Doctoral Thesis

Decisionmaking in Conceptual Phase of Product Development

March 2013

Md. Mamunur Rashid

Doctoral Thesis

Decisionmaking in Conceptual Phase of Product Development

Md. Mamunur Rashid

Table of Contents

Table of Contents continues

Pages 3-4, 12, 28, 50, 64, 78, 82, 90, 93-4, 96, and 98-9 are intentionally left blank.

Abstract

Product Development studies the activities underlying a product life cycle in a concurrent manner. In the conceptual phase of product development, a set of key solutions are determined by using an appropriate decisionmaking approach. However, decisionmaking in this phase is a difficult task to perform due to incomplete information, lack of knowledge, and abundance of choice. This thesis describes logical approaches for making decisions in conceptual phase of product development. In particular, the emphasis is given on such issues as customer needs, sustainability, and creativity. Multi-valued logic and information content from the context of epistemic uncertainty have been used for the sake of computation. The thesis is structured, as follows:

Chapter 2 describes the key mathematical entities used in this study such as fuzzy number, imprecise probability, information content, and discrete event simulation.

Chapter 3 describes customer needs assessment in conceptual phase of product development. In this study, a set of field data has been collected from Bangladesh by using Kano-model-based questionnaires on some features of small passenger vehicles. The opinions obtained exhibit a high variability and controversy and simple relative-frequency-based approaches have been found less effective in assessing the product features, correctly. To solve this problem, a logical customer needs assessment approach has been developed. The approach has been found effective in classifying a product feature into the following categories: the feature “must,” “should,” and/or “could” be included in the product. The findings are useful for developing more customer-focused passenger vehicles.

Chapter 4 describes a decisionmaking approach for assessing the sustainability in conceptual phase of product development. One of the key sustainability issues of a product is whether or not the product is made of environmentally friendly materials. To assess the environmental burden of a material in conceptual phase of product development, the information of greenhouse gas emissions (CO_2, NO_X, SO_X) and

resource consumptions (e.g., water usage) of primary material production is needed. This kind of information exhibits a high variability and incompleteness. To deal with this issue, an entity called range compliance is used that logically defines the degree of belongingness of a given numerical range to a linguistically defined class. Using range compliance, the environmental burdens of hard materials used to produce a grinding wheel (i.e., Alumina, Zirconia, Silicon Carbide, and Boron Carbide/Nitride) have been identified. The findings help develop more environmentally friendly abrasive tools (products) used in precision engineering.

Chapter 5 describes a decisionmaking approach for assessing a creative concept in conceptual phase of product development. Creative concept is one of key ingredients of developing a product. According to a theory called C-K theory, a creative concept means a concept that is undecided with respect to the existing knowledge at the point of time when it (the concept) is conceived. In this study, a logical decisionmaking approach has been developed to assess the degree of creativeness of a set of concepts. In particular, it has been found that for conceiving a creative concept one should maximize the information content (in the epistemic sense) of conceptual phase of product development. The findings help manage the cognitive processes of conceptual phase of product development.

The last chapter, Chapter 6, provides the concluding remarks and discusses the scope of further research opportunities.

Chapter 1
Introduction

This chapter describes the general background, scope, and limitation of this thesis. For the sake of better understanding this chapter is structured into the following sections: Product Development, Decisionmaking in General, Decisionmaking in Conceptual Phase of Product Development, and Thesis Structure.

1.1. Product Development

Product Development is a field of study wherein the activities underlying product lifecycle are studied in a concurrent manner (Ulrich and Eppinger 2004, Dieter and Schmidt 2009). The lifecycle of a product can be represented in many ways. One of the ways, which is relevant to this thesis, is schematically illustrated in Fig. 1.1.

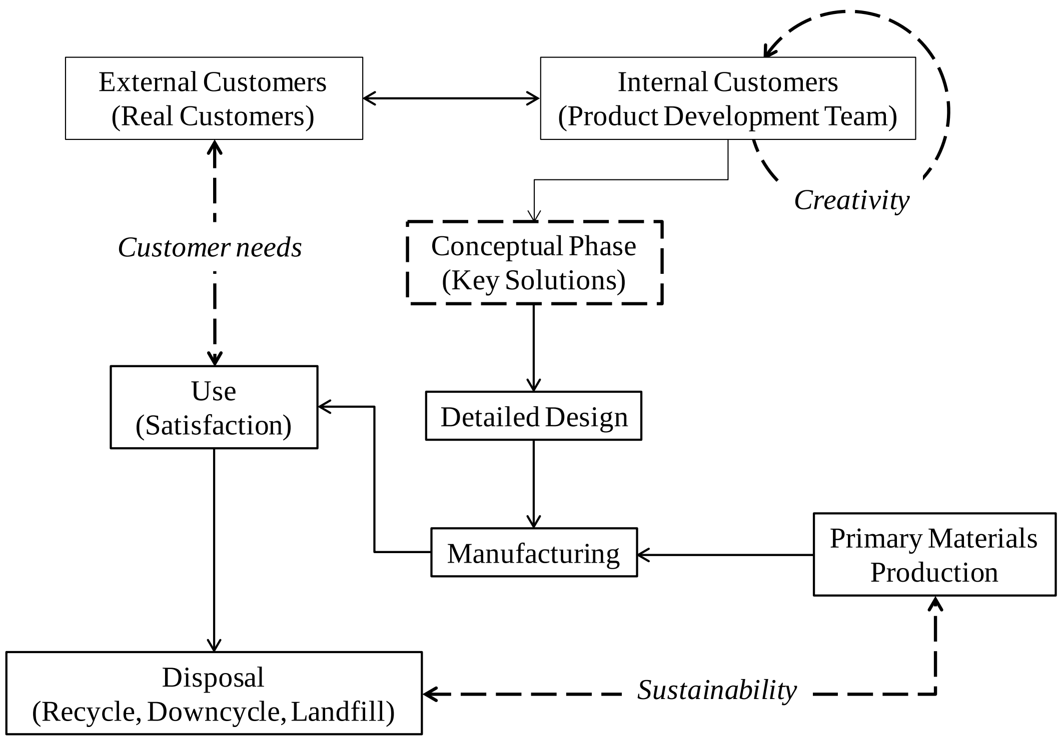

Figure 1.1. A product development scenario.

A product development process first decides a set of key solutions (conceptual phase). The key solutions are further pursued and a detailed design of the product is produced. Based on the detailed design, manufacturing of the product is conducted. The manufactured product is then made available to the external customers (real customers) for use. Using the product, an external customer gets satisfied. If the product can no longer be used, the product is disposed off. In this phase, the product might experience recycling, down-cycling, remanufacturing, and/or land-filling.

However, the activities of product development are carried out by a team (hereinafter referred to as internal customers) wherein a group of individuals from different departments of an organization (or different organizations) work together to materialize a product or a family of products. The internal customers first try to make sure the liking-disliking of external customers (the potential real-customers who will use the product to get satisfied). The internal customers need to be creative to suggest many potential key solutions for satisfying the needs of external customers. Therefore, the following questions might arise in the conceptual phase of product development:

How to differentiate a creative key solution from a non-creative key solution?

What is the appropriate customer need model?

How to deal with the unknown customer needs?

How to classify the key solutions based on customer responses?

Nowadays, sustainability has become an important issue (Fiksel 2009). Sustainability often means that the product is environmentally benign on top of other desired performances. One should incorporate so-called Life-Cycle Assessment (LCA) into the product development processes to ensure the sustainability (Donnelly et al. 2004, Kobayashi, 2006). In addition to conventional sustainability assessment (i.e., LCA), it is important to do scenario analysis (Umeda 2009, Fukushige et al. 2012) taking a broader perspective into the consideration. One of the remarkable finding underlying scenario-analysis-based sustainability assessment is that the primary production of materials used in the product plays a critical role to ensure the sustainability (Higuchi et al. 2012). This implies the following question:

How to deal with the sustainability of materials (used in the product) in key solution determination process?

However, around 80% cost of a product is decided by the key solution determination process (in the conceptual phase) and it cannot be rectified by making adjustments in the downstream of product lifecycle (Wood and Agonigo 1996). This means that the decisionmaking in conceptual phase of product development is a critical task. In addition, in conceptual phase the knowledge is very limited and there is an abundance of choice (Dieter and Schmidt 2009). This means that the decisionmaking in conceptual phase is a very difficult task to perform on top of its criticalness, as mentioned before.

1.2. Decisionmaking in General

In late 1940s, Neumann and Morgenstern introduced a theory called game theory. This theory has been accepted as a means to develop methods and tools for *rational* decisionmaking. Two approaches have emerged from the game theoretic practices. One of the approaches uses traditional settings of game theory (e.g., conflict/coalition analysis method using graph theory (e.g., see Fang et al. 1993, Inohara and Hipel 2008 and the references therein)). The other approach has taken the form of multiple-attribute utility analysis, wherein a set of attributes and their relative weights are used to simultaneously evaluate (tradeoff) a set of given alternatives, and, thereby, to select the optimal alternative corresponding to the maximal utility (Saaty 1980, 1990). However, many authors have studied the applicability of the multi-attribute utility analysis from the context of *real-life* decisionmaking. Some of the salient points are briefly described below. In real-life decisionmaking, a decision-maker often seeks a balanced alternative rather than an optimal alternative and it is important to visualize the state of an alternative rather than to automate the decisionmaking process (Kujawski 2005). Sometimes mental biases of decision-makers affect the utility-based tradeoff and it is important to take measures for reducing the biases in terms of problem statement, weights of importance, alternative solution, evaluation data, scoring function, and combining function (Smith et al. 2007). Sometimes the sequence of acts (i.e., bring the required parties together, determine the needs, analyze the data, make a decision and implement it) is important than the calculation process of tradeoff (Briggs and Little 2008). Sometimes determining the relevant set of criteria and their weights for tradeoffs is a cumbersome task that involves the opinions of stakeholders (Keller et al. 2008). Thus, in real-life settings it is not an easy task to utilize the utility based decisionmaking approaches (i.e., rational decisionmaking approaches).

Opposed to rational decisionmaking, there is a faculty of thought of decisionmaking called *naturalistic* decisionmaking (Klein 1989, Rasmussen 1993, Hutton and Klein 1999, Klein 2008). In particular, human experts perform naturalistic decisionmaking under the following context: time pressure, incomplete/unreliable information, ill-defined goal, organizational constraints, multiple decision-makers, and alike. Humans make decision under the abovementioned context using a decisionmaking approach called recognition-primed process (Klein 2008) that consists of the following steps: plausible goals, cues to monitor, expectancies, and sequential action evaluation (Klein 1989, Hutton and Klein 1999). There are three types of cognitive controls in recognition-primed process, namely, 1) skill-based spontaneous act, 2) ruled-based conscious attention and selection of relatively familiar action, and 3) knowledge-based conscious attention and selection of relatively unfamiliar action (Rasmussen 1993).

Either it is a rational decisionmaking process or it is a naturalistic decisionmaking process, the decision-relevant information may not necessarily be crisp in nature. It might be granular in nature (Bellman and Zadeh 1970, Zadeh 1965, 1975, 1997). Zadeh and his colleagues have argued that the manifestation of human cognitive is a set of “granular information”—imprecisely defined linguistic classes or clusters of points—and multi-valued logic (known as fuzzy logic) is needed to formally compute the linguistically expressed imprecise arguments (i.e., granular information). Multi-attribute utility analysis community (i.e., rational decisionmaking community) has integrated this idea to make the rational decisionmaking more realistic (Yager 1978, Herrera and Herrera-Viedma 2000). There are different models available to deal with the computational complexity of stakeholder-driven heterogeneous formulation of decision problem and imprecisely defined decision-relevant information (e.g., Herrera and Herrera-Viedma 2000, Shamsuzzaman et al. 2003, Chen and Ben-Arieh 2006, Ullah 2005, Noor-E-Alam et al. 2011). This kind of decisionmaking approach is suitable when the decision-relevant information is dominated by personal preferences, judgments, and vaguely defined alternatives, weights, and requirements.

1.3. Decisionmaking in Conceptual Phase of Product Development

As mentioned before, decisionmaking in conceptual phase of product development decides around 80% cost of the product and the decisionmaking process suffers lack of knowledge and abundance of choice (Wood and Agonigo 1996, Dieter and Schmidt 2009, Ullman 2009, Ulrich and Eppinger 2004, Ullah 2005). Therefore, the decision-relevant information in conceptual phase is predominated by personal preferences, judgments, and vaguely defined alternatives, weights, and requirements. As a result, granular information based decisionmaking approach is suitable for making decisions in conceptual phase of product development (Ullah 2005).

However, decisionmaking in conceptual phase of product development requires an explicit measure that quantifies the lack/abundance of knowledge. For example, consider the measures called degree of certainty of knowledge in robust decisionmaking (Ullman 2006) and certainty compliance (entropy) in general-pinion-desire based decisionmaking (Ullah 2005). In addition, a measure is needed to quantify the degree of fulfillment of requirement, though the requirement might be vaguely defined or vary across the external customers. For example, consider the measure called criteria satisfaction in robust decisionmaking (Ullman 2006) and requirement compliance (entropy) in general-opinion-desire based decisionmaking (Ullah 2005).

The explanation refers to the fact that a two-dimensional decision measure is needed for making decisions in conceptual phase of product development. One of the coordinates of the measure should measure the degree of certainty of knowledge and the other should measure the degree of fulfillment. However, it would be convenient if the decision measure is directly related to some of the important principles of systems design. In this case, general-opinion-desire based decisionmaking is a desirable one because the certainty entropy and requirement entropy (Ullah 2005) are directly related to general systems design principles (i.e., information axiom of axiomatic design of systems) (Suh 1990, 1998, Ullah 2005b).

1.4. Thesis Structure

The remainder of this thesis is organized as follows:

Chapter 2 describes the key mathematical entities used in this study namely, fuzzy number, range compliance, linguistic likelihood, information content, and discrete event simulation.

Chapter 3 describes customer needs assessment in conceptual phase of product development. In this study, a set of field data has been collected from Bangladesh by using Kano-model-based questionnaires on some features of small passenger vehicles. The opinions obtained exhibit a high variability and controversy and simple relative-frequency-based approaches have been found less effective in assessing the product features, correctly. To solve this problem, a logical customer needs assessment approach has been developed. The approach has been found effective in classifying a product feature into the following categories: the feature "must," "should," and/or "could" be included in the product. The findings are useful for developing more customer-focused passenger vehicles.

Chapter 4 describes a decisionmaking approach for assessing the sustainability in conceptual phase of product development. One of the key sustainability issues of a product is whether or not the product is made of environmentally friendly materials. To assess the environmental burden of a material in conceptual phase of product development, the information of greenhouse gas emissions (CO_2, NO_X, SO_X) and resource consumptions (e.g., water usage) of primary material production is needed. This kind of information exhibits a high variability and incompleteness. To deal with this issue, an entity called range compliance is used that logically defines the degree of belongingness of a given numerical range to a linguistically defined class. Using range compliance, the environmental burdens of hard materials used to produce a grinding wheel (i.e., Alumina, Zirconia, Silicon Carbide, and Boron Carbide/Nitride) have been identified. The findings help develop more environmentally friendly abrasive tools (products) used in precision engineering.

Chapter 5 describes a decisionmaking approach for assessing a *creative concept* in conceptual phase of product development. Creative concept is one of key ingredients of developing a product. According to a theory called C-K theory, a creative concept means a concept that is undecided with respect to the existing knowledge at the point of time when it (the concept) is conceived. In this study, a logical decisionmaking approach has been developed to assess the degree of creativeness of a set of concepts. In particular, it has been found that for conceiving a creative concept one should maximize the information content (in the epistemic sense) of conceptual phase of product development. The findings help manage the cognitive processes of conceptual phase of product development.

The last chapter, Chapter 6, provides the concluding remarks and discusses the scope of further research opportunities.

Chapter 2

Mathematical Settings

Chapter 2 describes the mathematical entities used in this thesis, namely, fuzzy number, range compliance, linguistic likelihood, information content, and discrete event simulation. For the sake of better understanding, this chapter is organized into the following five sections: Fuzzy Number, Operations on Fuzzy Numbers, Linguistic Likelihood, Information Content, and Monte Carlo Simulation of Discrete Events.

2.1 Fuzzy Number

A *fuzzy number A* is a special type of fuzzy subset (Zadeh 1965) wherein the universe of discourse X is a segment of real-line $\Re$ and the maximum membership value of the membership function $\mu_A(x)$ is equal to 1 (condition of normality). In addition, $\mu_A(x)$ fulfills the conditions of convexity, continuity, and compactness (Dubois and Prade 1978, Ullah and Harib 2006). Fuzzy numbers are suitable for bringing the linguistically defined qualitative entities into a formal computation.

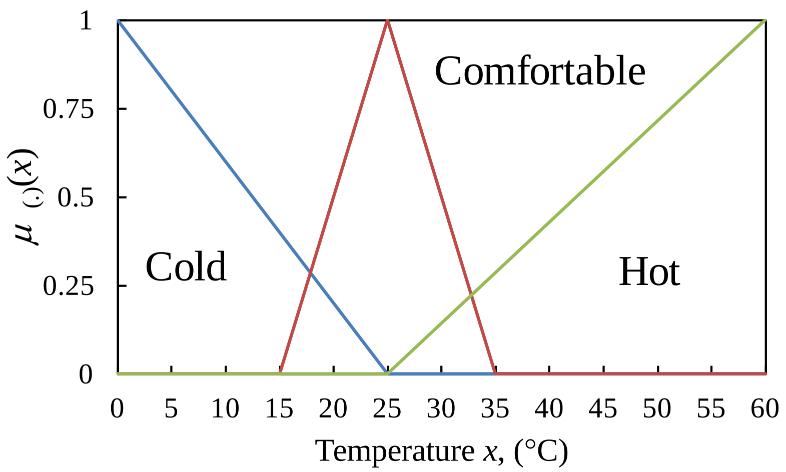

Figure 2.1. Example of fuzzy number.

For the sake of understanding, consider the three fuzzy numbers labeled Hot, Cold, and Comfortable in the universe of discourse X = [0°C,60°C]. The membership functions are as follows:

$$\mu_A : X = [0,60] \to [0,1]$$

$$x \mapsto \mu_A(x) = \max\left(0, \min\left(1, \frac{25-x}{25-0}\right)\right) \qquad A = \text{Cold}$$

$$x \mapsto \mu_A(x) = \max\left(0, \min\left(\frac{x-15}{25-15}, \frac{35-x}{35-25}\right)\right) \qquad A = \text{Comfortable} \tag{2.1}$$

$$x \mapsto \mu_A(x) = \max\left(0, \min\left(\frac{x-25}{60-25}, 1\right)\right) \qquad A = \text{Hot}$$

Note that $\mu_A(x)$ is called the *membership value* of x with respect to A. It, $\mu_A(x)$, is also called the *degree of belief* of x in terms of A. The *Truth-Value* (*TV*) of the proposition "x is A" is also equal to $\mu_A(x)$.

