A VALUE-CENTRIC QFD FOR ESTABLISHING REQUIREMENTS SPECIFICATION

Xinwei Zhang[1,2], Guillaume Auriol[1,2], Anne Monceaux[3], Claude Baron[1,2]
(1) CNRS ; LAAS France (2) Université de Toulouse France (3) Intelligent and semantic systems, EADS Innovation Works

ABSTRACT
Quality function deployment (QFD) is commonly recognized as a tool or methodology for developing customer-focused products. There is, however, no explicit clarification about customer values in QFD. In this paper a value-centric QFD with qualitative and quantitative thinking of value is proposed for understanding customer needs and establishing requirements specification. The techniques of fundamental objectives hierarchy and means-ends objectives networks are utilized to structure reasonably initially identified customer statements, which are possibly of different levels and granularities, and to uncover the implicit customer needs. Then quantitative analysis on value, e.g. value model and weight importance, is made possible by incorporating multi-attribute preference theory. It is believed that some underlying methodological problems in QFD can be interpreted and resolved in the value-centric framework. The business benefit of the value-centric QFD is that customer needs can be understood in terms of value and the design of alternatives is driven by their contribution to customer values.

Keywords: Quality function deployment, value, value model, requirements engineering, preference theory

1 INTRODUCTION
Establishment of appropriate requirements specification is critical for customer-focused product development. It is, however, not a trivial task, and cannot be achieved in a simple and unconscious way, especially for complex products. Initially identified customer statements may be in different levels and granularities, depending on customers' different experience with and familiarity to the product to-be developed. The diversity of customer statements adds cognitive burden to connect and trace one statement to another. It is not appropriate to document all customer statements together without explicitly distinguishing the levels and granularities of statements, although experienced engineers may be able to establish their relationships in some reasonable way (In this paper only customer statements are discussed, but the techniques proposed are straightforwardly applicable to statements or needs from other stakeholders). It is a fact that some methods [1, 2], e.g. affinity diagrams or certain cluster algorithms, categorize identified customer statements into groups according to their similarity and relevance without clear clarification of the relationships among them and uncovering implicit customer needs. A beneficial opportunity exists to reasonably structure customer statements and to uncover hidden customer needs behind initial customer statements.
After having appropriate structures, it is important to quantify reasonable customer needs and engineering characteristics (ECs) [3] to enable certain intuitively attractive calculations. However, the available quantification in traditional methods may only be valid for limited contexts. For example, the additive linear function form for computing customer satisfaction is valid only when customer needs are of additive independence among each other and when single attribute utility functions are of linear form (An attribute, also called measurement of effectiveness, is used for measuring the achievement of customer statements, so there are attributes for customer needs, ECs and design parameters, respectively, but almost all the discussion about attributes in this paper is about those attributes for measuring the attainment of customer needs). Furthermore, the subjective assessment procedure for assigning weights to customer needs is always performed independently of attributes information, which may produce weights conforming inconsistently to real customer preferences. It will be more rational and rigorous to check independence conditions among attributes and to incorporate nonlinear

function forms over single attribute when performing meaningful calculations. We can then assess weights on the basis of function form and available attributes information.

In this paper a value-centric QFD with qualitative and quantitative thinking of value is proposed, which is intended to help establishing a value-based requirements specification. Fundamental objectives hierarchy and means-ends objectives networks that conform to the typical abstractions for solving complex problems are used to structure customer statements. Value of single attributes and value model among attributes are quantified using multiple attributes preference theory. (Preference includes preference under certainty (value in a narrow sense) and preference under uncertainty (utility). In this paper, we think of value in a broad sense and value is equal to preference). The integration of these theories and methods into QFD brings three mainly potential benefits: (1) the customer statements are structured rationally in the network or hierarchy according to their levels and granularities, (2) Value becomes an explicit construct in requirements specification and QFD, and (3) Some of methodological problems in QFD are resolved, e.g. additive linear form for measuring customer satisfaction is extended into the more general value model.

