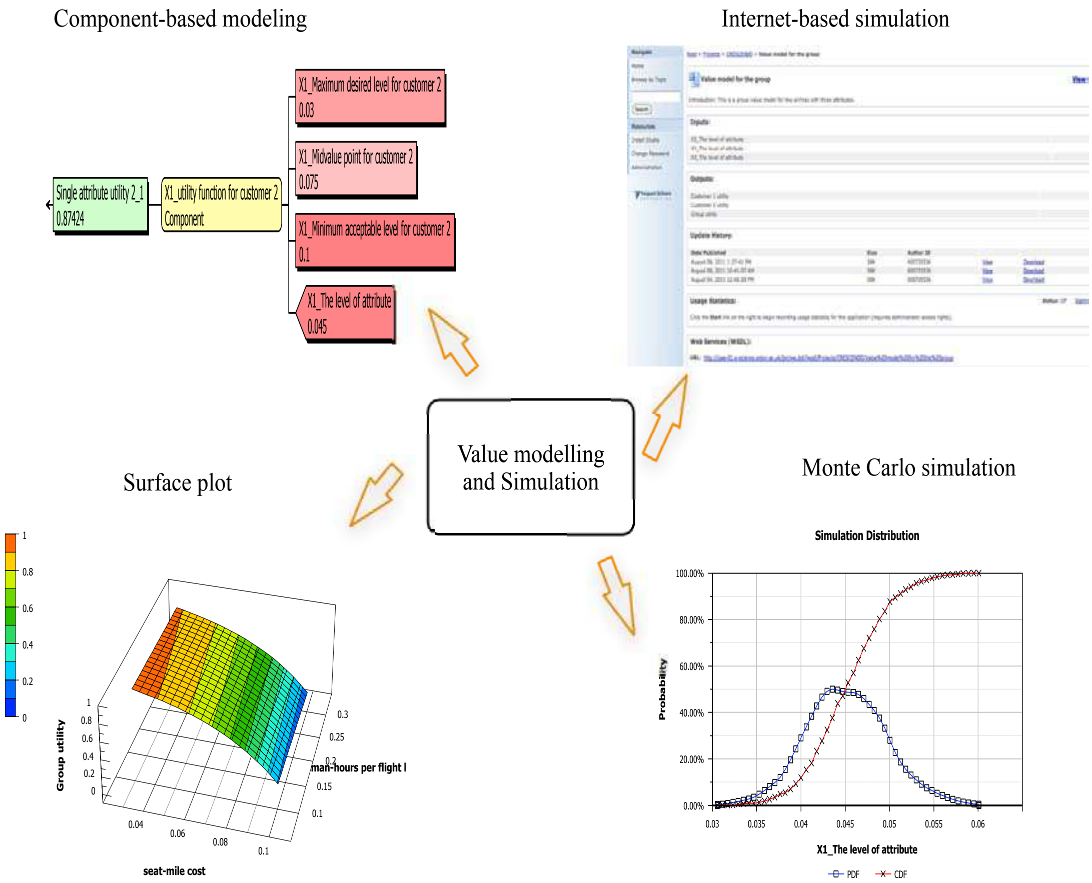


Figure 11. Value modelling and simulation

Grâce à cette application de l'approche de RE d'avions commerciaux, le modèle des compagnies aériennes groupe de valeurs est construit. Il y a plusieurs avantages par rapport l'approche traditionnelle de RE:

(1) L'approche permet de résoudre les problèmes méthodologiques des approches traditionnelles, y compris les P1, P2, P3 et P4. Il fournit également une solution pour identifiées attentes industrielles, y compris E1, E2 et E3.

(2) les perceptions de valeur des compagnies aériennes peuvent être explicitement qualifiés, quantifiés, modélisé et simulé, ce qui a été présentée par l'étude de cas dans cette section. Cette information a été utilisée pour permettre basée sur la valeur RE d'avions commerciaux. Par conséquent, fondée sur la valeur RE peut être intégrées dans les modèles existants d'ingénieries quantitatives.

(3) modèles de valeur des compagnies aériennes peuvent être utilisées pour évaluer les alternatives d'avions disponibles ou potentielles, lorsque l'information nécessaire des solutions de rechange concept de l'aéronef est recueillie. Une valeur scalaire est calculée pour l'ensemble des attributs d'information d'une

alternative aéronef particulier. C'est une caractéristique très attrayante qui améliore le processus de prise de décision.

(4) dimensions de valeurs et des modèles de valeur peuvent être explicitement partagé aux différents niveaux de développement au sein de l'entreprise étendue, qui offre un potentiel significatif pour permettre le développement d'aéronefs qui sont perçus par les compagnies aériennes clientes d'être de grande valeur. Cette information basée sur la valeur peut être utilisée pour l'orientation conceptuelle à tous les niveaux de développement différents, lorsque les exigences techniques validées à ces niveaux ne sont pas encore disponibles. Par conséquent, l'approche réduite les risques de développement de l'entreprise étendue, et réduit le temps de commercialiser de nouveaux avions.

6 Conclusions

Comprendre les besoins des clients et la spécification des exigences découlant en termes de valeur est de nature subjective et nécessite un processus logique et les méthodes de qualification et la quantification. Certains problèmes méthodologiques demeurent sans réponse, telles que les problèmes discutés dans la section 2. Visant à atténuer ces problèmes méthodologiques et de rationaliser le processus d'établissement des exigences, cette thèse présente une approche normative pour soutenir basée sur la valeur d'ingénierie des exigences. Les justifications sous-jacentes et les fondations sont énumérées en détail. Elles comprennent l'utilisation d'objectifs, moyens et des fins d'analyse, partie-tout l'analyse et la théorie de l'utilité multi-attributs. Rien n'est particulièrement nouvelle pour les communautés de conception d'ingénierie, mais nous prétendons l'approche ne fournissent un moyen normatif et logique à comprendre les besoins des clients en termes de valeur. La principale contribution de cette recherche est de dégager des modèles de valeur à partir des déclarations de clients initiaux, ce qui permet une progression de la valeur axée sur la conception du modèle de valeur économique basé sur le modèle de la valeur multidimensionnelle, et certains problèmes méthodologiques sont résolus.

Toutefois, il n'est pas un processus trivial pour transformer subjectives, les déclarations ambiguës des clients dans les valeurs des clients mesurables. Entrées plus subjectives des clients sont nécessaires. Il exige beaucoup de travail et de réflexion créative sur la valeur. Cette approche exige aussi plus de connaissances et de compétences d'ingénieurs exigences pour permettre à sa fonction réelle dans la pratique.