For example, let x be 20°C. According to equation (2.1), the membership value of x = 20°C is equal to 0.2 for A = Cold, 0.5 for A = Comfortable, and 0 for A = Hot. This means that the *TV* of a proposition "20°C is a Cold temperature" is equal to 0.2, of a proposition "20°C is a Comfortable temperature" is equal to 0.5, and of a proposition "20°C is a Hot temperature" is equal to 0.

In this thesis, fuzzy numbers are used to define such entities as linguistic likelihoods, linguistic truth values, and classes like high, low, moderate, and alike for the sake of formal computation.

2.2 Operations on Fuzzy Number

There are many operations applied on a fuzzy number or on a set of fuzzy numbers. The operations relevant to this thesis are *Alpha-cut* (Dubois and Prade 1978), *Expected Value* (Dubois and Prade 1978), and *Range Compliance* (Ullah 2008).

An Alpha-cut of a fuzzy number A denoted by A_α is the crisp range for all $\mu_A(x) \geq \alpha$, $\alpha \in (0,1]$. Thus,

$$A_\alpha = \{x \mid \mu_A(x) \geq \alpha \in (0,1]\} \tag{2.2}$$

For example, $A_{0.5}$ = [20°C,30°C], if A = Comfortable (see equation (2.1)). The largest alpha-cut is called Support (*Supp*(.)). Thus,

$$Supp(A) = (a,b) \cup \{a,b\} = [a,b] \quad max(A_\alpha \mid \forall \alpha \in (0,1]) = (a,b) \tag{2.3}$$

For example, $Supp(A)$ = [15°C,35°C], if A = Comfortable (see equation (2.1)).

Expected value of a fuzzy number A is the first moment of the shape of its membership function μ_A, denoted as $E(A)$. Thus,

$$E(A)=\frac{\int \mu_A(x)xdx}{\int \mu_A(x)dx} \tag{2.4}$$

For example, $E(A)$ = 25°C, if A = Comfortable (see equation (2.1)).

Range compliance of a numerical range L is its average membership value with respect to a fuzzy number A, denoted as $R(L,A)$.

$$R(L,A)=\frac{\int_L \mu_A(x)dx}{|L'|} \quad (L' \subseteq L)\wedge(L' \subseteq Supp(A)) \tag{2.5}$$

Here, L' is the segment of L that belongs to $Supp(A)$.

For example, $R(L,A)$ = 0.583, if L = [10°C,30°C] and A = Comfortable.

Range compliance as defined in equation (2.5) will be used in Chapter 4 for sustainability assessment. Other operations will be used in Chapters 3 and 5.

2.3 Linguistic Likelihood

In real-life cases, probability of an event is difficult to known accurately (O'Hagan and Oakley 2004). One of the useful representations of real-life probability is called imprecise probability ($\Pr_{imp}$) wherein both upper and lower limits of probability are used to define the probability of an event (Walley 1991). Alternatively, the imprecision associate with the probability of an event can be represented by a set of fuzzy numbers defined in the universe of discourse [0,1] (i.e., possible values of probability). The labels of the fuzzy numbers are called *Linguistic Likelihood*s (*LL*s) (most likely, less unlikely, and alike). It is useful in determining the probability of an event given the relative frequency (*fr*) of the event (Ullah and Harib 2006, Ullah and Tamaki 2011). It is needless to say that the membership functions of *LL*s denoted as $\mu_{LLi}(.)$, i = 1,...,n, are defined in the universe of discourse [0,1].

However, the linguistic counterpart of *fr* corresponds to an LLj, $j \in \{1,...,n\}$ that corresponds to the maximum membership value for *fr*. This means that if $\max(\mu_{LLi}(fr)\ i = 1,...,n) = \mu_{LLj}(fr)$ then $\Pr_{imp}(fr) = LLj$, $j \in \{1,...,n\}$. Later the fuzzy number corresponding to LLj can be used for having a crisp probability for the sake of calculation. In this thesis, three cases of *LL* are considered.

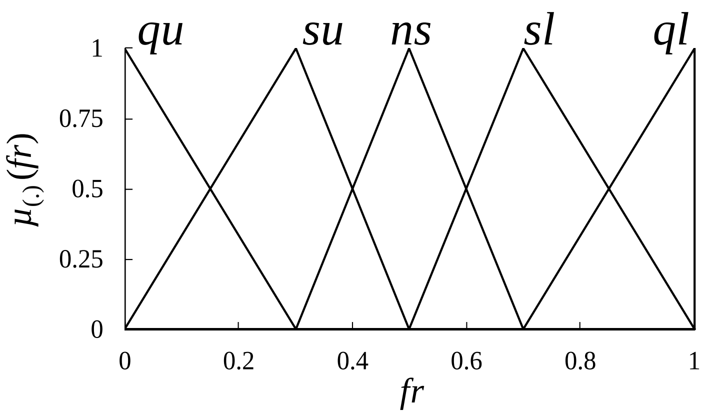

Figure 2.2. Membership functions of five *LL* (Case 1).

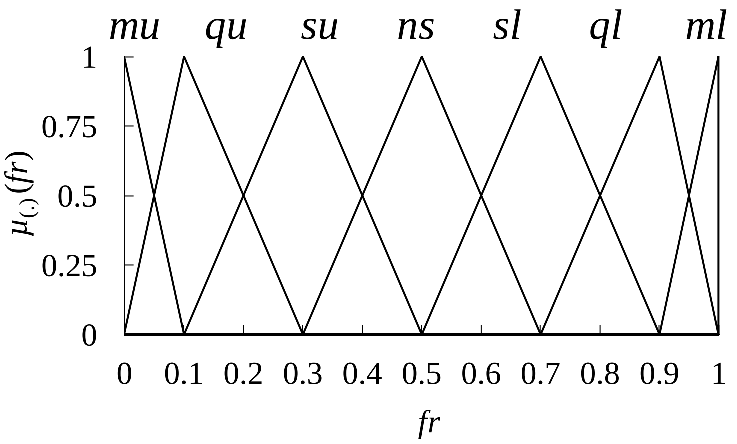

Figure 2.3. Membership functions of seven *LL* (Case2).

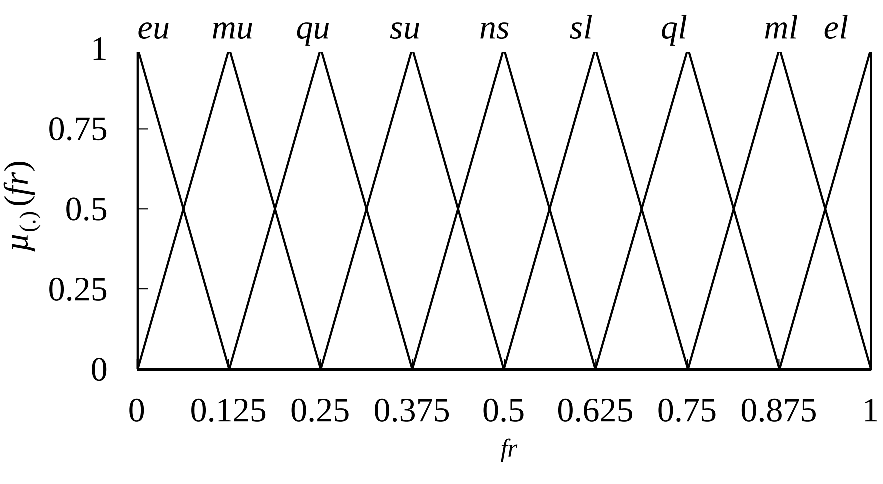

Figure 2.4. Membership functions of seven *LL* (Case 3).

Case 1 corresponds to five *LL*s, namely, quite unlikely (*qu*), some unlikely (*su*), not sure (*ns*), some likely (*sl*), and quite likely (*ql*). Case 2 corresponds to seven *LL*s, namely, most unlikely (*mu*), quite unlikely (*qu*), some unlikely (*su*), not sure (*ns*), some likely (*sl*), quite likely (*ql*), and most likely (*ml*). Case 3 corresponds to nine

*LL*s, namely, extremely unlikely (*eu*), most unlikely (*mu*), quite unlikely (*qu*), some unlikely (*su*), not sure (*ns*), some likely (*sl*), quite likely (*ql*), most likely (*ml*), and extremely likely (*el*).

Figure 2.2 illustrates the membership functions corresponding to Case 1. The definitions of the membership functions illustrated in Fig. 2.2 are as follows:

$$\mu_{qu}(fr) = max\left(0, min\left(1, \frac{0.3 - fr}{0.3 - 0}\right)\right) \tag{2.6.1}$$

$$\mu_{su}(fr) = max\left(0, min\left(\frac{fr - 0}{0.3 - 0}, \frac{0.5 - fr}{0.5 - 0.3}\right)\right) \tag{2.6.2}$$

$$\mu_{ns}(fr) = max\left(0, min\left(\frac{fr - 0.3}{0.5 - 0.3}, \frac{0.7 - fr}{0.7 - 0.5}\right)\right) \tag{2.6.3}$$

$$\mu_{sl}(fr) = max\left(0, min\left(\frac{fr - 0.5}{0.7 - 0.5}, \frac{1 - fr}{1 - 0.7}\right)\right) \tag{2.6.4}$$

$$\mu_{ql}(fr) = max\left(0, min\left(1, \frac{fr - 0.7}{1 - 0.7}\right)\right) \tag{2.6.5}$$

Figure 2.3 illustrates the membership functions corresponding to Case 2. The definitions of the membership functions illustrated in Fig. 2.3 are as follows:

$$\mu_{mu}(fr) = max\left(0, min\left(1, \frac{0.1 - fr}{0.1 - 0}\right)\right) \tag{2.7.1}$$

$$\mu_{qu}(fr) = max\left(0, min\left(\frac{fr - 0}{0.1 - 0}, \frac{0.3 - fr}{0.3 - 0.1}\right)\right) \tag{2.7.2}$$

$$\mu_{su}(fr) = max\left(0, min\left(\frac{fr - 0.1}{0.3 - 0.1}, \frac{0.5 - fr}{0.5 - 0.3}\right)\right) \tag{2.7.3}$$

$$\mu_{ns}(fr) = max\left(0, min\left(\frac{fr - 0.3}{0.5 - 0.3}, \frac{0.7 - fr}{0.7 - 0.5}\right)\right) \tag{2.7.4}$$

$$\mu_{sl}(fr) = max\left(0, min\left(\frac{fr - 0.5}{0.7 - 0.5}, \frac{0.9 - fr}{0.9 - 0.7}\right)\right) \tag{2.7.5}$$

$$\mu_{ql}(fr) = max\left(0, min\left(\frac{fr - 0.7}{0.9 - 0.7}, \frac{1 - fr}{1 - 0.9}\right)\right) \tag{2.7.6}$$

$$\mu_{ml}(fr) = max\left(0, min\left(1, \frac{fr - 0.9}{1 - 0.9}\right)\right) \tag{2.7.7}$$

Figure 2.4 illustrates the membership functions corresponding to Case 3. In the conceptual phase of product development, a set of key solutions are determined by using an appropriate decisionmaking approach.

$$\mu_{eu}(fr) = max\left(0, min\left(1, \frac{0.125 - fr}{0.125 - 0}\right)\right) \quad (2.8.1)$$

$$\mu_{mu}(fr) = max\left(0, min\left(\frac{fr - 0}{0.125 - 0}, \frac{0.25 - fr}{0.25 - 0.125}\right)\right) \quad (2.8.2)$$

$$\mu_{qu}(fr) = max\left(0, min\left(\frac{fr - 0.125}{0.25 - 0.125}, \frac{0.375 - fr}{0.375 - 0.25}\right)\right) \quad (2.8.3)$$

$$\mu_{su}(fr) = max\left(0, min\left(\frac{fr - 0.25}{0.375 - 0.25}, \frac{0.5 - fr}{0.5 - 0.375}\right)\right) \quad (2.8.4)$$

$$\mu_{ns}(fr) = max\left(0, min\left(\frac{fr - 0.375}{0.5 - 0.375}, \frac{0.625 - fr}{0.625 - 0.5}\right)\right) \quad (2.8.5)$$

$$\mu_{sl}(fr) = max\left(0, min\left(\frac{fr - 0.5}{0.625 - 0.5}, \frac{0.75 - fr}{0.75 - 0.625}\right)\right) \quad (2.8.6)$$

$$\mu_{ql}(fr) = max\left(0, min\left(\frac{fr - 0.625}{0.75 - 0.625}, \frac{0.875 - fr}{0.875 - 0.75}\right)\right) \quad (2.8.7)$$

$$\mu_{ml}(fr) = max\left(0, min\left(\frac{fr - 0.75}{0.875 - 0.75}, \frac{1 - fr}{1 - 0.875}\right)\right) \quad (2.8.8)$$

$$\mu_{el}(fr) = max\left(0, min\left(1, \frac{fr - 0.875}{1 - 0.875}\right)\right) \quad (2.8.9)$$

Table 2.1 Summary of *LL*s

Items	Cases	Linguistic Likelihoods (*LL*s)								
		eu	*mu*	*qu*	*su*	*ns*	*sl*	*gl*	*ml*	*el*
Expected value	1	-	-	0.1	0.267	0.5	0.733	0.9	-	-
	2	-	0.033	0.133	0.3	0.5	0.7	0.867	0.967	-
	3	0.042	0.125	0.25	0.375	0.5	0.625	0.75	0.875	0.958
Alpha-cut at $\alpha = 0.5$	1	-	-	[0,0.15]	[0.15,0.4]	[0.4,0.6]	[0.6,0.85]	[0.85,1]	-	-
	2	-	[0,0.05]	[0.05, 0.2]	[0.2,0.4]	[0.4,0.6]	[0.6,0.8]	[0.8,0.95]	[0.95,1]	-
	3	[0,0.0625]	[0.0625, 0.1875]	[0.1875, 0.3125]	[0.3125, 0.4375]	[0.4375, 0.5625]	[0.5625, 0.6875]	[0.6875, 0.8125]	[0.8125, 0.9375]	[0.9375, 1]
Range of *fr*	1	-	-	[0,0.15)	[0.15,0.4)	[0.4,0.6)	[0.6,0.85)	[0.85,1]	-	-
	2	-	[0,0.05)	[0.05, 0.2)	[0.2,0.4)	[0.4,0.6)	[0.6,0.8)	[0.8,0.95)	[0.95,1]	-
	3	[0,0.0625)	[0.0625, 0.1875)	[0.1875, 0.3125)	[0.3125, 0.4375)	[0.4375, 0.5625)	[0.5625, 0.6875)	[0.6875, 0.8125)	[0.8125, 0.9375)	[0.9375, 1]

Table 2.1 summarizes the expected values, alpha-cuts at $\alpha = 0.5$, and ranges of *fr* for three cases of *LL*s as defined above. In particular, the ranges of *fr* will be used to find out the linguistic counterparts of a given *fr*. For example, if $fr = 0.3$ then its

linguistic counterpart is *su* according to Case 1, is *su* according to Case 2, is *qu* according to Case 3. See the ranges of *fr* in Table 2.1 wherein *fr* = 0.3 belongs. Once the linguistic counterpart of fr is determined, the corresponding linguistic likelihood will be used to carry out the subsequent calculations. For example, if *fr* = 0.3 then its linguistic counterpart is *su* according to Case 1 and the expected value of it (*su*), 0.267 according to Table 2.1, will be used to carry out the subsequent calculation. Similarly, if *fr* = 0.3 then its linguistic counterpart is *su* according to Case 2 and the expected value of it (*su*), 0.3 according to Table 2.1, will be used to carry out the subsequent calculation. Again, if *fr* = 0.3 then its linguistic counterpart is *qu* according to Case 3 and the expected value of it (*qu*), 0.25 according to Table 2.1, will be used to carry out the subsequent calculation. This kind of scheme is helpful in discrete event simulation using a relatively small set of data points.

2.4 Linguistic Truth Value

It is mentioned that the membership value can be considered the truth value of proposition. For example, recall the proposition of Section 2.1: *p* = "20°C is a Cold temperature." The truth value of *p* is equal to 0.2, *TV*(*p*) = 0.2, because $\mu_{Comfortable}(x =$ 20°C) = 0.2 according to the membership function of the fuzzy number "Comfortable" as shown in Fig. 2.1 and defined in equation (2.1).

However, there are cases wherein it would be difficult to explicitly construct a membership function and calculate *TV* of a proposition from it. In such cases, one can assign a preferential/judgmental *TV* using a phrase (mostly true, some false, etc.) to a proposition. For example, consider the following proposition: *p*(*Z*, attractive) = "Z is an attractive attribute for this product." One can assign a *TV* = "quite true" to *p*(*Z*, attractive) based her/is judgment. To bring such preferential/judgmental *TV*, one can use linguistic *TV* defined by a set of fuzzy numbers, as it is done for linguistic likelihoods.

Figure 2.5 illustrates the linguistic *TV* defined by five fuzzy numbers labeled mostly false (*mf*), perhaps false (*pf*), not sure (*ns*), perhaps true (*pt*), and mostly true (*mt*). These *TV*s are used in Chapter 5. Note that the membership functions are the same compared to those of Case 1 *LL*s.

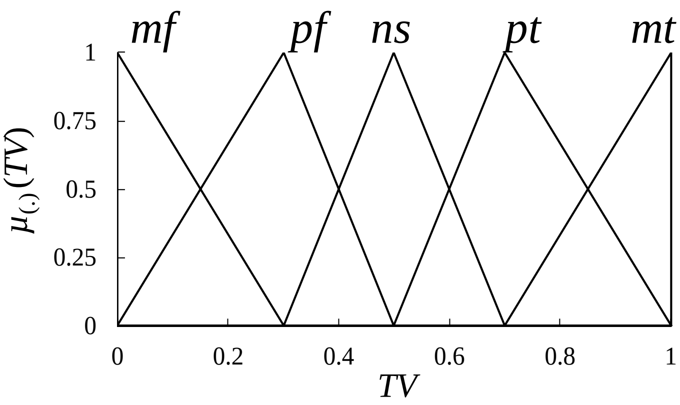

Figure 2.5. Linguistic *TV* using five fuzzy numbers.