The rest of the paper is organized as follows. Section 2 outlines the foundational ideas of QFD and the underlying problems hindering from establishing rational requirements specification. Section 3 and Section 4 introduce the value-centric QFD, with Section 3 covering Customer Attributes (CAs) part of the house of quality, and Section 4 dealing with the transformation from CAs to ECs. Section 5 gives a further discussion about the implications of value-focused thinking to QFD. Finally, a conclusion is given in Section 6.

2 THE FOUNDATION OF QFD AND UNDERLYING PROBLEMS

QFD is a systematic methodology to implement customer needs in product design and development by deploying four-stages of quality planning. Customer needs act as the driver of engineering design and manufacture 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 house of quality taken from [3] is shown in Figure 1 in order to display its basic elements.

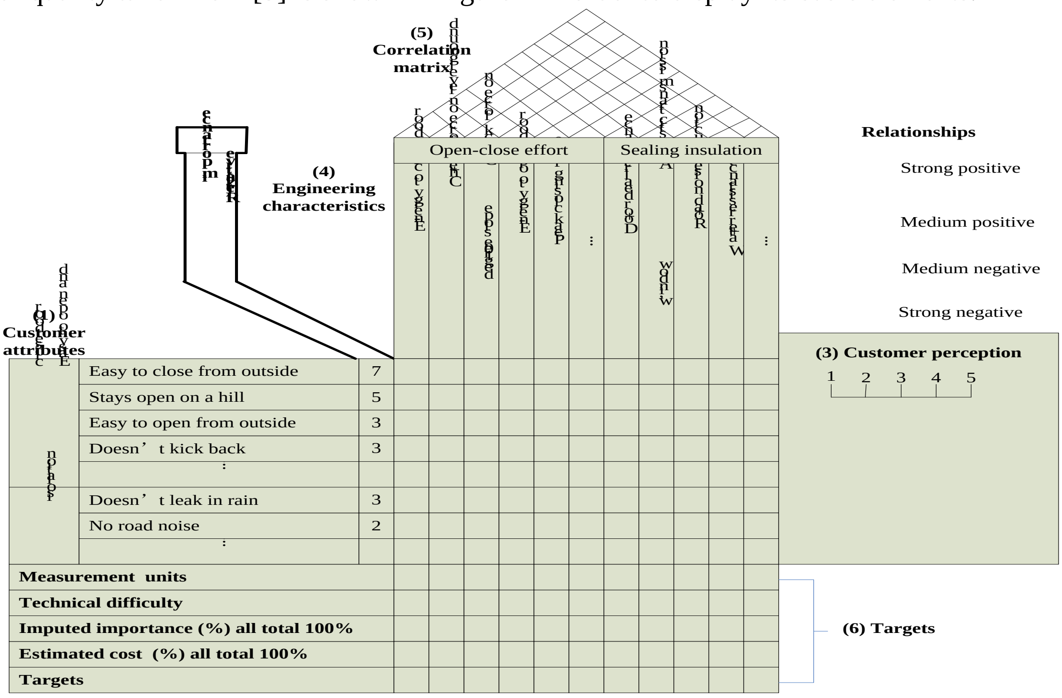

Figure 1 House of quality [3]

A process underlying QFD for thinking about customer needs (called CAs in QFD) includes the following steps:

1. Identify and structure customer needs,
2. Assign relative weights to customer needs,
3. Incorporate customer perceptions with perception map,
4. Transform customer needs into 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 understanding customer needs to some extent, even if they are made qualitatively. The house is also useful for organizing the available information. 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 basis of strong assumptions.

Typical variables and calculations in house of quality are introduced in Table 1. They are introduced to facilitate illustrating the methodological problems in terms of quantification. De Poel gives extensive discussion about those methodological problems in [4].

Table 1 Typical variables and calculation in house of quality from [4]

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

We explore some possible problems in QFD, which may hinder the optimization based on customer values:

1. Different levels of customer statements are not structured with sound logic, making it nearly impossible to trace their relationships quickly and difficult to identify implicit customer needs,
2. Each customer need is almost always given a weight independent from attribute information that is utilized for measuring the attainment of the need,
3. The additive linear form is used to measure customer satisfaction. Although additive form may be a robust approximation for many practical applications [5], the function form between perceived value and different levels of attainment of a particular customer need may not be linear, and
4. The influence of one EC on customer needs may be positive for some needs and be negative for other needs as shown in Figure 1, but the weight of EC is usually not given on the basis of total influence of the EC on all relevant customer needs.