The membership functions are defined as follows:

$$\mu_{mf}(TV) = max\left(0, min\left(1, \frac{0.3 - TV}{0.3 - 0}\right)\right) \tag{2.9.1.1}$$

$$\mu_{pf}(TV) = max\left(0, min\left(\frac{TV - 0}{0.3 - 0}, \frac{0.5 - TV}{0.5 - 0.3}\right)\right) \tag{2.9.1.2}$$

$$\mu_{ns}(TV) = max\left(0, min\left(\frac{TV - 0.3}{0.5 - 0.3}, \frac{0.7 - TV}{0.7 - 0.5}\right)\right) \tag{2.9.1.3}$$

$$\mu_{pt}(TV) = max\left(0, min\left(\frac{TV - 0.5}{0.7 - 0.5}, \frac{1 - TV}{1 - 0.7}\right)\right) \tag{2.9.1.4}$$

$$\mu_{mt}(TV) = max\left(0, min\left(1, \frac{TV - 0.7}{1 - 0.7}\right)\right) \tag{2.9.1.5}$$

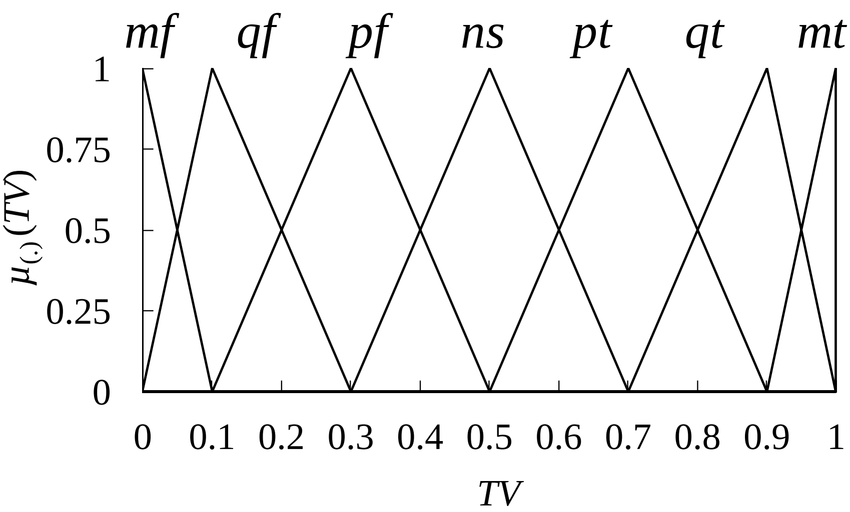

Figure 2.6. Linguistic *TV* using seven fuzzy numbers.

Similarly, Fig. 2.6 illustrates the linguistic *TV* defined by seven fuzzy numbers labeled mostly false (*mf*), quite false (*qf*), perhaps false (*pf*), not sure (*ns*), perhaps true (*pt*), quite true (*qt*), and mostly true (*mt*). The definitions of the membership functions illustrated in Fig. 2.3 are as follows:

$$\mu_{mf}(TV) = max\left(0, min\left(1, \frac{0.1 - TV}{0.1 - 0}\right)\right) \tag{2.9.2.1}$$

$$\mu_{qf}(TV) = max\left(0, min\left(\frac{TV - 0}{0.1 - 0}, \frac{0.3 - TV}{0.3 - 0.1}\right)\right) \tag{2.9.2.2}$$

$$\mu_{pf}(TV) = max\left(0, min\left(\frac{TV - 0.1}{0.3 - 0.1}, \frac{0.5 - TV}{0.5 - 0.3}\right)\right) \tag{2.9.2.3}$$

$$\mu_{ns}(TV) = max\left(0, min\left(\frac{TV - 0.3}{0.5 - 0.3}, \frac{0.7 - TV}{0.7 - 0.5}\right)\right) \tag{2.9.2.4}$$

$$\mu_{pt}(TV) = max\left(0, min\left(\frac{TV - 0.5}{0.7 - 0.5}, \frac{0.9 - TV}{0.9 - 0.7}\right)\right) \tag{2.9.2.5}$$

$$\mu_{qt}(TV) = max\left(0, min\left(\frac{TV - 0.7}{0.9 - 0.7}, \frac{1 - TV}{1 - 0.9}\right)\right) \tag{2.9.2.6}$$

$$\mu_{mt}(TV) = max\left(0, min\left(1, \frac{TV - 0.9}{1 - 0.9}\right)\right) \tag{2.9.2.7}$$

These *TV*s are used in Chapter 3. Note that the membership functions are the same compared to those of Case 2 *LL*s.

Table 2.2 summarizes the expected values of the linguistic *TV*s defined above. If one assigns the truth value of a proposition equal to perhaps true (*pt*), then the subsequent computation will be carried out by using its expected value 0.733.

Table 2.2. Summary of linguistic *TV*s.

Items		Linguistic *TV*s						
		mf	*qf*	*pf*	*ns*	*pt*	*qt*	*mt*
Expected Value	Five	0.1	-	0.267	0.5	0.733	-	0.9
	Seven	0.033	0.133	0.3	0.3	0.7	0.867	0.967

2.5 Information Content

In 1940s, Shannon introduced the concept of information content as a part of his information theory wherein an obvious event has low information content and less likely event has high information content. Thus, if the probability of an event is *Pr*, then the information content of the event is given by -log(1/*Pr*). In systems design, Suh have utilized this concept introducing an axiom called the Information Axiom: *minimize the information content of a design* (Suh 1990, 1998). According to the information axiom, the information content of a functional requirement (*FR*) of a system is defined as follows:

$$I(FR) = -log\left(\frac{1}{S}\right) \tag{2.10}$$

In equation (2.10), *S* is the area under the probability density function of system range (*sr*) (the performance of the system designed) for a given design range (*dr*) (the requirement defined the designer). A schematic illustration of *S*, *sr*, and *dr* is shown in Fig. 2.7.

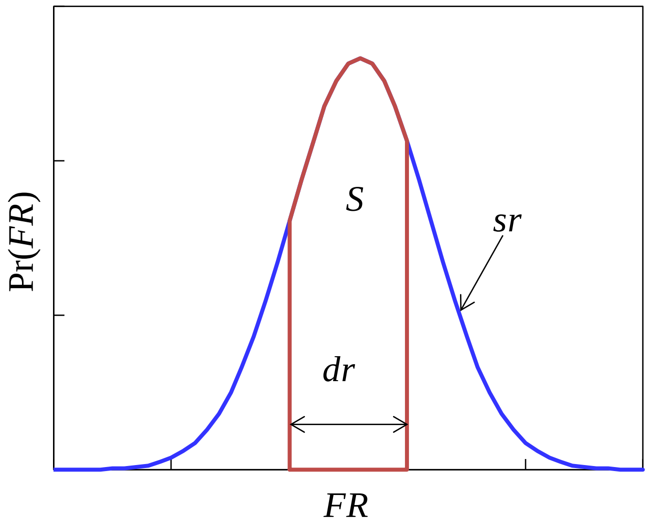

Figure 2.7. Definition of information content for systems design.

I(*FR*) can be minimized by increasing the value of *S*, i.e., matching *sr* with respect to *dr*. This means that minimization of information content means maximization of requirement fulfillment. Therefore, information content defined in equation (2.10) actually determines the degree of requirement fulfillment.

Note that in conceptual phase of product development (the focus of this thesis), it would be difficult to clearly define the probability density function to represent *sr* and the range called *dr*. Therefore, information content defined in equation (2.10) (i.e., degree of fulfillment of requirement) may not be applied in conceptual phase of product development. In addition, in conceptual phase of product development, not only the degree of fulfillment requirement but also the degree of knowledge should get proper attention (Ullah 2005a-b, Ullman 2006).

The above explanation implies that for conceptual phase of product development, information content of a key solution has two facets, one is the degree of knowledge and the other is the degree of fulfillment. In this thesis, a two-dimensional information content (*CE*,*RE*) scheme is used. Here *CE* means Certainty Entropy that measures the degree of knowledge in the interval [0,1] and *RE* means Requirement Entropy (*RE*) that measures the degree of fulfillment of a linguistically defined requirement (see Ullah 2005a, Ullah and Harib 2008). The calculation is done on the truth values of a set of propositions, $TV(P1),...,TV(Pn),TV(P_R)$. Here, $P1,...,Pn$ are general propositions and P_R is the requirement proposition. The truth values of $P1,...,Pn$, $TV(P1),...,TV(Pn)$, are assigned or calculated and the truth value of P_R, $TV(P_R)$, is calculated from $TV(P1),...,TV(Pn)$.

In particular, CE is defined as follows:

$$CE = \frac{\sum_{i}^{n} I_c(TV(Pi))}{n} \tag{2.11.1}$$

This means that *CE* is the average epistemic information content, $I_c(.)$, of $TV(P1),...,TV(Pn)$. The epistemic information content $I_c(.)$ is determined as follows:

$$I_c(TV(Pi)) = max\left(0, min\left(\frac{TV-0}{0.5-0}, \frac{1-TV}{1-0.5}\right)\right) \tag{2.11.2}$$

Figure 2.8 illustrates $I_c(.)$. As seen from Fig. 2.8, epistemic information content of the truth value of a proposition is a tent function in the universe of discourse of [0,1].

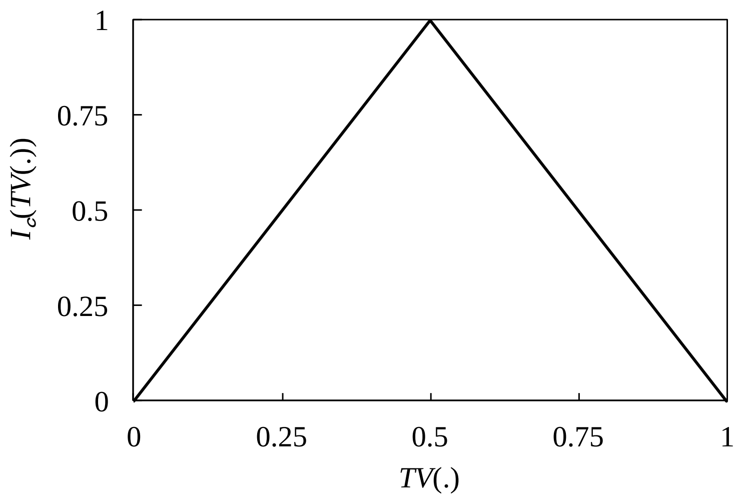

Figure 2.8. Epistemic information content.

This function ensures that a completely true or false proposition does not have any information content ($I_c(TV = 1 \text{ or } 0) = 0$), whereas if the proposition is neither true nor false, it has the highest information content ($I_c(TV = 0.5) = 1$). For other cases, the information content is between 0 and 1.

Recall the other coordinate of information content of a key solution in conceptual phase of product development, *RE,* Requirement Entropy. *RE* measures the entropy of the requirement given by P_R, which is just the opposite of the degree of fulfillment of requirement given by P_R. Thus, if the requirement is fully fulfilled, *RE* should be equal to zero (lowest entropy) and if the requirement is fully unfulfilled, *RE* should be equal to unit (highest entropy). If the requirement is partially fulfilled, *RE* is between 0 and 1. The following function can be used to measure *RE* (Ullah 2005a):

$$RE = max\left(0, min\left(1, \frac{a - TV(P_R)}{a - b}\right)\right) \qquad (2.11.3)$$
$$a = max(TV(Pi) \mid i = 1, \ldots, n) \quad b = min(TV(Pi) \mid i = 1, \ldots, n)$$

The procedure to determine the $TV(P_R)$ from $TV(P1)$,...,$TV(Pn)$ shown in Ullah 2005a is used in this thesis. A typical nature of RE is illustrated in Fig. 2.9 corresponding to $a = 0.9$ and $b = 0.05$.

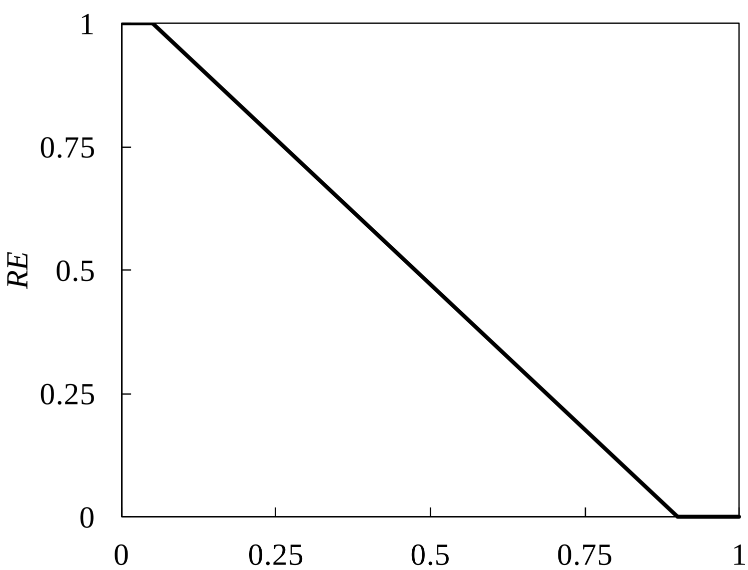

Figure 2.9. A function to determine requirement entropy.

The two-dimensional information content of key solutions can be plot on a *RE* versus *CE* plot and a measure called coherency measure (λ) can be determined. The coherency measure actually aggregates the variability in the information content of a key solution using the following expression:

$$\lambda = e + f + g + h + (f - e)(h - g) \quad (2.11.4)$$

In ideal case, λ = 0 that means the solution fully fulfills the requirement the knowledge of the solution is complete. In reality it does not happen. What is seen in reality is schematically illustrated in Fig. 2.10. As seen from Fig. 2.10, both key solutions suffer lack of knowledge and partial fulfillment of requirement, both *CE*, *RE* > 0. However, the variability and magnitude in (*CE*,*RE*) points is less for key solution 1 compared to those of key solution 2. This results a relatively low λ for key solution 1 compared to that of key solution 2, i.e., $\lambda_1 < \lambda_2$. Therefore, key solution 1 is a preferable key solution compared to the other. This way decisionmaking can be carried out in conceptual phase of product development.

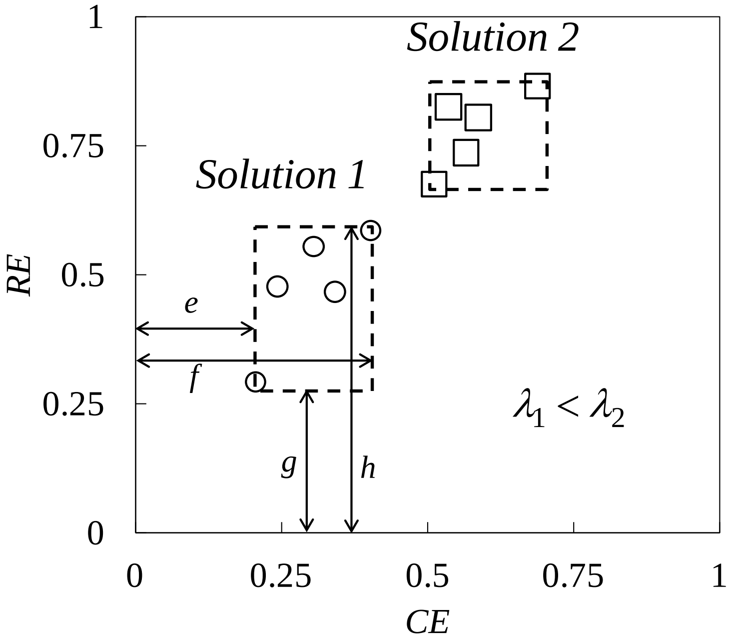

Fig. 2.10. Decisionmaking using two-dimensional information content.

2.6 Monte Carlo Simulation of Discrete Events

Monte Carlo simulation of discrete events is a useful method to know the unknown answers of external customers (Ullah and Tamaki 2011). In this thesis, similar method is used to simulate the unknown answers of external customers. The simulation steps are explained in Table 2.3. As explained in Table 2.3, the simulation needs two inputs: a vector of events (*ev*(1) = Attractive (*A*), *ev*(2) = One-dimensional (*O*), *ev*(3) = Must-be (*M*), *ev*(4) = Indifferent (*I*), *ev*(5) = Reverse (*R*), *ev*(6) = Questionable (*Q*)) and another vector of their relative frequencies (*fr*(*ev*(*i*))) (e.g., (0.1,0.4,0.3,0.1,0.1,0). An example is shown in Table 2.3. Afterward, the user chooses a set of linguistic likelihoods either from Case 1 or from Case 2 or from Case 3. The linguistic counterpart of each relative frequency *fr*(*i*) denoted by *LL*(*i*) is determined by using the ranges listed in the "Range of *fr*" rows of Table 2.1. For example, if *fr*(*i*) = 0.1, then its linguistic counterpart is *qu*. The reason is that *fr*(*i*) = 0.1 belongs to the range [0,0.15)--a range derived from the alpha-cut *qu* corresponding to Case 1 (see Table 2.1). The expected values of the respective linguistic likelihoods, *E*(*i*), are used in the subsequent calculations.

In the subsequent calculations, first, the probability of each event is calculated by normalizing each expected value, as follows:

$$Pr(i) = \frac{E(i)}{\sum_{i=1}^{6} E(i)} \tag{2.12.1}$$

Afterward, the cumulative probability of an event is calculated, as follows:

$$CPr(i) = \sum_{j=1}^{i} Pr(i) \tag{2.12.2}$$

Table 2.3. An example of the settings of simulation

Items	Vector of events (input)					
	ev(1)	*ev*(2)	*ev*(3)	*ev*(4)	*ev*(5)	*ev*(6)
	A	*O*	*M*	*I*	*R*	*Q*
fr(*i*) (input)	0.1	0.4	0.3	0.1	0.1	0
LL(*i*) (based on *LL*s of Case 1)	*qu*	*ns*	*su*	*qu*	*qu*	*qu*
E(*i*) (calculated)	0.1	0.5	0.267	0.1	0.1	0.1
Pr(*i*) (calculated)	0.079	0.395	0.211	0.079	0.079	0.079
CPr(*i*) (calculated)	0.079	0.474	0.684	0.763	0.842	0.921

Using the following algorithm a set of simulated events, *se*(*s*), *s* = 1,...,*N*, are generated.

Define the number iterations *N* (a relatively large integer)

For *s* = 1,...,*N*

Generate a random number *RAND* in the interval [0,1]

If *RAND* = [0,CPr(*ev*(1))) Then *se*(*s*) = *ev*(1)

For *k* = 2,...,6

If *RAND* = [CPr(*ev*(*k*-1)), CPr(*ev*(*k*))) Then *se*(*s*) = *ev*(*k*)

If *RAND* = [CPr(*ev*(5)), CPr(*ev*(6))] Then *se*(*s*) = *ev*(6)

Needless to say that *se*(*s*) $\in$ {*A*, *O*, *M*, *I*, *R*, *Q*} for all *s* = 1,...,*N*.

Chapter 3

Customer Needs Assessment

This section deals with the customer needs assessment based on the work of Rashid et al. 2010 and Rashid et al. 2012. The following issues are emphasized:

How to deal with the unknown customer needs?

How to classify the key solutions based on customer responses?

The framework used in the customer needs assessment process is illustrated in Fig. 3.1.

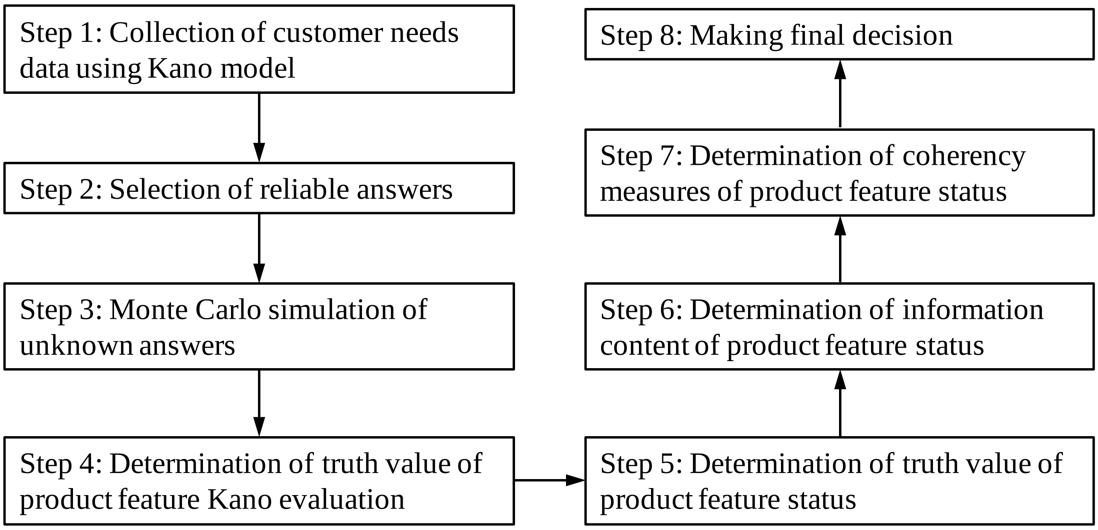

Figure 3.1. Customer needs assessment framework.

As seen from Fig. 3.1, the framework consists of eight steps, as follows:

Step 1: Collection of customer needs data using Kano model

Step 2: Selection of reliable answers

Step 3: Monte Carlo simulation of unknown answers

Step 4: Determination of truth value of product feature Kano-evaluation

Step 5: Determination of truth value of product feature status

Step 6: Determination of information content of product feature status

Step 7: Determination of coherency measure of product feature status

Step 8: Making final decision

Step 1 deals with the customer needs data collection using Kano model from Bangladesh on some selected features of small passenger vehicles (cars). This step is described in details in Section 3.1. Step 2 deals with the determination of reliable answers of the respondents. This step is described in Section 3.2. Step 3 deals with the Monte Carlo simulation of unknown answers. This step is described in Section 3.3. Step 4 deals with the determination of truth value of Kano evaluation of product feature. This step is described in Section 3.4. Step 5 deals with the determination of truth value of product feature status. This step is described in Section 3.5. Step 6 deals with the determination of information content of product feature status. This step is described in Section 3.6. Step 7 deals with the determination of coherency measure of product feature status. This step is described in Section 3.7. The final step, Step 8, deals with the final decisionmaking using the coherency measure. This step is described in Section 8.

3.1. Customer needs data collection

Recall Fig. 1.1. As shown in Fig. 1.1, the external customers should get the desired satisfaction using a product. Therefore, the internal customers (product development team members) should be aware of the customer needs beforehand. Otherwise, the product might not be a useful one. The internal customers first decide a preliminary set of key solutions and prepare a set of questions. A selected segment of potential external customers (real customers) then answer the questions. Using the answers obtained, the internal customers try to identify the usefulness of a proposed key solution or a set of key solutions. Kano model is one of the useful models by which one can ask questions regarding a product feature so as to classify it (product feature) into One-dimensional (*O*) feature, Attractive (*A*) feature, Must-be (*M*) feature, Indifferent (*I*) feature, Reverse (*R*) feature, or Questionable (*Q*) feature (Kano et al. 1984, Berger et al. 1993, Kahn 2004, Yang 2008, Xu et al. 2009, Ullah and Tamaki 2011). Figure 3.2 schematically illustrates the implication of *O*, *A*, *M*, *I*, *R*, and *Q*. According to Fig. 3.2, a feature is considered *M*, if its absence produces absolute dissatisfaction and its presence does not increase the satisfaction. A feature is considered *O*, if its fulfillment helps increase the satisfaction and vice versa. A feature is considered *A*, if it leads to a greater satisfaction, whereas it is not expected to be in the product. A feature is considered *I*, if its presence or absence does not contribute to the customers' satisfaction. A feature is considered *R* if its presence causes dissatisfaction and vice versa. If the customer answers inconsistently, the feature is considered *Q*. However, to know whether or not a feature is *O*, *A*, *M*, *I*, *R*, *Q* a two-dimensional questionnaire is prepared for each feature. Table 3.1 shows an example of Kano questionnaire.

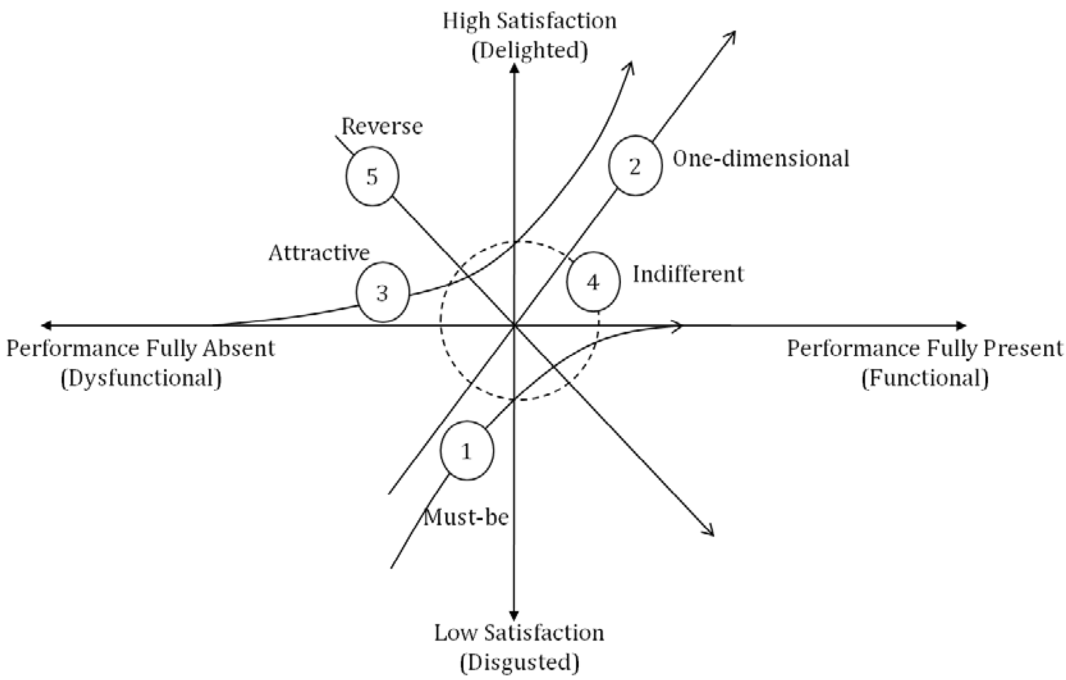

Figure 3.2. Kano model of customer needs (based on Ullah and Tamaki 2011).

Table 3.1. An example of Kano questionnaire

Functional answer			*Dysfunctional answer*		
My car is Sedan 	Like		My car is *not* Sedan	Like	
	Must-be	☑		Must-be	
	Neutral			Neutral	☑
	Live-with			Live-with	
	Dislike			Dislike	

As seen from Table 3.2, the two-dimensional questionnaire has two questions, one deals with customer opinion when function (or feature) is present (functional answer) and other deals with customer opinion when function (or feature) is not present (dysfunctional answer). The respondent needs to choose one of the options (Like, Must-be, Neutral, Live-with, or Dislike) from the functional side. At the same time, the respondent needs to choose one of the options (Like, Must-be, Neutral, Live-with, or Dislike) from the dysfunctional side. The combination of the answers provides the Kano evaluation of the feature of the product. For example, the case shown in Table 3.1 represents a combination (Must-be, Neutral). As such, the product feature, i.e., Sedan, is an Indifferent (*I*) feature--Sedan does not contribute to the satisfaction or dissatisfaction of the respondent. All possible Kano evaluations with are summarized in Table 3.2. Note that when a respondent answers Like for both functional and dysfunctional sides or Dislike for both functional and dysfunctional sides, the answer should not be trusted, i.e., the product feature is Questionable (*Q*) feature.

Table 3.2. Kano evaluation of product feature and function.

		Dysfunctional answer				
		Like	Must-be	Neutral	Live-with	Dislike
Functional answer	Like	*Q*	*A*	*A*	*A*	*O*
	Must-be	*R*	*I*	*I*	*I*	*M*
	Neutral	*R*	*I*	*I*	*I*	*M*
	Live-with	*R*	*I*	*I*	*I*	*M*
	Dislike	*R*	*R*	*R*	*R*	*Q*

A total of 100 respondents are selected at random from Bangladesh and asked to answer according to Kano questionnaire (e.g., Table 3.1) on 38 features of small vehicles. The goal is to know the preferences of the respondents so that a key solutions (or a key solutions) can be determined for product development (i.e., here the product means a small passenger vehicle). The functional questions of these 38 features are listed in Table 3.3. The demographic and psychographic details of the respondents are shown in Appendix A.

However, one of the important key solutions for developing a small passenger vehicle is the type of vehicles. In Table 3.3, there are three types of vehicle, namely, SUV, Sedan, and Van (No. 21-23). The Kano evaluation of these types of vehicles is shown in Table 3.4 that has been determined using the answers of 100 respondents.

Table 3.3. Small passenger vehicle feature.

No	Feature
1	I bought a new vehicle
2	I bought a pre-owned vehicle
3	My vehicle runs 10-15 km/liter
4	My vehicle runs 15-20 km/liter
5	My vehicle runs 25-30 km/liter
6	My vehicle runs 30-35 km/liter
7	My vehicle runs 5-10 km/liter
8	My vehicle color is black
9	My vehicle color is metallic
10	My vehicle color is red
11	My vehicle color is white
12	My vehicle engine has a 2 year warranty
13	My vehicle engine has a 3 year warranty
14	My vehicle engine has a 5 year warranty
15	My vehicle engine is above 1300 cc
16	My vehicle engine is below 1000 cc
17	My vehicle engine is between 1000-1300 cc
18	My vehicle is a 2-door vehicle
19	My vehicle is a 4-door vehicle
20	My vehicle is a 5-door vehicle
21	My vehicle is a Sedan type vehicle
22	My vehicle is a SUV type vehicle
23	My vehicle is a Van (microbus) type vehicle
24	My vehicle is equipped with airbags
25	My vehicle is equipped with bumper guards
26	My vehicle is equipped with keyless-entry system
27	My vehicle is equipped with seatbelts
28	My vehicle is made in Germany
29	My vehicle is made in India
30	My vehicle is made in Japan
31	My vehicle is made in Korea
32	My vehicle needs regular maintenance every after 10,000 km
33	My vehicle needs regular maintenance every after 20,000 km
34	My vehicle needs regular maintenance every after 25,000 km
35	My vehicle needs regular maintenance every after 5,000 km
36	My vehicles runs on CNG
37	My vehicles runs on Diesel
38	My vehicles runs on Petrol

Table 3.4. Kano evaluation of different types of vehicle

Vehicle Type	Kano evaluation					
	A	*O*	*M*	*I*	*R*	*Q*
SUV	14	10	17	41	16	2
Sedan	20	10	12	37	17	4
Van	15	8	11	21	43	2

The evaluation listed in Table 3.4 exhibits a complex situation as far as formal computation is concerned. Most of the respondents evaluated a vehicle either *I* or *R*. In Bangladesh, Sedan is the most frequently used type of small passenger vehicle. This type of vehicle is not that much suitable for the users in Bangladesh because of the road condition, average size of a family, and life-style (travelling in a large group). Thus, the Kano evaluation shown in Table 3.4 does not match the reality in Bangladesh. This necessities the subsequent steps of customer needs assessment.

3.2. Selection of reliable answers

In Kano model, a respondent needs to choose an element drawn from {Like, Must-be, Neutral, Live-with, Dislike} for both functional and dysfunctional sides. Not the option called Neutral. Due to the lack of motivation and/or comprehensibility, the respondent tends to answer this option for frequently. Since the goal is to get an opinionative answer not an indecisive answer (Neutral), the answers equal to Neutral should be avoided. For example, consider the case shown in Table 3.4. The functional and dysfunctional answers are listed in Tables 3.5-6. As seen from Table 3.5, around 30% of the answers are "Neutral" for SUV and Sedan. This number is however low for Van because it has been disliked by many respondents. On the other hand, for all three types of vehicle more than 30% of the respondents have answered Neutral, which is the highest percentage compared to those of other answers.

Table 3.5. Functional answers on vehicle type

Question	Functional Answer				
	Like	Must-be	Neutral	Live-with	Dislike
My car is SUV	26	19	34	9	12
My car is Sedan	31	16	30	8	15
My car is Van	24	7	17	11	41

Table 3.6. Dysfunctional answers on vehicle type

Question	Dysfunctional Answer				
	Like	Must-be	Neutral	Live-with	Dislike
My car is not SUV	11	9	37	16	27
My car is not Sedan	11	9	31	24	25
My car is not Van	26	12	31	11	20

As mentioned before, since the goal is to get an opinionative answer not an indecisive answer (Neutral), the answers equal to Neutral either from functional side or from dysfunctional side or from both sides should be not be considered for the assessment. Applying this elimination strategy results the Kano evaluation shown in Table 3.7. As seen from Table 3.7, the acceptable answers have reduced to 45, 53, and 61 from 100 for SUV, Sedan, and Van, respectively. Compare Table 3.4 and Table 3.7. Needless to say that an acceptable answer means here an answer that is not a Neutral (i.e., not indecisive answer).

Table 3.7. Kano evaluation based on the answers of acceptable respondents

Vehicle Type	Kano evaluation						Number of acceptable respondents
	A	*O*	*M*	*I*	*R*	*Q*	
SUV	6	10	9	9	9	2	45
Sedan	10	10	6	8	15	4	53
Van	6	8	6	5	34	2	61

3.3. Monte Carlo simulation of unknown answers

The above section describes that a limited number of answers are available for the customer needs assessment. This means that a large number of answers are unknown. Monte Carlo simulation can be used to know the unknown answers (Ullah and Tamaki 2011, Rashid et al. 2012). The simulation process described in Section 2.6 is adopted here. The explanation is as follows: Table 3.8 shows the settings of probability of events (A, O, M, I, R, Q) using the Case 1 LLs (see Chapter 2). The relative frequencies listed in Table 3.8 correspond to results shown in Table 3.7.

Table 3.8 Settings of probability using Case 1 *LL*s.

Feature	*ev*(*i*)	*fr*(*i*)	Case 1			
			LL(*i*)	*E*(*i*)	*Pr*(*i*)	*CPr*(*i*)
SUV	*A*	0.133	*qu*	0.1	0.750	0.079
	O	0.222	*su*	0.267	2.003	0.289
	M	0.200	*su*	0.267	2.003	0.500
	I	0.200	*su*	0.267	2.003	0.711
	R	0.200	*su*	0.267	2.003	0.921
	Q	0.044	*qu*	0.1	0.750	1.000
Sedan	*A*	0.189	*su*	0.267	2.003	0.211
	O	0.189	*su*	0.267	2.003	0.421
	M	0.113	*qu*	0.1	0.750	0.500
	I	0.151	*su*	0.267	2.003	0.711
	R	0.283	*su*	0.267	2.003	0.921
	Q	0.075	*qu*	0.1	0.750	1.000
Van	*A*	0.098	*qu*	0.1	0.750	0.100
	O	0.131	*qu*	0.1	0.750	0.200
	M	0.098	*qu*	0.1	0.750	0.300
	I	0.082	*qu*	0.1	0.750	0.400
	R	0.557	*ns*	0.5	3.750	0.900
	Q	0.033	*qu*	0.1	0.750	1.000

Table 3.9 Settings of probability using Case 2 *LL*s.

Feature	*ev*(*i*)	*fr*(*i*)	Case 2			
			LL(*i*)	*E*(*i*)	*Pr*(*i*)	*CPr*(*i*)
SUV	*A*	0.133	*qu*	0.133	0.097	0.097
	O	0.222	*su*	0.3	0.220	0.317
	M	0.200	*su*	0.3	0.220	0.537
	I	0.200	*su*	0.3	0.220	0.756
	R	0.200	*su*	0.3	0.220	0.976
	Q	0.044	*mu*	0.033	0.024	1.000
Sedan	*A*	0.189	*qu*	0.133	0.138	0.138
	O	0.189	*qu*	0.133	0.138	0.276
	M	0.113	*qu*	0.133	0.138	0.413
	I	0.151	*qu*	0.133	0.138	0.551
	R	0.283	*su*	0.3	0.311	0.862
	Q	0.075	*qu*	0.133	0.138	1.000
Van	*A*	0.098	*qu*	0.133	0.125	0.125
	O	0.131	*qu*	0.133	0.125	0.250
	M	0.098	*qu*	0.133	0.125	0.375
	I	0.082	*qu*	0.133	0.125	0.500
	R	0.557	*ns*	0.5	0.469	0.969
	Q	0.033	*mu*	0.033	0.031	1.000

Table 3.10 Settings of probability using Case 3 *LL*s.

Feature	*ev*(*i*)	*fr*(*i*)	Case 3			
			LL(*i*)	*E*(*i*)	*Pr*(*i*)	*CPr*(*i*)
SUV	*A*	0.133	*mu*	0.125	0.107	0.107
	O	0.222	*qu*	0.25	0.214	0.321
	M	0.200	*qu*	0.25	0.214	0.536
	I	0.200	*qu*	0.25	0.214	0.750
	R	0.200	*qu*	0.25	0.214	0.964
	Q	0.044	*eu*	0.042	0.036	1.000
Sedan	*A*	0.189	*qu*	0.25	0.222	0.222
	O	0.189	*qu*	0.25	0.222	0.444
	M	0.113	*mu*	0.125	0.111	0.556
	I	0.151	*mu*	0.125	0.111	0.667
	R	0.283	*qu*	0.25	0.222	0.889
	Q	0.075	*mu*	0.125	0.111	1.000
Van	*A*	0.098	*mu*	0.125	0.120	0.120
	O	0.131	*mu*	0.125	0.120	0.240
	M	0.098	*mu*	0.125	0.120	0.360
	I	0.082	*mu*	0.125	0.120	0.480
	R	0.557	*ns*	0.5	0.480	0.960
	Q	0.033	*eu*	0.042	0.040	1.000

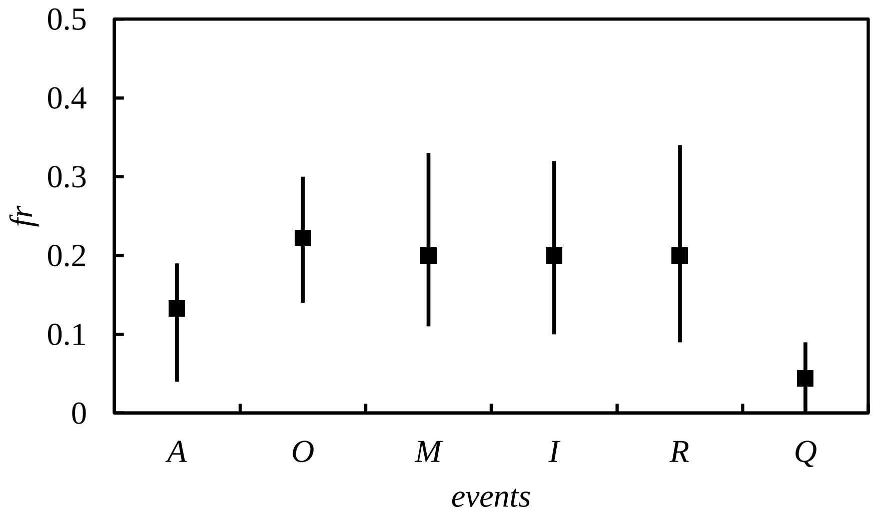

Figure 3.2. Variability in *fr* for SUV and Case 3 *LL*s due to Monte Carlo simulation.