In the next section, the value-centric QFD is proposed with value-focused thinking, which contributes to a feasible solution towards aforementioned problems.

3 THE VALUE-CENTRIC QFD ON BASIS OF VALUE-FOCUSED THINKING

What customers need is always different from the ways in which customer needs can be influenced. The former concerns the customers while the latter is about ECs and design parameters under the control of the engineers. Although separating *what* from *how* may not be necessary for effective problem solving, it is critically useful for deepening the understanding of each element, and it further encourages creative thinking about customer values and design alternatives.

The value-centric QFD is made up of *what* and *how* in a high-level abstraction. Discussion about *what* means to understand customer needs in terms of values. *What* in this sense includes the following information:

1. Fundamental objectives or customer needs,
2. An attribute to measure the degree to which the corresponding customer need is met,
3. Value model for integrating all attributes for conjoint measurement,
4. Single-attribute utility function and customer risk attitudes towards uncertainty, and
5. Scaling constants or weights implied by value trade-offs.

Discussion about *how* means to think about the means that can better achieve customer needs to certain degree. It should at least include the following:
1. Select ECs and establish their relationships with customer needs,
2. Identify design parameters for ECs,
3. Make design trade-offs between ECs based on design parameters, and
4. Set targets to maximize customer values.

3.1 Understanding What Customers Need in terms of Value

Before specifying attributes and assessing the value model, it is necessary to obtain a set of real customer needs that are fundamentally important to customers. But the fact is that customers tend to express statements of different types with different levels and granularities. The statements may be real customer needs, ECs, design parameters, attributes, constraints or goals as shown in table 2. It is desirable to structure these statements by making careful distinction of statement levels and granularities.

Table 2 different types of customer statements in context of cordless drill

Types	Examples	Transformed objectives	Attributes
Real needs	Maximize usefulness	Maximize usefulness (fundamental)	Objectives should be further specified to obtain attributes
EC	*Maximum* torque	*Maximize* torque (means)	Torque measured in inch-pound
Design parameter	Lithium-Ion battery	Provide Lithium-Ion battery (means)	Yes or No
Attribute	Cost of buying	Minimize cost (fundamental)	Cost measured in dollars
Constraint	Battery life must be longer than 3 hours	Maximize battery life (means)	Time measured in hours
Goal	Battery life is expected to achieve 5 hours	Maximize battery life (means)	Time measured in hours

In traditional QFD, a hierarchy is used to structure customer statements as shown in Figure 1. It is, however, not show how implicit customer needs are identified and what precise relationships exist between these statements. The techniques of means-ends objectives network and fundamental objectives hierarchy aim to mitigate these concerns.

3.1.1 Structuring Customer Statements

Two abstractions are typically used for structuring complex problems in human problem solving. One is causal relationship, and the other is part-whole relationship. Similarly, two customer statements may have a causal relationship and may be recognized as means (cause) and ends (effect), respectively. For example, “maximize torque” is a means influencing the ends “maximize usefulness”. Means is at a level lower than ends and it will influence the achievement of ends. It is useful to perform means-ends analysis through which a reasonably complete set of customer needs will be identified. A suitable technique for organizing these means-ends relationships among customer statements is means-ends objectives network. On the other hand, two customer statements may have part-whole relationship and be recognized as the part and the whole, respectively. For example, the whole “mass of cordless drill” includes at least three parts such as “motor mass”, “battery mass”, and “transmission mass”. Performing part-whole analysis promotes the understanding of customer needs in width and depth. A suitable technique for organizing these part-whole relationships between customer needs is fundamental objectives hierarchy. With these two abstractions it is rational to trace relationships among customer statements. More importantly, it provides a foundation for further modeling and measurement, and it is proved that it is easy to verify the preference conditions after utilizing these two abstractions [6].