Using the settings listed in Tables 3.8-10 and the simulation process shown in Section 2.6, the Monte Carlo simulation of the events (*A*, *O*, *M*, *I*, *R*, *Q*) has been performed for all SUV, Sedan, and Van. In the simulation, N = 100 (number of iteration) because the original number of respondents was 100 (see Table 3.4). The variability in the relative frequencies of the simulated events (*A*, *O*, *M*, *I*, *R*, *Q*) has been determined by repeating the simulation process for all features SUV, Sedan, and Van. As an example, the variability in the relative frequencies of events for SUV and Case 3 *LL*s is shown in Fig. 3.2. The dark rectangular point on each vertical bar in Fig. 3.2 is the original relative frequency of the event (see Table 3.7).

3.4. Determination of truth values of product feature Kano-evaluation

This section deals with the truth value (*TV*) determination process of Kano-evaluation of product feature. Needless to say that Kano evaluation of a product feature is either *A*, or *O*, or *M*, or *I*, or *R*, or *Q*. The truth value determination process uses the linguistic *TV*s (*LTk*), *k* = 1,2,..., defined by the seven fuzzy numbers namely, mostly false (*mf*), quite false (*qf*), perhaps false (*pf*), not sure (*ns*), perhaps true (*pt*), quite true (*qt*), and mostly true (*mt*), as defined by the membership functions in equations (2.9.2.1-7) (see Chapter 2).

Let *p*(*Fi*,*Xj*) be a proposition of the following form: *Fi* is *Xj*. Here, $Fi \in$ {SUV, Sedan, Van} and $Xj \in \{A, O, M, I, R, Q\}$. The problem is to assign a $TV \in [0,1]$ to *p*(*Fi*,*Xj*) from the relative frequency of *Xj*, *fr*(*Xj*), obtained after performing Monte Carlo simulation as explained in the previous section. An example of how to determine *TV* is illustrated in Fig. 3.3. In this particular case, the linguistic counterpart of *fr*(*Xj*) = 0.25 is *perhaps false* (*pf*) (linguistic *TV* shown in bold in Fig. 3.3) because *fr*(*Xj*) = 0.25 belongs to *pf* more it belongs to any other linguistic *TV*.

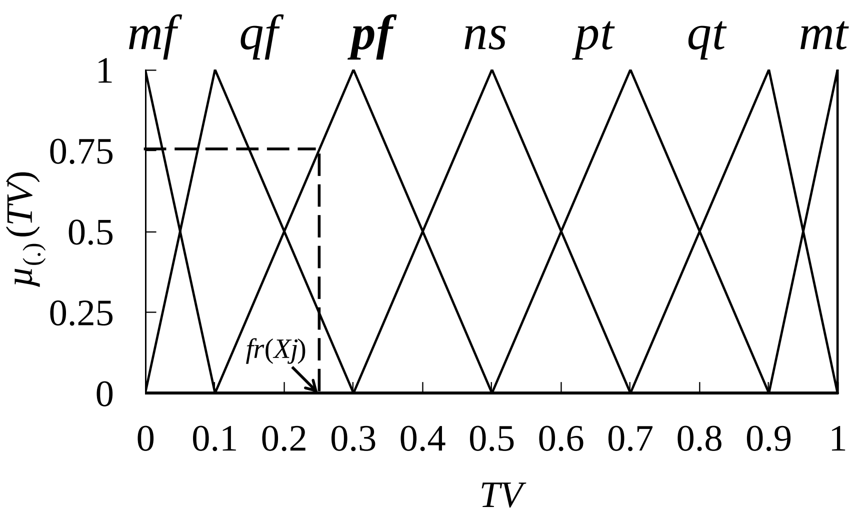

Figure. 3.3. Converting a relative frequency to a linguistic *TV*.

In general, the membership value of a linguistic *TV* denoted as $\mu_{LTk}(TV = fr(Xj))$ represents the degree of belongingness of $fr(Xj)$ to a linguistic *TV*, $LTk \in \{mf, qf, pf, ns, pt, qt, mt\}$. If $\mu_{LTk}(fr(Xj)) > \mu_{LTl}(fr(Xj))$, $l \in \{1, \ldots, 7\} - \{k\}$ and $\exists k \in \{1, \ldots, 7\}$, then $fr(Xj)$ belongs to *LTk* more than it belongs to any other linguistic *TV*. This way, *LTk* is the linguistic counterpart of $fr(Xj)$ and the expected value of *LTk*, $E(LTk)$, is the truth value of $p(.,Xj)$, i.e., $TV(p(.,Xj)) = E(LTk)$.

Note that $fr(Xj)$ is not a constant value in the interval [0,1]. It depends on the simulation instance. For example, consider the variability in the relative frequencies shown in Fig. 3.2. In particular, consider the variability of relative frequency of *A*, $fr(Xj = A)$ = [0.04,0.19]. This means that the truth value ($TV(p)$) of the proposition $p(SUV,A)$ = "SUV is *A*" (i.e., SUV is an attractive car) is around [0.04,0.19], i.e., $TV(p) \approx fr(A)$ = [0.04,0.19]. If $TV(p) \approx 0.04$ in some simulations, then its linguistic counterpart is mostly false (*mf*) and the expected value of *mf*, $E(mf) = 0.033$, becomes the truth value of *p*, i.e., the truth value of the proposition "SUV is an attractive car is equal to 0.033." Similarly, if $TV(p) \approx 0.19$ in some simulations, then its linguistic counterpart is quite false (*qf*) and the expected value of *qf*, $E(qf) = 0.133$, becomes the truth value of this *p*, i.e., the truth value of the proposition "SUV is an attractive car is equal to 0.133." This means that in some other cases $TV(p) = 0.133$.

Therefore, the *TV* of $p(Fi,Xj)$ may vary based on the result of Monte Carlo simulation. As a result, variability in the information content of product feature might be observed.

3.5. Determination of truth value of product feature status

This section deals with the determination process of truth value of the status of a product feature. Product feature status is defined by using the Kano evaluations, *O*, *A*, *M*, *I*, *R*, and *Q*. Therefore, the truth value of the product feature status is calculated from the truth value of its Kano evaluation. Here a product feature status means one of the following: *must be included*, *should be included*, and *could be included*. Let *Fi* be a product feature and *Yj* be an element of {must be included, should be included, and could be included}. Therefore, the problem is to determine the truth value of a proposition of the following form: *Fi Yj in the product*.

Recall the schematic illustration of Kano evaluation shown in Fig. 3.2.

According to Fig. 3.2, if a product feature is classified as One-dimensional (*O*) or Must-be (*M*) and it is not included in the product, the customers are not satisfied. Therefore, a product feature "must be included" in the product means it is "either *O* or *M*." This leads to the following formulation:

$$\begin{aligned} &Fi\ must\ be\ included \rightarrow (F_i\ is\ O) \vee (F_i\ is\ M) \\ &TV(Fi\ must\ be\ included) = max(TV(Fi,O),TV(Fi,M)) \end{aligned} \tag{3.1}$$

Recall the definition of *A* illustrated in Fig. 3.2. If the feature is classified as Attractive (*A*), then it is an unexpected but customer satisfaction-enriching feature. Thus, a product feature classified as *A*, it "should be included" in the product for enhancing the level of customer satisfaction. This yields the following formulation:

$$\begin{aligned} &Fi\ should\ be\ included \rightarrow F_i\ is\ A \\ &TV(Fi\ should\ be\ included) = TV(Fi,A) \end{aligned} \tag{3.2}$$

On the other hand, if a feature is classified as Indifferent (*I*), it is not that much helpful in increasing or decreasing the level of customer satisfaction even though it is included or not included in the product, respectively. In addition, if a feature is classified as Reverse (*R*), its inclusion in the product creates a great deal of dissatisfaction. Moreover, if a feature is classified as Questionable (*Q*), then it is an unreliable feature. This means that if a feature is "*I* or not *R* or not *Q*," it "could be included" in the product. This yields the following formulation:

$$\begin{aligned} &Fi\ could\ be\ included \rightarrow (F_i\ is\ I) \vee (F_i\ is\ \neg R) \vee (F_i\ is\ \neg Q) \\ &TV(Fi\ could\ be\ included) = \max(TV(Fi,I), 1-TV(Fi,R), 1-TV(Fi,Q)) \end{aligned} \tag{3.3}$$

Table 3.11 shows an example of truth value determination process of the status of product features defined in equations (3.1-3). The relative frequencies of Kano evaluation found after performing Monte Carlo simulation (Section 3.3) are used to determine the *TV* of Kano evaluation, *A*, *O*, *M*, *I*, *R*, and *Q*. Afterward, the *TV* of the status of the product features, namely, must be include, should be included, and could be included, are calculated using equations (3.1-3), respectively. It is observed that the relative frequency of Kano evaluation depends on both the simulation instance and the case of linguistic likelihoods. The example shown in Table 3.11 refers to a simulation instance. The simulated relative frequencies are quite different (compare the relative frequencies of Cases 1-3) but the truth values (calculated from the linguistic counterparts as explained in Section 3.4) are quite similar (not exactly the same (compare the truth values of status of Cases 1-3)). This is not only true for the case shown in Table 3.11 but also for other simulation instances.

Table 3.11. An example of product feature status truth value determination.

Case 1							
Kano evaluation	*A*	*O*	*M*	*I*	*R*	*Q*	Remarks
fr	0.11	0.2	0.23	0.2	0.17	0.09	After simulation
TV	0.133	0.3	0.3	0.3	0.133	0.133	
Status	must be included		should be included		could be included		
TV	0.3		0.133		0.867		
Case 2							
Kano evaluation	*A*	*O*	*M*	*I*	*R*	*Q*	
fr	0.15	0.21	0.22	0.2	0.19	0.03	After simulation
TV	0.133	0.3	0.3	0.3	0.133	0.033	
Status	must be included		should be included		could be included		
TV	0.3		0.133		0.967		
Case 3							
Kano evaluation	*A*	*O*	*M*	*I*	*R*	*Q*	
fr	0.16	0.2	0.22	0.2	0.17	0.05	After Simulation
TV	0.133	0.3	0.3	0.3	0.133	0.133	
Status	must be included		should be included		could be included		
TV	0.3		0.133		0.867		

However, consider the relative frequencies of Kano evaluation corresponding to Case 1 in Table 3.11: $fr(A) = 0.11$, $fr(O) = 0.2$, $fr(M) = 0.23$, $fr(I) = 0.2$, $fr(R) = 0.17$, $fr(Q) = 0.09$. The linguistic counterpart of $fr(A) = 0.11$ is quite false (*qf*), $fr(O) = 0.2$ is perhaps false (*pf*), $fr(M) = 0.23$ is perhaps false (*pf*), $fr(I) = 0.2$ is perhaps false (*pf*), $fr(R) = 0.17$ is quite false (*qf*), and $fr(Q) = 0.09$ is quite false (*qf*). This is in accordance with the procedure explained in Section 3.3 and with the seven-fuzzy-number-based linguistic truth values defined in Chapter 2. Thus, the truth value of the proposition "Sedan is *A*" is equal to the expected value of *qf* (0.133), i.e., $TV(A) = 0.133$. Similarly, the propositions "Sedan is *R*," "Sedan is *Q*" also have the truth value 0.133, i.e., $TV(R) = 0.133$ and $TV(Q) = 0.133$. On the other hand, the propositions “Sedan is *O*,” “Sedan is *M*,” and Sedan is *I*” have the truth value 0.3 because 0.3 is the expected value of the linguistic truth values of these propositions, i.e., perhaps true (*pf*). This means that *TV*(*O*), *TV*(*M*), and *TV*(*I*) = 0.3. Thus, the truth value of the proposition “Sedan must be included in the product” is equal to max(*TV*(*O*),*TV*(*M*)) = max(0.3,0.3) = 0.3. The truth value of the proposition “Sedan should be included in the product” is equal to *TV*(*A*) = 0.13. The truth value of the proposition “Sedan could be included in the product” is equal to max(*TV*(*I*),1-*TV*(*R*),1-*TV*(*Q*)) = max(0.3,1-0.133,1-0.133) = 0.867.

3.6. Determination of information content of product feature status

This section describes the information content determination process of product feature status. The information content means here the two-dimensional information content wherein one of the dimensions is the Certainty Entropy (*CE*) and the other dimension is the Requirement Entropy (*RE*). Note that *CE* and *RE* have already been defined in Section 2.5 (equations 2.11.1-3). *CE* measures the variability in the truth values of a feature and *RE* measures the degree of fulfillment of requirement given by P_R. For this particular case, P_R = "The feature is a must be included feature," or "The feature is a should be included feature," or "The feature is a could be included feature." For an example, consider the truth values of the status of the product feature shown in Table 3.11. For the sake of better understanding these truth values are organized in Table 3.12. Table 3.12 also lists the calculated *CE* and *RE* based on these truth values and also on the P_R. The P_R in Table 3.12 is *The feature is a must be included feature* for all three cases. Case 1 and Case 3 underlie the same amount of information content (*CE*,*RE*) = (0.377,0.722), whereas the information content underlying the Case 2 is (*CE*,*RE*) = (0.311,0.8). The value of *CE* = 0.377 means that there is great deal of consensus among the respondents. The degree of consensus is comparatively much higher for Case 2 because for Case 2 *CE* has reduced to 0.311 (less than that of Case 1 and Case 3). One the other hand *RE* is quite high for all three cases. This means that the requirement "the feature is a must be feature" has hardly been fulfilled. This means that if one considers this feature a must be feature, it might create problem in fulfilling this expectation. However, if one resets the requirement to "the feature is a could be feature," then *RE* = 0. This also means that the feature is a could be feature rather than a must be or should be feature.

Table 3.12. An example of information content determination process

Case 1			
Status	must be included	should be included	could be included
TV	0.3	0.133	0.867
Ic	0.6	0.266	0.266
CE	0.377		
P_R	*The feature is a must be included feature*		
RE	0.722		
Case 2			
Status	must be included	should be included	could be included
TV	0.3	0.133	0.967
Ic	0.6	0.266	0.067
CE	0.311		
P_R	*The feature is a must be included feature*		
RE	0.8		
Case 3			
Status	must be included	should be included	could be included
TV	0.3	0.133	0.867
Ic	0.6	0.266	0.266
CE	0.377		
P_R	*The feature is a must be included feature*		
RE	0.722		

3.7. Determination of coherency measures of product feature status

This section describes the coherency measure of product feature status. As explained in the previous sections, the values of truth values product feature status might change due to the result of simulation. As such, the information contents (*CE*,*RE*) might also vary with the simulation instance. Therefore, the variability in the information content (*CE*,*RE*) should play a role in the customer needs assessment process. As explained in Section 2.5 (see equation (2.11.4) and Fig. 2.10) a quantity called coherency measure (λ) measures the variability in (*CE*,*RE*) for a given feature and requirement.

Figure 3.4 shows the variability in (*CE*,*RE*) for the product feature called SUV for all cases, Cases 1-3. The information content is high for should be and must be included and low for could be included.

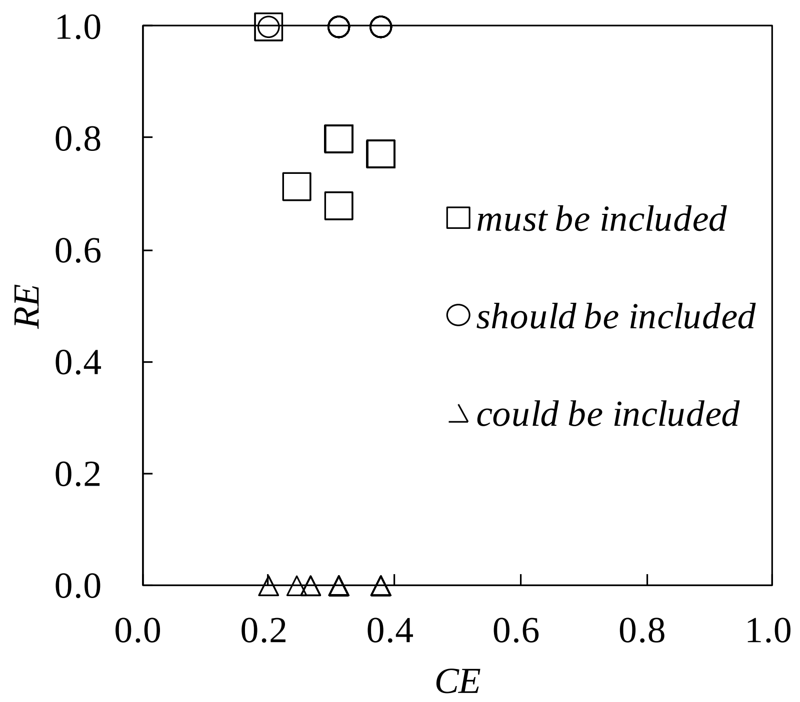

Figure 3.4. Variability in the information content of SUV.

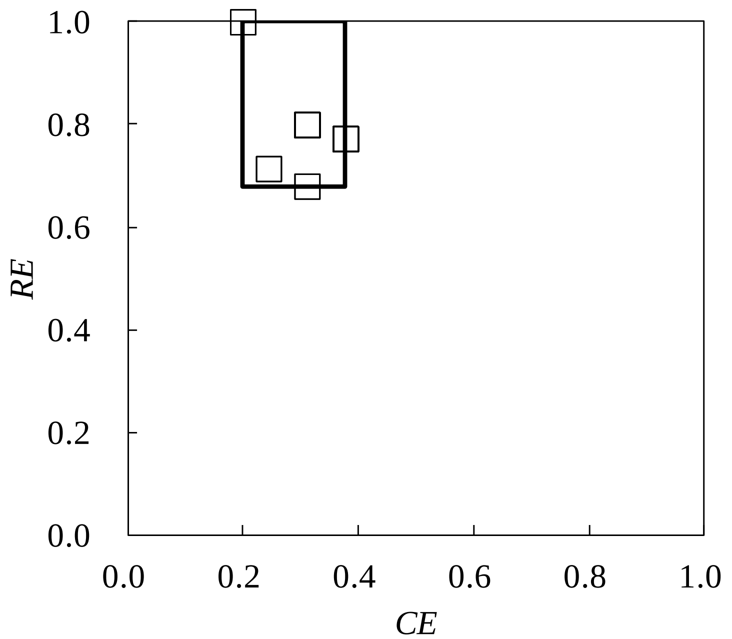

Figure 3.5. Determining the coherency measure of SUV for the status called "must be included."