Customer statements are obviously important to customers, although they can be expressed in many different forms. Objectives are statements of something that one desires to achieve [6, 7], so it is straightforward to transform all customer statements into objectives. These transformations help to form a common expression and facilitate the process of structuring. One example objective in the context of developing a cordless drill is to maximize battery life, which is expressed with a verb and a noun. Then the goal “battery life is expected to achieve 5 hours” and the constraint “battery life must be longer than 3 hours” are transformed into the common objective. The transformation does not eliminate these original customer statements. Compared with goals and constraints, objectives are more suitable for evaluating design alternatives [8, 9] and for value-driven design as in such case an attribute interval will be found. However, it is not the same for goals and constraints, which can be satisfied or not. As values are made explicit through objectives, these transformations provide the opportunity to qualify and quantify customer values.

Three kinds of objectives are needed to organize sufficiently different types of objectives: fundamental objectives, means objectives and strategic objectives. Fundamental objectives in the context are recognized as real customer needs for product to-be developed, e.g. maximize usefulness. Means objectives may be ECs or design parameters e.g. maximize torque or maximize battery life. Strategic objectives are much more essential and cover all possible product development contexts, e.g. maximize quality of life.

The input of the structuring process is a set of initially identified customer statements while the output is an appropriate set of customer needs or fundamental objectives. A means-ends objectives network is firstly established by performing means-ends analysis on the initial objectives transformed from initial customer statements. Then a fundamental objectives hierarchy is explored on the basis of the identified fundamental objectives in the network. An example of means-ends objectives network and fundamental objectives hierarchy, respectively, for developing cordless drill is shown in figure 2 and figure 3.

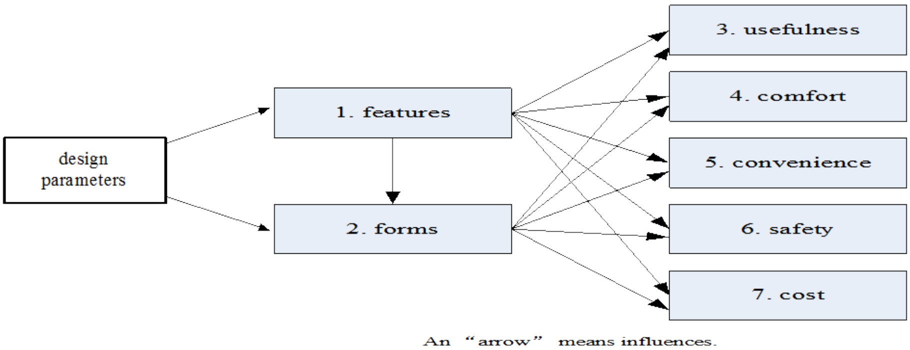

Figure 2 part of means-ends network of cordless drill

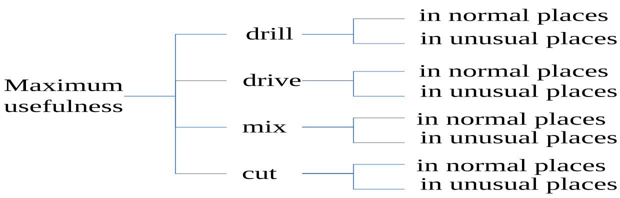

Figure 3 objective hierarchy of “usefulness”

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 this kind of why question, it is possible to identify the customer needs hidden in initial customer statements. However, customer needs, e.g. maximize usefulness, in this high level context is too vague to be measured. Further questions should be pursued to clarify the exact meaning of them. By asking questions, such as “what do you mean by maximum usefulness?”, it is possible to extend the understanding of usefulness and to identify missing needs in the initial statements. It is not a trivial and easy task. Creative thinking is necessary and decision should be made to determine when it is possible to stop asking these questions. More discussion about this kind of decisions should refer to [6, 10]. Objectives in the lowest level of fundamental objectives hierarchy are desired when we reach at a 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 the objectives and their attributes are found, and more information is needed to be collected for attributes.