Based on the data shown in Fig. 3.4, the coherency measure of SUV for three requirements can be calculated separately. For example, consider the requirement

"SUV is a must be included feature." The variability in the information content for this requirement is shown in Fig. 3.5, which is the segment of data points already shown in Fig. 3.4 corresponding to must be included. The value of coherency measure λ is equal to 2.313 because e = 0.199, f = 0.377, g = 0.68, h = 1 (see equation (2.11.4) and Fig. 2.10). Similarly, the values of coherency measure of SUV for should be included and could be included have been found to be 2.577 and 0.577, respectively.

However, Figs. 3.6-7 show the variability in (*CE*,*RE*) for the other two product features called Sedan and Van for all cases, Cases 1-3. Similar to the case shown in Fig. 3.4, the information content is high for should be and must be included and low for could be included for both cases in Figs. 3.6-7. Based on the data points shown in Figs. 3.4,6-7, the value of the coherency measure has been determined using the procedure illustrated in Fig. 3.5. The values are listed in Table 3.13. Note that Sedan exhibits high values of coherency measure compared to those of SUV and Van. This means that SUVs and Vans might be good options to replace Sedans.

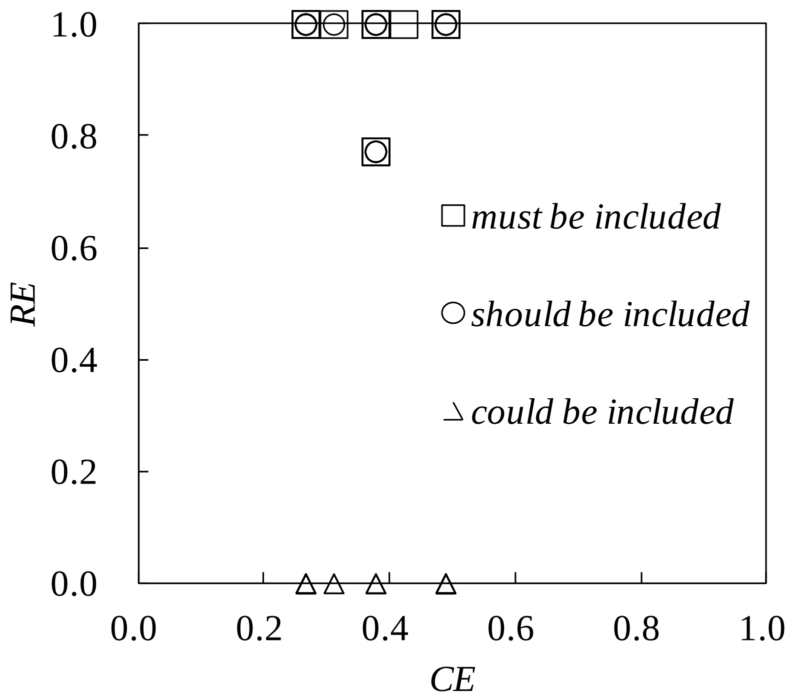

Figure 3.6. Variability in the information content of Sedan.

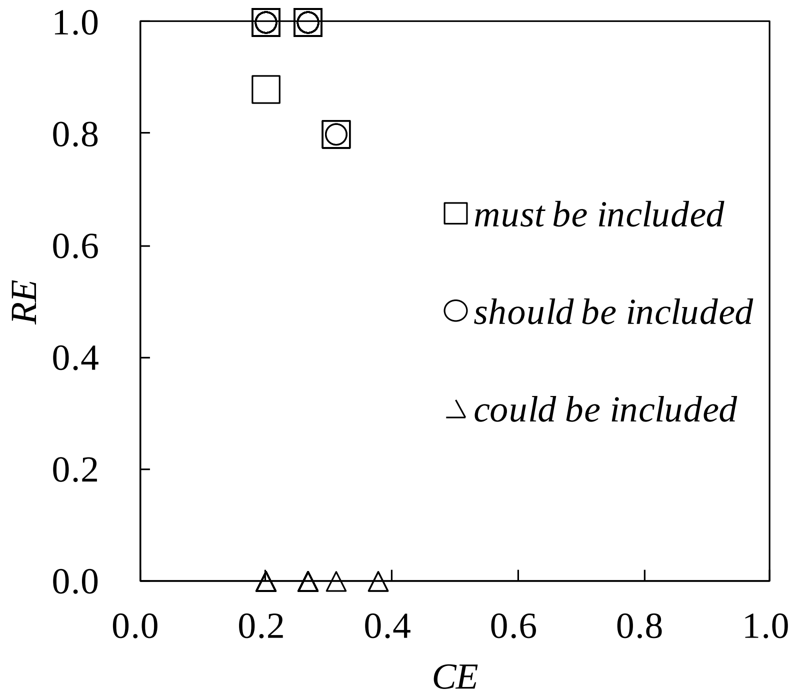

Figure 3.7. Variability in the information content of Van.

Table 3.13. Coherency measure of product features.

Features	Status		
	must be included	should be included	could be included
SUV	2.314	2.577	0.577
Sedan	2.578	2.578	0.755
Van	2.332	2.332	0.577

3.8. Making final decision

This section describes process of how to making a final decision (customer needs assessment). In this case, the customer needs assessment means to identify the level of satisfaction of SUV, Sedan, and Van based on the value of the respective coherency measure (overall information content). Note that a low value of coherency measure is desirable. Section 2.5 describes the details of the implication of coherency measure.

However, recall the situation in Bangladesh. Sedan is the most frequently used vehicles in Bangladesh. This type of vehicle is not that much suitable for the users in Bangladesh because of the road condition, average size of a family, and life-style (travelling in a large group). Thus, all Sedan, SUV, and Vans could be suitable for but it would be difficult to conclude precisely that they are must/should be the vehicle for users in Bangladesh. At least it can be said that increase in the number of SUV and Van compared to that of Sedan might lead to an enhancement in the customer satisfaction.

Whether or not the above conclusion holds if a decision is made based on the values of coherency measure is an important issue to investigate. As such, the values of the coherency measure are plotted separately for each requirement. Figure 3.8 shows the value of coherency measure when the requirement refers to "could be included" for Sedan, SUV, and Van. Needless to say that the values correspond to the values listed in Table 3.13. As seen from Fig. 3.8, if SUV and Van are introduced side by side Sedan in a large volume in Bangladesh, the level of satisfaction of vehicle users "could" increase. In this case, SUV and Van are indifferent.

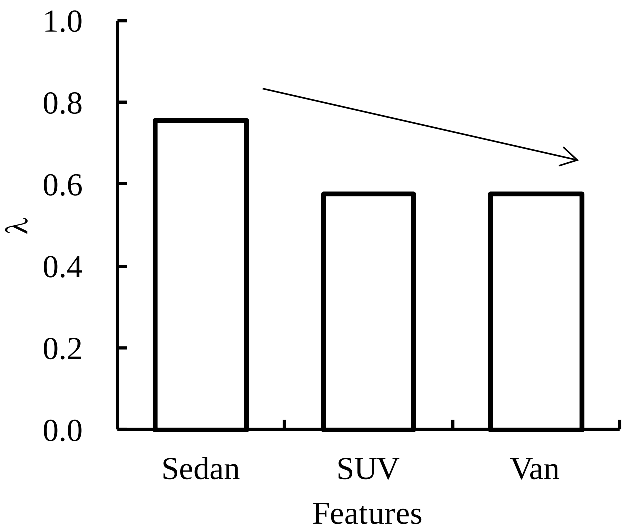

Figure 3.8. Reduction in overall information content for could be included.

Figure 3.9 shows the value of coherency measure when the requirement refers to "should be included" for Sedan, SUV, and Van. Needless to say that the values correspond to the values listed in Table 3.13. As seen from Fig. 3.9, if Van is introduced side by side Sedan in a large volume in Bangladesh, the level of satisfaction of vehicle users "should" increase. This time, SUV does not increase the level of satisfaction compared to that of Sedan. This decision however, underlies a great deal of uncertainty (a large value of coherency measure).

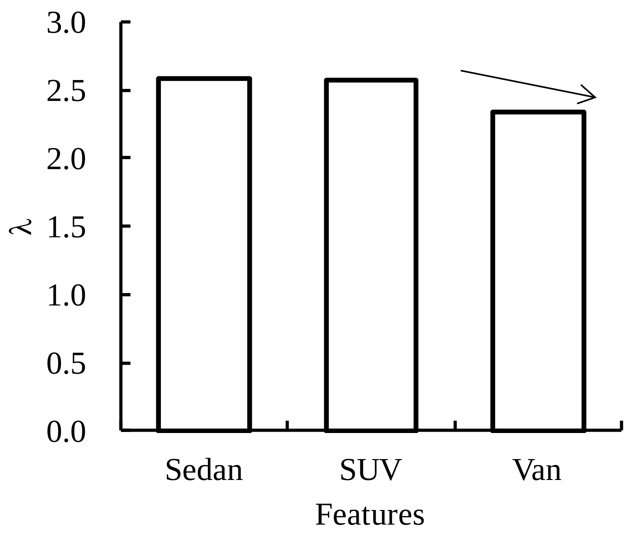

Figure 3.9. Reduction in overall information content for should be included.

Figure 3.10 shows the value of coherency measure when the requirement refers to "must be included" for Sedan, SUV, and Van. Needless to say that the values correspond to the values listed in Table 3.13. As seen from Fig. 3.10, if SUV and Van are introduced side by side Sedan in a large volume in Bangladesh, the level of satisfaction of vehicle users "must" increase. The trend seen here similar to that of could be included (Fig. 3.8). This time a great deal of uncertainty (a large value of coherency measure) is associated with the decision.

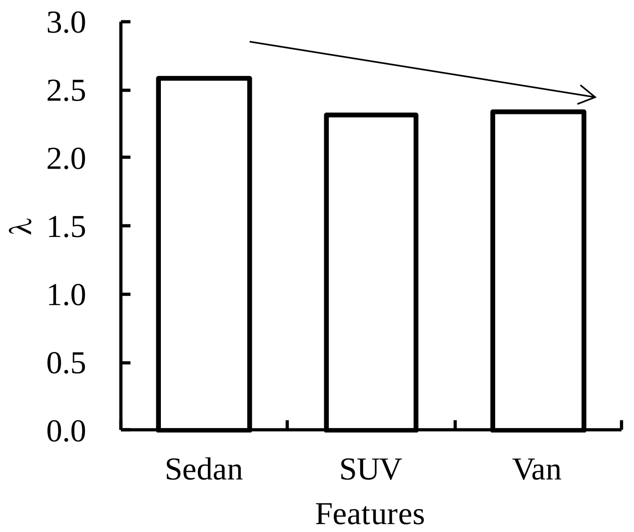

Figure 3.10. Reduction in overall information content for must be included.

In synopsis, the following statements can be made:

- ✧ Injecting more and more SUV and Van into the market could increase the level of satisfaction of car users in Bangladesh (Fig. 3.8).
- ✧ SUV and Van are not that much unexpected surprises to the car users in Bangladesh (Fig. 3.9)
- ✧ SUV and Van must increase the level of satisfaction of car users in Bangladesh but this conclusion possesses a great deal of uncertainty (Fig. 3.10).

Similar to the case of car types (Sedan, SUV, Van), other features in Table 3.3 can be studied and similar conclusions can be made. This way, customer needs assessment can be carried out and the key solutions to develop the product can be determined in the conceptual phase of product development.

Chapter 4
Sustainability Assessment

This chapter deals with the sustainability assessment of key solutions in conceptual phase of product development. This chapter is based on work of Rashid et al. 2011. In this chapter, a product means a grinding wheel, i.e., a cutting tool used to remove hard materials and also to finish surfaces of precision parts.

For the sake of better understanding, recall Fig. 1.1 as repeated in Fig. 4.1.

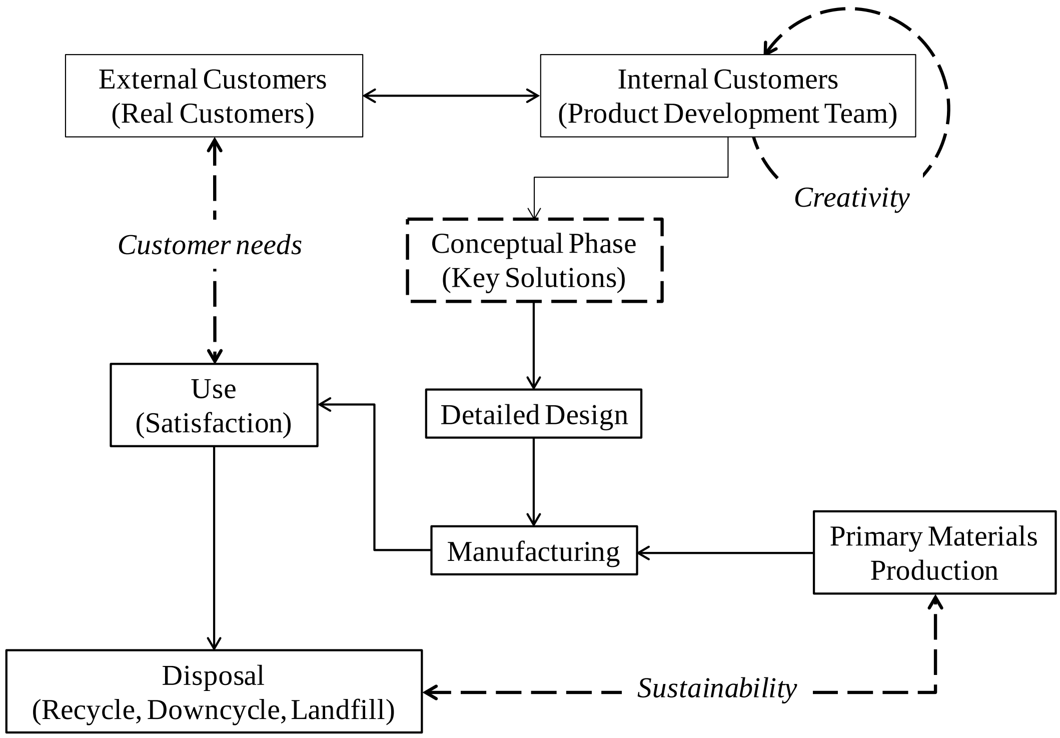

Figure 4.1. A product development scenario (Fig. 1.1 repeated).

As mentioned in Chapter 1, sustainability has become an important issue of product development (Fiksel 2009) that refer to the fact that the product is environmentally benign on top of other desired performances. One should incorporate so-called Life-Cycle Assessment (LCA) into the product development processes to ensure the sustainability (Donnelly et al. 2004, Kobayashi, 2006). In addition to conventional sustainability assessment (i.e., LCA), it is important to do scenario analysis (Umeda 2009, Fukushige et al. 2012) taking a broader perspective into the consideration. However, one of the remarkable finding underlying scenario-analysis-based sustainability assessment is that the primary production of materials used in the product plays a critical role to ensure the sustainability (Higuchi et al. 2012). This implies the following question:

How to deal with the sustainability of materials (used in the product) in the key solution determination process in the conceptual phase of product development?

This section provides an answer to this question by taking the example of a grinding wheel. This means that the grinding wheel is the product here and sustainability factors of the primary material production of the materials used in manufacturing a grinding wheel are the important decision-relevant information. This also means that the possible type of materials used to manufacture a grinding wheel is the key solutions. The remainder of this chapter is as follows:

Section 4.1 describes the information relevant to the sustainability of primary material production of the materials used to manufacture a grinding wheel. Section 4.2 describes the fuzzy numbers used to formally compute the uncertainty/imprecision associated with decision-relevant information. Section 4.3 describes the results and discusses the implication of the results.

4.1. Decision-relevant information

In general, very hard materials based on technical ceramics are used to produce the abrasive grains of a grinding wheel. The abrasive grains actually provide the main cutting action, i.e., they are the main ingredients of a grinding wheel. There are many hard materials (Ullah et al. 2011), e.g., price, annual production, density, energy consumption for primary production of bulk material, energy for processing (powder formation, bulk deformation, etc.) materials, CO_2 footprint for primary production and processing, NO_X emission of primary production, SO_X emission of primary production, water usage of primary production, recycle fraction, CO_2 emission and energy for recycling, and alike. Obtaining reliable data on these sustainability attributes is not an easy task. In most cases, an estimation is given in the form of a numerical range on an eco-attribute compiling data/information from many sources. Some of the sustainability attributes do not have any information (e.g., recycle fraction, gel formation, etc.).

However, more than 320 types of technical ceramics based hard materials available in the database of a material evaluation system called CES Selector™ (version 5.1.0) developed by the Granta Design Limited have been studied (reference [1]). The maximum and minimum ranges of each sustainability attribute (in particular, CO_2 footprint (or emission), NO_X emission, SO_X emission, and water usage of primary production) for five different classes of hard material, namely, Alumina (AN), Silica (SC), Boron Nitride (BN), Boron Carbide (BC), and Zirconia (ZN) are identified. The variants of AN, SC, BN, BC, and ZN not used for producing abrasive grains are excluded from this study. Figure 4.2 shows the variability in CO_2 footprint (kg-CO_2/kg-material) and water usage (l-water/kg-material) of AN, SC, BN, BC, and ZN. As seen from Fig. 4.2, the information of CO_2 footprint underlies low uncertainty/impression whereas water usage exhibit a relatively high uncertainty/imprecision.

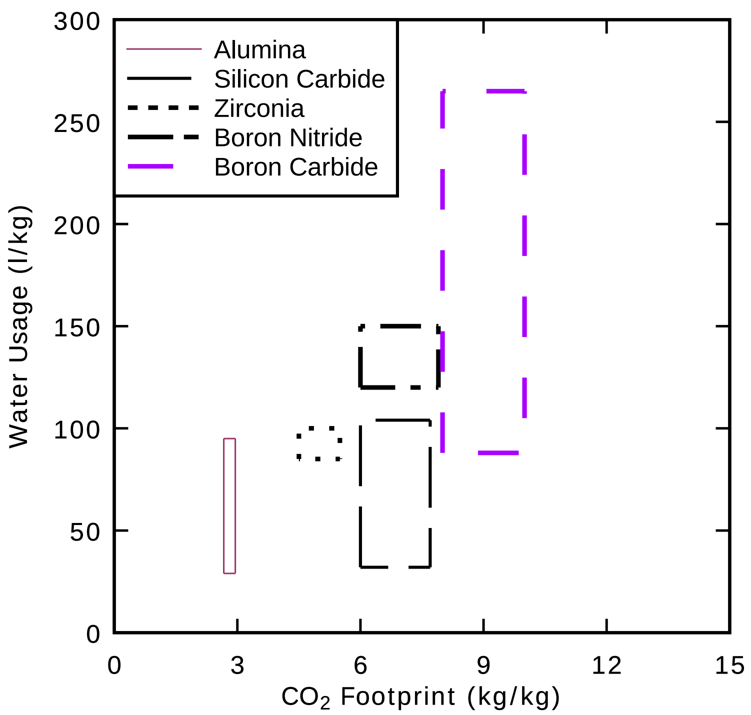

Figure 4.2. CO_2 footprint and water usage of some selected hard materials.