3.1.2 Quantifying Customer Needs in terms of Value

The output of the structuring process, that is, the hierarchy of customer needs is the input of a quantification process. An attribute then is carefully selected to measure the degree to which each customer need is met. They are, however, usually missing in a traditional QFD analysis as shown in figure 1, so it is not always clear how to measure the achievement of customer needs s_i's. Absence of attributes results in a serious barrier to assign meaningful eights to customer needs. There are two undesired possibilities in assigning weights:

1. One possibility is that weights of customer needs are assigned independently from the attributes and their range information. According to classic utility theory, it makes no sense to say that for example, "minimize cost" is more important than "maximize safety", or vice versa, in context of selecting the best suitable car to buy. It all depends on how much you consider cost and safety, respectively, and on where you start. It is meaningful to say that cost is more important than safety when the range of change in cost from some starting level is more important than the range of change in safety from certain starting level, and
2. Another possibility is that weights are assigned through implicit value trade-offs having implicit attributes information in mind, which adds cognitive burden to customers and makes reasonable assessment of weights a difficult task. It has been shown in literature of decision analysis that it is error-prone to directly assess relative weights for objectives and their attributes when the set of objectives is large [5].

Three kinds of attributes are used to measure customer needs. A natural attribute is used to measure directly one customer need with a common understanding to everyone [6]. For example, "cost measured in dollars" is a natural attribute of "minimize cost". Constructed attribute is used when it is difficult to identify natural attribute [6], for example, an N-level attribute is constructed for "maximize safety" and different pictures are provided to measure beauty and style of car. However, it may be sometimes too difficult to identify direct measurement for some needs. Indirect attributes are then used as proxies. "Torque measured in inch-pound" is typically used as a proxy attribute for performance of cordless drill while it is a direct attribute for the objective "maximize torque". It is desirable that the set of selected attributes satisfies desired properties of attributes, e.g. measurable, operational, direct and unambiguous [6, 10], and that there are one-to-one relationships rather than multiple-to-multiple relationships between needs and attributes. The weight of one attribute is equal to the weight of the corresponding need.

The final set of attributes, e.g. $\{X_1, X_2, \ldots, X_M\}$ is then checked in terms of independence conditions. When attributes $\{X_1, X_2, \ldots, X_M\}$ are additive independent, that is, the preference order for lotteries depends only on their marginal possibility distribution [10], additive function form

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

exists, where u_i is a single attribute utility function over attribute X_i, and the k_i's are scaling constants subject to $\sum_{i=1}^{M} k_i = 1, k_i \geq 0, M \geq 2$. The function form, however, is just one of possible function forms. It is similar to equation (2) for computing customer satisfaction in a traditional QFD analysis.

$$S = \sum_{i=1}^{M} d_i s_i \tag{2}$$

But, there are at least two obvious distinctions.

1. k_i in equation (1) is a relative weight of attribute X_i. It is determined by making value trade-offs among M attributes. To assess k_i, at least M equations with k_i's (i=1, …, M) as unknowns should be found and solved while it is necessary to identify a pair of two consequences $C_1=(x_1, x_2, \ldots, x_M)$ and $C^*=(x_1^*, x_2^*, \ldots, x_M^*)$ that are indifferent to customers to construct one equation. d_i, however, is usually determined by direct weighting, e.g. 9-point direct-rating scale, and then followed by a normalization process without explicitly considering attributes information, and
2. u_i is a single attribute utility function over attribute X_i,. It can be increasing, decreasing or non-monotonic and be of concave, linear or convex sharp. For example, one customer is of risk aversion over cost of buying cordless drill, the function form will be in shape of concave as shown in Figure 4. When customer is of risk neutrality over attributes X_i, the utility function over X_i, is linear and is consistent with s_i in the equation (2). Then every unit of achievement of attribute has the same effect on customer satisfaction. s_i is the degree of attainment of the i^{th} customer need can be seen as equating to the parameter x_i in $u_i(x_i)$. Qualitatively, the introduction of single attribute

utility function for measuring customer satisfaction over single customer need is similar to the discussion on KANO model [11] that distinguishes three categories of customer needs with distinctive influences on customer satisfaction, respectively. However, there is no assessment of mathematical function between customer satisfaction and attribute for measuring customer need in the KANO model. There is also no consideration of risk attitudes toward uncertainty of attribute achievement.

Figure 4 a hypothetical utility curve for the cost to buy cordless drill

After comparison, it is straightforward to find out that equation (2) of additive linear function form is a special case of additive function form, which in turn is a special form of multiplicative utility function, and that using appropriately equation (2) is subject to strong assumptions. It is then necessary to carefully verify the preference assumptions that enable choosing of certain function form.
However, it is not equivalent to say that it is wrong to use equation (2) in QFD, or it is too restrictive to apply equation (2). In fact, some practical approximations are still acceptable, which possibly enable equation (2) as a reasonable approximation. For example, when the range of cost is narrowed to a certain degree, it is possible to have a linear relationship between cost and utility as an acceptable approximation. However, most of the realistic applications do not fall into this category, which helps the success of the QFD.

3.2 Identifying Means Influencing Customer Needs

When customer needs are analysed and assessed sufficiently, it is time to identify the means that can influence the achievement of them. It is usually carried out by asking such question as “how can the needs be better achieved?” On the other hand, there may be product features or specifications described by multiple ECs, which may conflict with each other in nature. For example, “maximize torque” is possibly conflicting with “minimize mass”, because in order to achieve more torque more batteries are required, which simultaneously increases the mass. The design trade-offs among the conflicting ECs depend on value trade-offs among attributes, as the objective of design trade-offs is to maximize customer values. It is then necessary to model the interface between performance model and value model, mapping ECs to customer needs as shown in Figure 5.

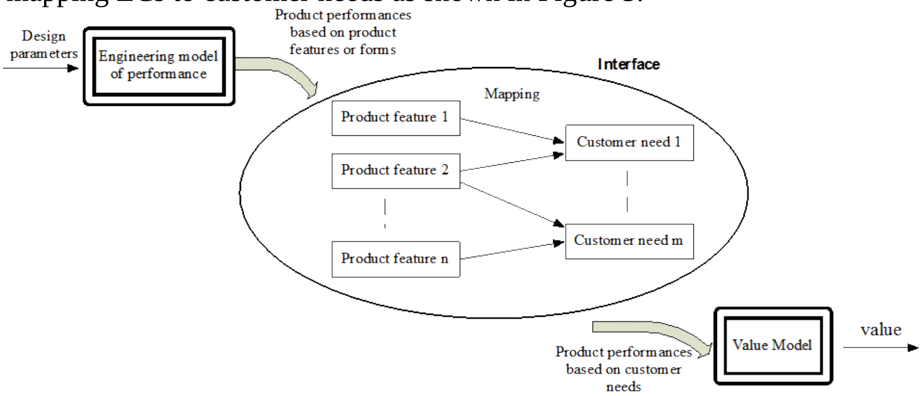

Figure 5 two kinds of models and their interface

The interface is modelled with the help of the relationship matrix in QFD. ECs are means to influence customer needs, they are in a lower level than customer needs in the means-ends objectives network. The two-dimensional relationship matrix models well the adjacent two level means-ends relationships. Entries of the relationship matrix are filled with symbols to establish intensity of their relationships (see Figure 1). Some EC impacts positively one customer need and impacts negatively another customer need, for example, “door seal resistance” influences positively “easy to open from outside” and influences negatively “easy to close from outside”. Two levels are typically used to measure the strength of influence in positive and negative case, respectively. There are also cases where the entries are filled with numbers, for example, the 1-3-9 scales. In such situation, the number is always positive [3, 12, 13]. The function form is given by

$$s_i = \sum_{j=1}^{N} a_{ij} e_j \tag{3}$$

where a_{ij} is discrete and always not smaller than 0 and e_j is defined in Table 1.

It is easy to find out that the function is oversimplified and may only be reasonable in some contexts. A general formalization of the relationships should be given by

$$s_i = f_i(EC_1, EC_2, ..., EC_N) \tag{4}$$

where EC_j is a performance level of the j^{th} EC, f_i is a function modelling the influence of EC_i’s on s_i. Then it is possible to combine value model (1) and interface model (4) to get

$$u(s_1, ..., s_M) = \sum_{i=1}^{M} k_i u_i(f_i(EC_1, EC_2, ..., EC_N)) \tag{5}$$

This equation is especially useful to compute the utility of design alternatives that have the same set of ECs with different numbers in ECs.