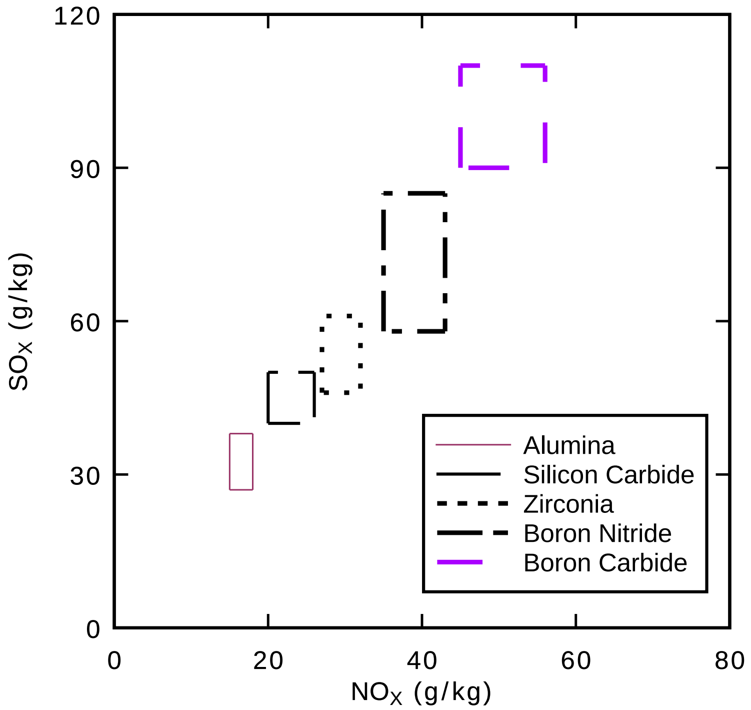

Figure 4.3. NO_X/SO_X emissions of some selected hard materials.

Figure 4.3 shows the variability in NO_X and SO_X emissions (g-NO_X or SO_X/kg-material) of the primary production of AN, SC, BN, BC, and ZN. As seen from Fig. 4.3, the variability in the information increases with the increase in NO_X or SO_X emission. This means that underlying uncertainty/impression increases with the increase in the emission of NO_X or SO_X.

4.2. Computational framework

To deal with the uncertainty/imprecision associated with the parameters described above computational framework based on "range compliance" is proposed here. Range compliance has already been explained in Section 2.2 (equation (2.5). Range compliance is an operation on a fuzzy number using a numerical range. In particular, range compliance $R(L,A)$ of a numerical range L is its average membership value with respect to a fuzzy number A. The expression of $R(L,A)$ is as follows:

$$R(L,A) = \frac{\int_L \mu_A(x)dx}{|L'|} \quad (L' \subseteq L) \wedge (L' \subseteq Supp(A)) \qquad (4.1)$$

In equation (4.1), L' is the segment of L that belongs to $Supp(A)$. Note that the equation (4.1) is the repetition of equation (2.5).

However, to be more specific consider the following objects. Let G be a member of the set of materials {AN, SC, BN, BC, ZN}, i.e., $G \in$ {AN, SC, BN, BC, ZN}. Let S be a member of the set of sustainability parameters {CO_2 footprint, water usage, NO_X emission, SO_X emission}, i.e., $S \in$ {CO_2 footprint, water usage, NO_X emission, SO_X emission}. Let F_S be a member of the set of fuzzy numbers {VL_S, L_S, M_S, H_S, VH_S}. Here, VL refers to very low, L refers to low, M refers to moderate, H refers to high, and VH refers to very high. The subscript "S" means that the sustainability parameter is S. Let X_S be a point on the real line, $X_S \in \Re$. The interval $[0, X_S]$ is the universe of discourse of a fuzzy set F_S. The membership functions of the fuzzy numbers VL_S, L_S, M_S, H_S, and VH_S (in general F_S) can thus be defined as follows:

$$\mu_{VL_S}(x_S) = max\left(0, min\left(1, \frac{0.3X_S - x_S}{0.3X_S - 0}\right)\right) \quad (4.2)$$

$$\mu_{L_S}(x_S) = max\left(0, min\left(\frac{x_S - 0.1X_S}{0.3X_S - 0.1X_S}, \frac{0.5X_S - x_S}{0.5X_S - 0.3X_S}\right)\right) \quad (4.3)$$

$$\mu_{M_S}(x_S) = max\left(0, min\left(\frac{x_S - 0.3X_S}{0.5X_S - 0.3X_S}, \frac{0.7X_S - x_S}{0.7X_S - 0.5X_S}\right)\right) \quad (4.4)$$

$$\mu_{H_S}(x_S) = max\left(0, min\left(\frac{x_S - 0.5X_S}{0.7X_S - 0.5X_S}, \frac{0.7X_S - x_S}{0.9X_S - 0.9X_S}\right)\right) \quad (4.5)$$

$$\mu_{VH_S}(x_S) = max\left(0, min\left(1, \frac{x_S - 0.7X_S}{X_S - 0.7X_S}\right)\right) \quad (4.6)$$

Figures 4.2-3 provide an estimation of X_S. As seen from Figs. 4.2-3, X_S could be a point in the interval [12,15] if S = CO_2 footprint, X_S could be a point in the interval [280,300] if S = water usage, X_S could be a point in the interval [70,80] if S = NO_X emission, and X_S could be a point in the interval [110,120] if S = SO_X emission. Figure 4.4 illustrates the membership functions for S = CO_2 footprint and X_S = 15. At the core L_S, M_S, or H_S (a point corresponding to unit membership value) the membership values of other fuzzy numbers are equal to zero. This nature of remains the same for all fuzzy numbers irrespective of the state of S and the value of X_S because of the definitions in equations (4.2-6).

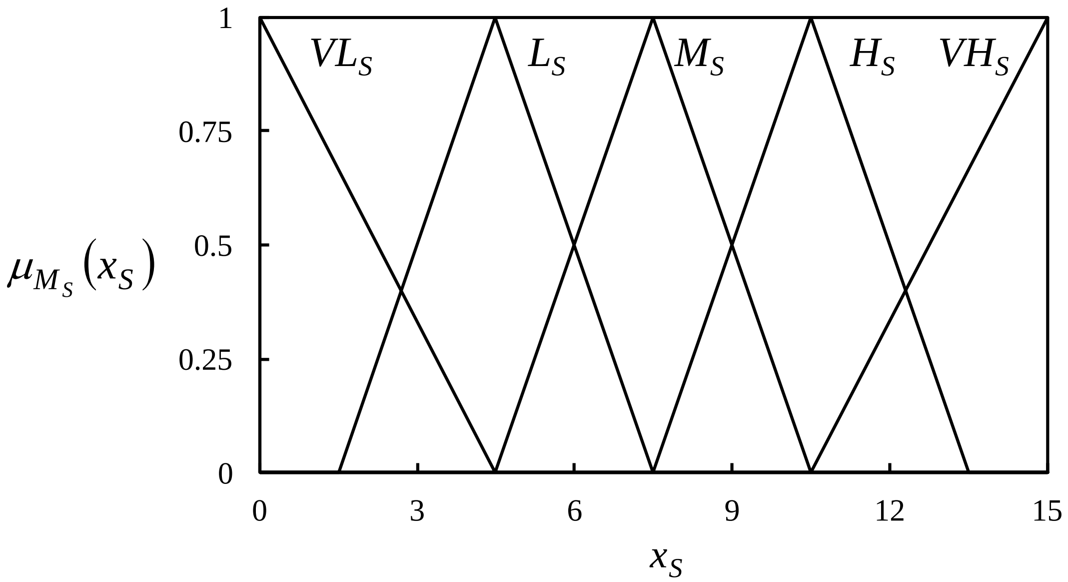

Figure 4.4. Membership functions when S = CO_2 footprint and X_S = 15.

Let $L_S(G)$ is the range of sustainability parameter S for a material G. One can calculate the range compliance $R(L_S(G), F_S)$ with respect to F_S, as follows:

$$R(L_S(G),F_S)=\frac{\int_{L_S(G)}\mu_{F_S}(x_S)dx_S}{|L'_S(G)|}\quad (L'_S(G)\subseteq L_S(G))\wedge(L'_S(G)\subseteq Supp(F_S)) \tag{4.7}$$

In equation (4.7), $L'_S(G)$ is the largest segment of $L_S(G)$ that belongs to the support of F_S, $Supp(F_S)$.

For example, if S = CO_2 footprint, G = SC, the $L_S(G)$ = [6,7.8] (see Fig. 4.2). This yields the following range compliances: $R(L_S(G),F_S)$ = 0 for F_S = VL_S, $R(L_S(G),F_S)$ = 0.25 for F_S = L_S, $R(L_S(G),F_S)$ = 0.783 for F_S = M_S, $R(L_S(G),F_S)$ = 0.05 for F_S = H_S, $R(L_S(G),F_S)$ = 0 for F_S = VH_S.

To achieve a better sustainability all CO_2 footprint, NO_X emission, SO_X emission, and water usage should be minimized. This means that the material that complies more with VL_S or L_S is good material and the material that complies more with M_S, H_S, or VH_S is not-so-good material. Based on this contemplation two indices can be derived called *Desirable Impact* ($DI_S(G)$) and *Undesirable Impact* ($UI_S(G)$), as follows:

$$DI_S(G)=R(L_S(G),VL_S)+R(L_S(G),L_S) \tag{4.8}$$

$$UI_S(G)=R(L_S(G),M_S)+R(L_S(G),H_S)+R(L_S(G),VH_S) \tag{4.9}$$

The above formulation provides an two-dimensional decision space, wherein a sustainable material *G* means its $DI_S(G)$ is high and $UI_S(G)$ is low with respect to all *S*s. This decision space is schematically illustrated in Fig. 4.5.

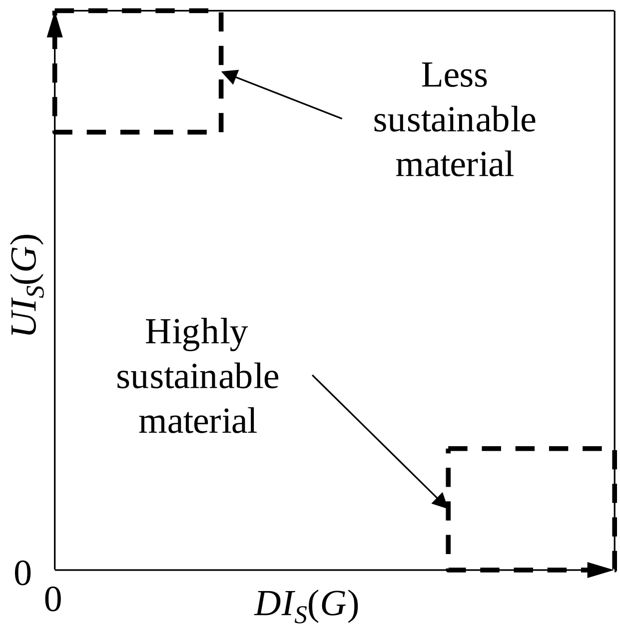

Figure 4.5. Decision space for sustainability assessment.

4.3. Results

This section describes the results obtained by using the framework described in the previous section. The range compliance $R(L_S(G),F_S)$ has been calculated for all materials and sustainability parameters for two different cases Case 1 and Case 2. These cases are listed in Table 4.1. Needless to say that the values of X_S in Table 4.1 define the universe of discourses of the fuzzy numbers defined in equations (4.2-6).

Table 4.1 Cases of setting the universe of discourse

Case	X_S			
	CO_2 footprint	water usage	NO_X emission	SO_X emission
1	15	300	80	120
2	12	280	70	110

The values of X_S listed in Table 4.1 underlies the observation mentioned before, i.e., X_S could be a point in the interval [12,15] if S = CO_2 footprint, X_S could be a point in the interval [280,300] if S = water usage, X_S could be a point in the interval [70,80] if S = NO_X emission, and X_S could be a point in the interval [110,120] if S = SO_X emission. In particular the maximum and minimum values are considered to see the sensitivity.

Table 4.2 shows the range compliances of AN, $R(L_S(\text{AN}),F_S)$. Figure 4.6 shows the position of AN in the two-dimensional decision space, wherein the data points $(DI_S(\text{AN}),UI_S(\text{AN}))$ have been calculated using the data points listed in Table 4.2.

Table 4.2. Range compliances of AN.

S	Case	F_S				
		VL_S	L_S	M_S	H_S	VH_S
CO_2 footprint	1	0.344	0.483	0	0	0
	2	0.181	0.729	0	0	0
water usage	1	0.333	0.5	0	0	0
	2	0.321	0.736	0.05	0	0
NO_X emission	1	0.315	0.531	0	0	0
	2	0.214	0.678	0	0	0
SO_X emission	1	0.152	0.87	0.083	0	0
	2	0.121	0.835	0.159	0	0

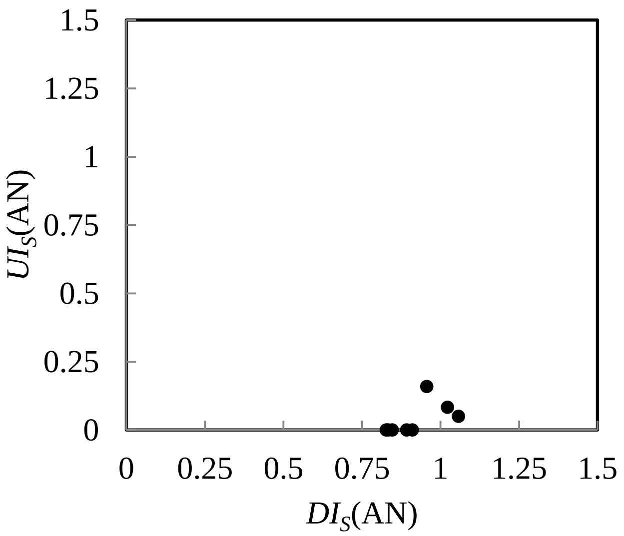

Figure 4.6. Sustainability of AN.

As seen from Fig. 4.6, the undesirable impact is very low and the desirable impact is very high for AN for all four sustainability parameters. Therefore, AN is a good material from the view point of sustainability and one should use this material to manufacture a grinding wheel unless there are other problems.

Table 4.3 shows the range compliances of SC, $R(L_S(\text{SC}),F_S)$. Figure 4.7 shows the position of SC in the two-dimensional decision space, wherein the data points (DI_S(SC),UI_S(SC)) have been calculated using the data points listed in Table 4.3.

Table 4.3. Range compliances of SC.

S	Case	F_S				
		VL_S	L_S	M_S	H_S	VH_S
CO_2 footprint	1	0	0.25	0.783	0.05	0
	2	0	0	0.625	0.375	0
water usage	1	0	0.25	0.75	0	0
	2	0	0.178	0.851	0.08	0
NO_X emission	1	0.104	0.938	0.031	0	0
	2	0.048	0.866	0.143	0	0
SO_X emission	1	0	0.625	0.375	0	0
	2	0	0.625	0.375	0	0

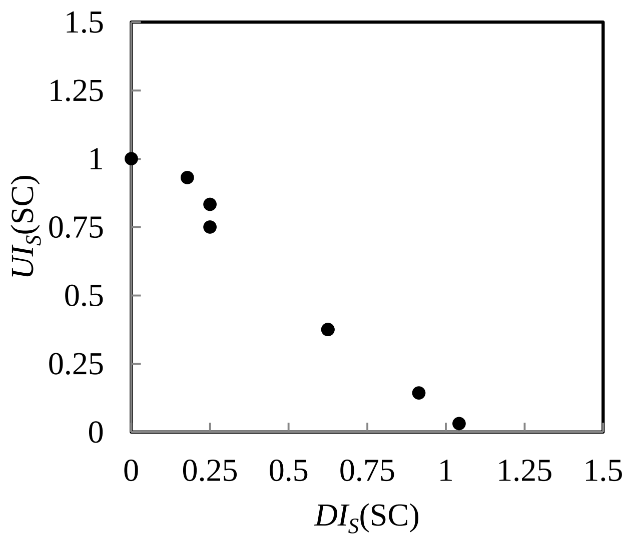

Figure 4.7. Sustainability of SC.

As seen from Fig. 4.7, the undesirable impact is high and the desirable impact is low for SC for all most of the sustainability parameters. For some parameters, the scenario is the opposite one. Therefore, SC is perhaps a not-so-good material from the view point of sustainability and one should avoid using this material for manufacturing grinding wheel unless there are other problems.

Table 4.4 shows the range compliances of SC, $R(L_S(\text{BN}),F_S)$. Figure 4.8 shows the position of BN in the two-dimensional decision space, wherein the data points $(DI_S(\text{BN}),UI_S(\text{BN}))$ have been calculated using the data points listed in Table 4.4.

Table 4.4. Range compliances of BN.

S	Case	F_S				
		VL_S	L_S	M_S	H_S	VH_S
CO_2 footprint	1	0	0.25	0.789	0.06	0
	2	0	0	0.604	0.396	0
water usage	1	0	0.208	0.791	0	0
	2	0	0.134	0.883	0.08	0
NO_X emission	1	0	0.186	0.84	0.046	0
	2	0	0.036	0.794	0.232	0
SO_X emission	1	0	0.042	0.535	0.559	0.05
	2	0	0	0.432	0.635	0.167

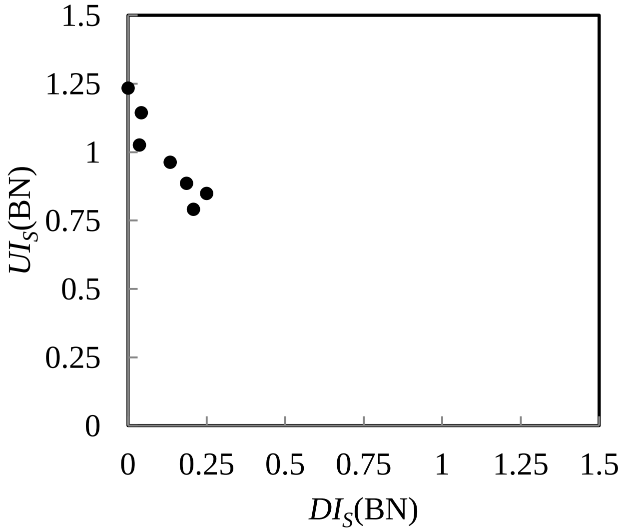

Figure 4.8. Sustainability of BN.

As seen from Fig. 4.8, the undesirable impact is very high and the desirable impact is very low for BN for all sustainability parameters. Therefore, BN is a not-so-good material from the view point of sustainability and one should avoid using this material for manufacturing grinding wheel unless there are other problems.

Table 4.5 shows the range compliances of BC, $R(L_S(\text{BC}),F_S)$. Figure 4.9 shows the position of BC in the two-dimensional decision space, wherein the data points

(DI_S(BC),UI_S(BC)) have been calculated using the data points listed in Table 4.5.

Table 4.5. Range compliances of BC.