However, it is sometimes hard to identify function form between s_i and EC_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. But approximation techniques are also acceptable and well adopted in industry. A reasonable approximation that is supported by the robustness of a linear model [5] is

$$s_i = \sum_{j=1}^{N} k_{ij} f_{ij}(EC_j) \tag{6}$$

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

If u_i’s are of linear form, weight importance of EC_j is given by

$$w_j' = \sum_{i=1}^{M} k_i \left(\frac{k_{ij}}{\sum_{j \in I1} k_{ij} - \sum_{j \in I2} k_{ij}} \right) \tag{7}$$

where I1 is a subset where all k_{ij}’s in this subset are positive, I2 is a subset where all k_{ij}’s in this subset are negative, and w_j' is the weight importance of the j^{th} EC.

The underlying fact in the value-centric QFD is that it is a two-step modelling process. In the first step the value model of customer needs is modelled and it is subjective, reflecting customer preferences. On the other side, the interface model from EC_i’s to s_i is modelled by considering the influences from one to the other with causal relationships. It is different from the one-step process that models directly the relationships from EC to value without identifying the implicit customer needs. It is also much easier to check the preference conditions among the customer needs than to check the preference conditions among ECs.

4 WHAT CAN BE FURTHER DONE IN THIS FRAMEWORK?

With the introduction of the discussed techniques into QFD, further work can be done in this framework, which will finally contribute to a value-based methodology for requirements engineering. Some most relevant extensions are follows.

The nature of correlations between ECs can be quite complex [12]. Higher achievement of one EC may impact positively or negatively the other ECs (see figure 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 directly. They are dependent variables while the design parameters that can be changed directly are independent variables. Z_{jk} can only be modelled 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 equation (5) and performance model to enable integrated optimization, which optimizes from controllable design parameters to customer value without concerning to the middle step of setting ECs. However, having performance model 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 structuring relationships from design parameters to ECs and provides knowledge for trade-offs between ECs.

Setting targets for ECs is an important decision in the house of quality. It is a resource allocation problem that is intended to maximize customer value under various constraints, e.g. cost, functionality and performance. By introducing multiple attributes preference theory, equation (2) is replaced by equation (5), which needs to be maximized.

Weights given by the customer is not always precise. Sometimes it is even hard for customers to clearly identify and state their preferences. It is then necessary to do a sensitivity analysis of weights. Changing weights will result in different targets for ECs that together maximize customer value. It is more useful to do the sensitivity analysis when there is a set of actual and potential design alternatives. Several kinds of simulation techniques are possible on the basis of different levels of available preference information [14, 15].

QFD is mostly controversial about its ability to capture group preference [4, 16]. These controversies mainly come from Arrow's Impossibility Theorem (AIM). According to AIM, it is impossible to find reasonable procedures to translating individual rankings into group rankings under a set of seemingly innocuous assumptions [10]. Ranking, however, is one special type of preference, and it is ordinal and not cardinal. When interpersonal comparison of preferences is addressed, group preferences can be derived from individual preferences, which are proved by Keeney [10, 16]. It is then possible to derive customers' group preferences based on individual customer preferences. And when customers have the same u_i's, the weight of each customer need conforming to group preferences is the sum of weights given by each individual adjusted by the number of customers.

5 CONCLUSION

In this paper the value-centric QFD is proposed for establishing requirements specification. It separates what (what are desired by customers) from how (how they can be implemented by engineers), and explores what in depth and width using value-focused thinking. Structuring customer statements with means-ends objectives network establishes traceability between customer statements and helps identify implicit customer needs. Organizing customer needs into the fundamental objectives hierarchy further explore and clarify the meaning of them. Quantifying customer needs in terms of value is made possible by introducing attributes for measuring customer needs. Value model is also constructed, which enables useful computing and simulation. The approach connects customer needs and customer values, and it also contributes to establishing value-based requirements specification.

Other benefits of the value-centric QFD are that several oversimplifications, e.g. assessing weight importance and computing customer satisfaction with linear additive form, are revised with theoretical support from multiple attributes preference theory. These revisions make value-centric QFD more precise in measurement and much more applicable in various contexts. It is also possible to derive simpler formulation as the formulation in traditional QFD from this approach. It is especially appropriate for optimizing customer values in complex and important product development programmes.

However, it takes much more time for customers to think about what they desire and how much, and for engineers to figure out possible creative design alternatives driven by customer values. It also requires testing rigorously the independence conditions among attributes. But it is not sure that it will clearly produce better outcomes in all applications than traditional QFD. As in certain contexts, it is enough to use the information in traditional QFD that will necessarily result in a ranked order of design alternatives conforming to customer values. It may also be possible that traditional QFD is preferred in certain contexts when considering necessary constraints from the available time or information. Then selecting appropriate formulations is a decision-making problem with multiple and conflicting evaluation criteria.

It is also interesting to conclude or develop some simplified versions that are still effective in the special set of application contexts. For example, it would be interesting to infer situations where linear approximation may be acceptable.

We are applying the methods presented in this paper to develop a value model for airlines and passengers and an interface model mapping customer needs into Top Level Aircraft Requirements (aircraft specification) in the context of CRESCENDO, which is a European project in aerospace industry. Expected outputs will be the value-based aircraft requirements specification that enables design trade-off in lower levels, e.g. subsystem or components level, to be rationally made to maximize customer values. Validation of the method in terms of feasibility and effectiveness will be reported in the near future, including the time it takes to assess, the insight it provides and comparisons with traditional QFD.

ACKNOWLEDGEMENTS

We thank Hakki Eres at University of Southampton for numerous discussions about value-driven design. The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) (www.crescendo-fp7.eu) under grant agreement n◦234344.

REFERENCE

[1] Pahl, G. and Beitz, W. *Engineering Design: A Systematic Approach*. 3rd edition, Springer, 2007.
[2] Ulrich, K. and Eppinger, S. D. *Product Design and Development*. 4th edition, McGraw-Hill/Irwin Press, 2007.
[3] Hauser, J. R. and Clausing, D. *The House of Quality*. Harvard Business Review, 66(3): 63-74, 1988.
[4] De Poel, I. V. *Methodological problems in QFD and directions for future development*. Research in Engineering Design, 18(1): 21-36, 2007.
[5] Butler, J. C., James, S. D. and Jia, J. *Using Attributes to Predict Objectives in Preference Models*. Decision Analysis, 3(2): 100-116, 2006.
[6] Keeney, R. L. *Value-Focused Thinking*. Harvard University Press, Cambridge, MA, 1992.
[7] Keeney, R. L. and von Winterfeldt, D. *Practical Value Models*. In Advances in decision analysis, Edwards, W., Miles, Jr., R., and von Winterfeldt, D., eds., Cambridge University Press, Cambridge, 2007.
[8] Keeney, R. L. *Common Mistakes in Making Value Trade-off*. Operation Research, 50(6):935-945, 2002.
[9] Keeney, R. L. *Selecting Attributes to Measure the Achievement of Objectives*. Operation Research, 53(1): 1-11, 2005.
[10] Keeney, R. L. and Raiffa, H. *Decisions with multiple objectives: preferences and value trade−offs*. Cambridge University Press, 1993.
[11] Bayus, B. *Understanding customer needs*. In Blackwell handbook of technology and innovation management, Cambridge, MA: Blackwell Publishes, 2007.
[12] Ramaswamy, R. and Ulrich, K. *Augmenting the house of quality with engineering models*. Research in Engineering Design, 5: 70-79, 1993.
[13] Bode, J. and Fung, R. *Cost engineering with quality function deployment*. Computers & Industrial Engineering, 35(3-4): 587-590, 1998.
[14] Butler, J. C., Morrice, D. J. and Mullarkey, P. *A Multiple Attribute Utility Theory Approach to Ranking and Selection*. Management Science, 47:800-816, 2001.
[15] Butler, J. C., Jia, J. and Dyer, J. S. *Simulation techniques for the sensitivity analysis of multi-criteria decision models*. European Journal of Operational Research, 103:531-545, 1997.
[16] Keeney, R. L. *The foundations of collaborative group decisions*. International Journal of Collaborative Engineering, 1 (1-2): 4-18, 2009.