S	Case	F_S				
		VL_S	L_S	M_S	H_S	VH_S
CO_2 footprint	1	0	0	0.533	0.467	0
	2	0	0	0.104	0.739	0.208
water usage	1	0.027	0.535	0.5	0.537	0.277
	2	0	0.491	0.504	0.5	0.381
NO_X emission	1	0	0	0.468	0.531	0
	2	0	0	0.25	0.766	0.143
SO_X emission	1	0	0	0	0.375	0.444
	2	0	0	0	0.206	0.697

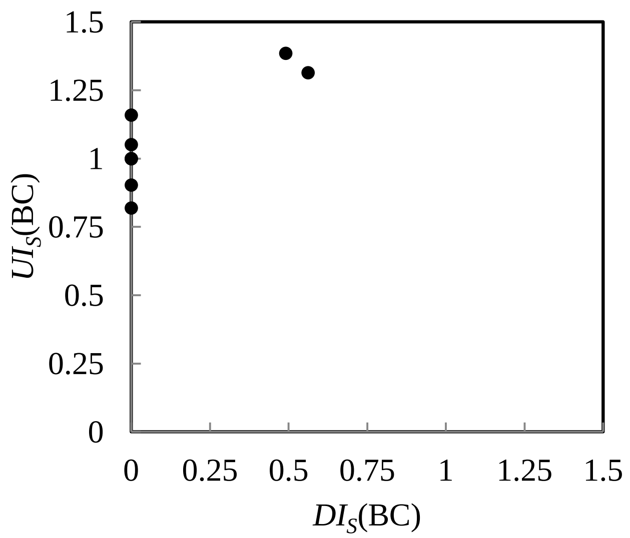

Figure 4.9. Sustainability of BC.

For BC, all sustainability parameters, except water usage, provide zero desirable impact, as seen from Fig. 4.9. The undesirable impact for all parameters are also very high. Therefore, similar to BN, BC is also an less preferable material to manufacture a grinding wheel. Thus, BC should also be avoided for manufacturing a grinding wheel unless there are other problems.

Table 4.6 shows the range compliances of ZN, $R(L_S(\text{ZN}),F_S)$. Figure 4.10 shows the position of ZN in the two-dimensional decision space, wherein the data points (DI_S(ZN),UI_S(ZN)) have been calculated using the data points listed in Table 4.6. The sustainability scenario of ZN is similar to that of SC (compare Fig. 4.10 with Fig. 4.7). Therefore, ZN is perhaps a not-so-good material from the view point of sustainability and one should avoid using this material for manufacturing grinding wheel unless there are other problems.

Table 4.5. Range compliances of ZN.

S	Case	F_S				
		VL_S	L_S	M_S	H_S	VH_S
CO_2 footprint	1	0	0.7	0.3	0	0
	2	0	0.25	0.75	0	0
water usage	1	0.027	0.919	0.083	0	0
	2	0	0.848	0.152	0	0
NO_X emission	1	0	0.75	0.25	0	0
	2	0	0.5	0.5	0	0
SO_X emission	1	0	0.27	0.756	0.041	0
	2	0	0.182	0.828	0.159	0

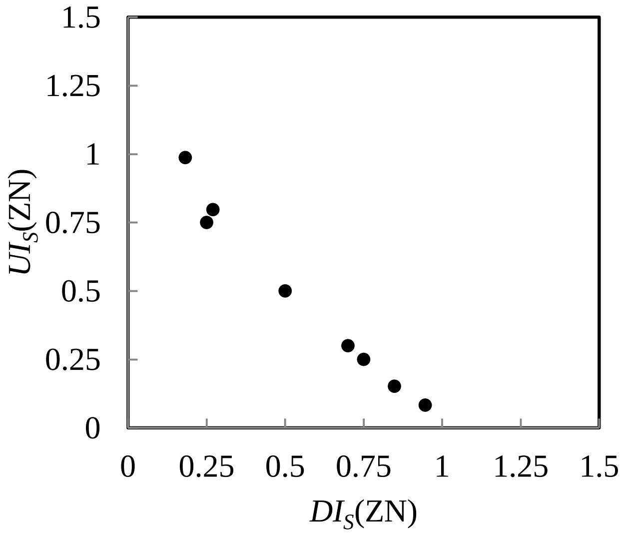

Figure 4.10. Sustainability of ZN.

Based on the findings described in the above, the following decision can be made, as shown in Table 4.7. As listed in Table 4.7, Alumina based hard materials are highly sustainable materials for manufacturing abrasive grains of a grinding wheel. Boron Nitride/Carbide based hard materials are less sustainable materials. Whereas, Zirconia/Silicon Carbide based materials are moderately sustainable materials for manufacturing abrasive grains of a grinding wheel. One may use this finding while developing more sustainable material removal tools (products) for precision engineering.

Table 4.7. Sustainability assessment of selected hard materials for abrasive grains of grinding wheel.

Categories	Materials
Highly sustainable materials	Alumina based hard materials
Moderately sustainable materials	Zirconia/Silicon Carbide based hard materials
Less sustainable material	Boron Nitride/Carbide based hard materials

Chapter 5

Creativity Assessment

This chapter deals with the assessment of creativity in key solutions determination process in the conceptual phase of product development. This chapter is based on the work of Ullah et al. 2012. For the sake of better understanding, recall Fig. 1.1 as repeated in Fig. 5.1.

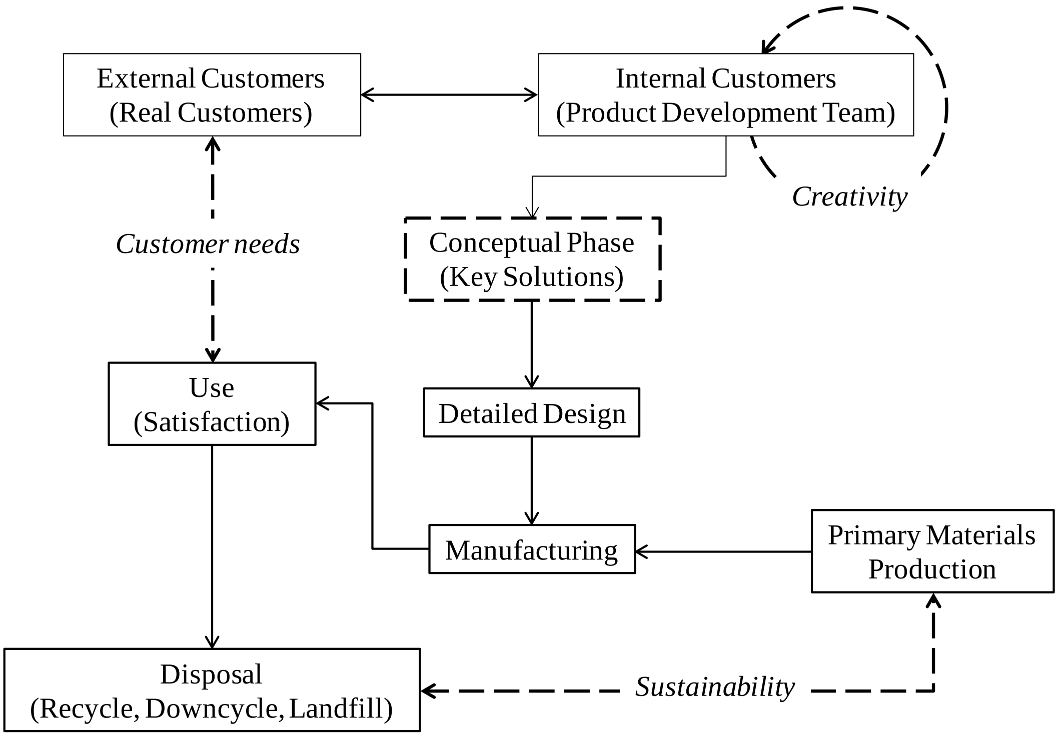

Fig. 5.1. A product development scenario (Fig. 1.1 repeated).

In the conceptual phase of product development the internal customers (product development team members) need to be creative so that a great deal of useful The internal customers need to be creative to suggest many potential key solutions for satisfying the needs of external customers (real customers). Therefore, the following question arise in the conceptual phase of product development:

How to differentiate a creative key solution from a non-creative key solution?

Creativity is a complex and multifaceted phenomenon (Puccio et al. 2010). In the industry in particular, lateral thinking (de Bono 1970) has been practiced to be creative. In addition, TRIZ (theory of innovative problem solving) (Altshuller 2001) has also been practiced to be creative (Puccio et al. 2010). However, to describe reasoning and processes of human creativity in product development, mappings of objects from one domain (or space) to another have been found effective. For example, consider the mappings i) among Functions (F), Behaviors (B), and Structures (S) introduced by Gero (Gero, 2000), ii) between Functional Requirements (FR) and Design Parameters (DP) introduced by Suh (Suh, 1998), and iii) between Concept (C) and Knowledge (K) introduced by Hatchuel and Weil (Hatchuel and Weil 2003, 2009). In particular, C-K theory (Hatchuel and Weil 2003, 2009) provides an clear definition of creative concept-- a creative concept is *undecided* entity with respect to the existing knowledge at the point of time when it (the concept) is conceived. Therefore, creation of new knowledge is associated with acceptance/rejection of a creative concept. Ullah et al. 2012 have shown that the processes involved in adopting a creative concept may not necessarily be an outcome of such logical processes as deduction, induction, and abduction (Yoshikawa 1981, Tomiyama et al. 2009, Ullah 2008, Zeng and Cheng 1991, Kazakci et al. 2005). Two different kinds of motivation called epistemic challenge and compelling reason are involved in adopting a creative concept and if one uses epistemic information content (CE,RE), as defined in Chapter 2 and used in Chapter 3, then one can easily differentiate a creative key solution from a non-creative key solution in the conceptual phase of product development. Based on this contemplation, this chapter is written. The remainder of this chapter is organized as follows: Section 5.1 describes the main elements of C-K theory. Section 5.2 explains the epistemic information contents for differentiating a creative key solution from a non-creative key solution. Section 5.3 describes the results and discusses the implication of the findings.

5.1. C-K theory

This section describes the main elements of C-K theory (Hatchuel and Weil 2003, 2009, Braha and Reich 2003, Kazakci et al. 2005, Ullah et al. 2012).

A schematic illustration of C-K theory is shown in Fig. 5.2. As seen from Fig. 5.2, there are two interdependent domains called Concept Domain and Knowledge Domain in C-K theory.

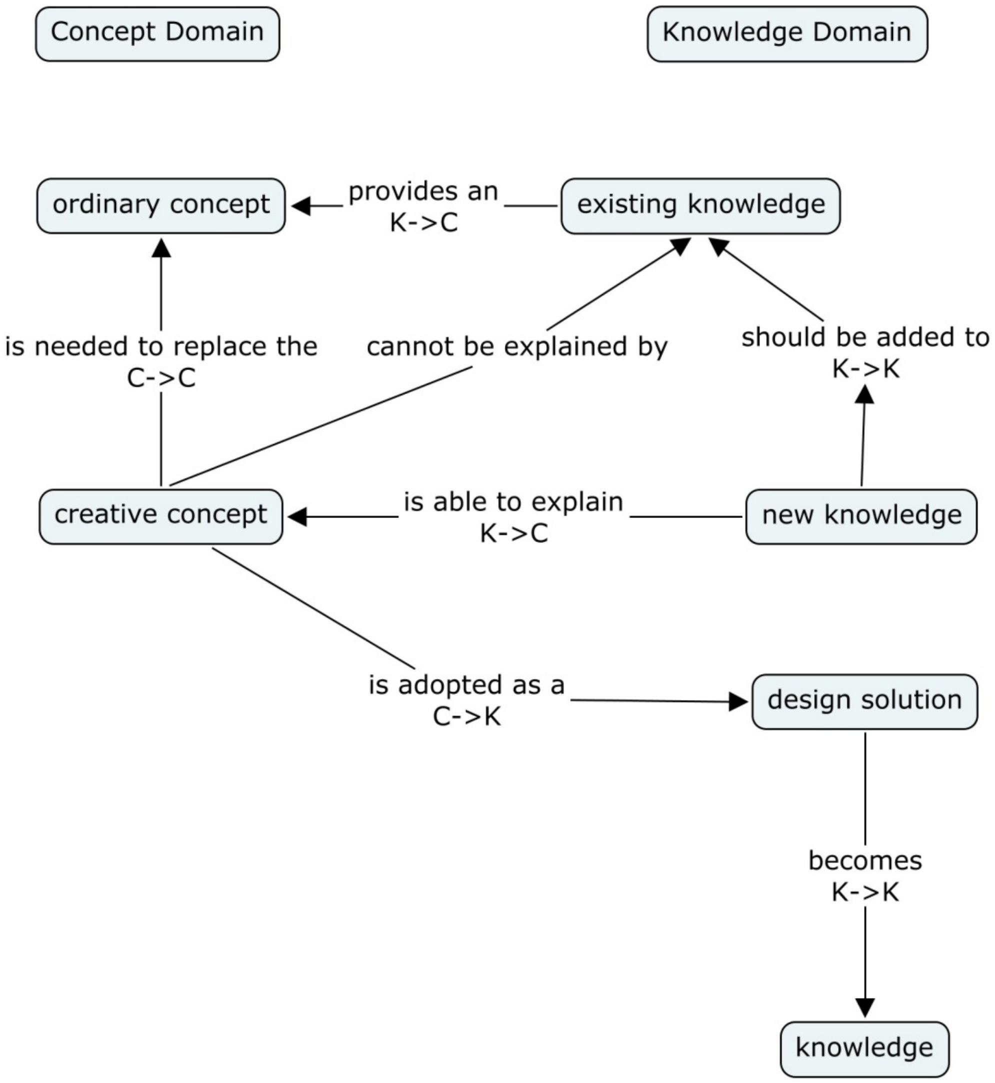

Figure 5.2. An illustration of C-K theory (Ullah et al. 2012).

In addition, there are mappings between C and K, i.e., C→K, K→C, C→C, and K→K. This mapping is somewhat different compared to those in other theories. For example, in Axiomatic Design (Suh, 1998) the mapping is allowed in a hierarchical manner: FR→DP→FR (new)→DP (new). The mapping FR to FR or DP to DP is not allowed in Axiomatic Design. However, one of the most remarkable features of C-K mapping is that it is able to deal with a creative concept—a concept that is undecided with respect to the existing knowledge at the point of time when it (the concept) is conceived. If such an undecided concept is pursued further, new knowledge might evolve in favor of the concept. As a result, both the knowledge evolved and the concept conceived become a part K Domain and C Domain, respectively. Thus, C-K mapping expands enriching both domains by the addition of undecided concepts and co-creation of new knowledge.

5.2. Differentiating creative and non-creative concepts

Let C1 be an existing concept (ordinary key solution) and C2 be an creative concept (creative key solution). Let K1 be the knowledge of suitableness of C1 and K2 be the knowledge of performance of C1. In addition, let K3 be the knowledge of suitableness of C2 and K4 be the knowledge of performance of C2.

One considers C2 because C1 is perhaps not suitable for the perceived need. This means that C1 should be replaced by C2 for the better fulfillment of the perceived need. This is called compelling reason. Thus, compelling reason acts as one of the motivations behind perusing C2 instead of C1 for a given need. One the other hand, at the beginning (when C2 is being conceived), K4 is empty (K4 = $\{\emptyset\}$), i.e., there is a lack of knowledge regarding the performance of C2. The performance of C2 is somewhat unknown when C2 is being conceived. This is called epistemic challenge. Thus, a challenge of seeking new knowledge emerges. Overcoming this challenge acts as the other motivation for pursing C2 instead of C1.

The motivations, compelling reason and epistemic challenge, can quantitatively be measured by the Certainty Entropy and Requirement Entropy (*CE*,*RE*). To do this, consider a set of propositions for C1 and C2.

First, consider the propositions regarding C1 (an ordinary or existing concept). The propositions regarding C1 (P11,...,P14) and their truth values are shown in Table 5.1. First, the linguistic truth values defined in Chapter 2 (i.e., five fuzzy numbers (mostly false (*mf*), perhaps false (*pf*), not sure (*ns*), perhaps true (*pt*), and mostly true (*mt*))) are used to determine the *TV* of the proposition P11,...,P14. The expected values (listed in Table 2.2) of the linguistic *TV* are used as the numerical *TV* for calculating *CE* and *RE*. Note that the *TV*s of P11,...,P14 underlie the knowledge K1 and K2. Based on the settings shown in Table 5.1, the two-dimensional information content (i.e., (*CE*,*RE*)) of C1 is calculated using the functions described in Chapter 2. The results are shown in Fig. 5.3. As seen from Fig. 5.3, the epistemic challenge exhibit low information content whereas compelling reason exhibits high information content. They are placed opposite to each other. High information content of compelling reason implies that it is not serving as a compelling reason as such. Low information content of epistemic challenge implies that it is not a challenge as such.

Table 5.1. State of ordinary concept (C1).

Propositions		Linguistic *TV*	Numerical *TV*	Requirement (P_R)	*TV*
P11:	C1 is suitable for the perceived need	mostly false (*mf*)	0.1	C1 should be suitable for perceived need	0.1
P12:	C1 is not suitable for the perceived need	perhaps true (*pt*)	0.733		
P13:	C1 performs well	mostly true (*mt*)	0.9	C1 should perform well	0.9
P14:	C1 does not perform well	mostly false (*mf*)	0.1		

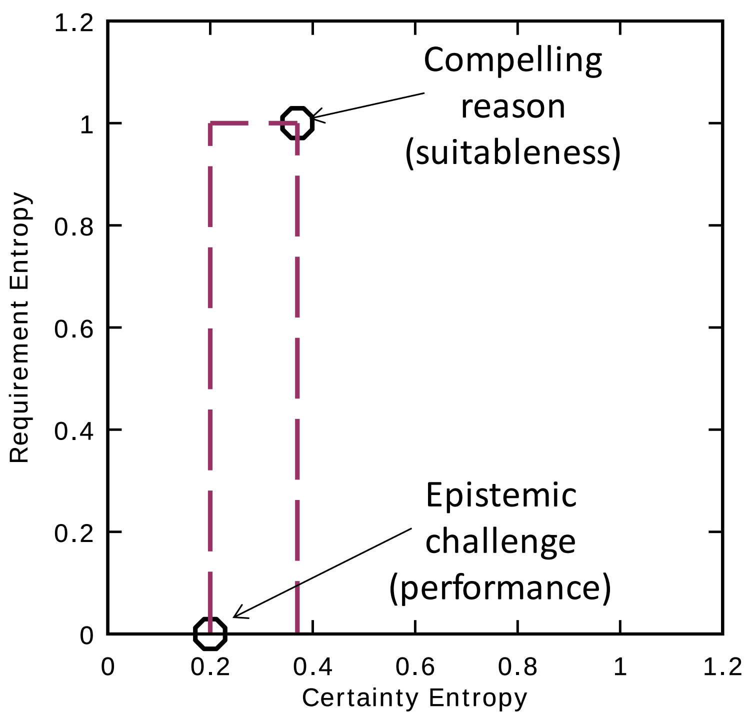

Figure 5.3. Information content of C1.

Similar to C1, consider the propositions regarding C2 (a creative concept). The propositions regarding C2 (P21,...,P24) and their truth values are shown in Table 5.2 and the information content is shown in Fig. 5.4. Note the opposite positions of epistemic challenge and compelling reason in Fig. 5.4. This time, the epistemic challenge has a very high information content (i.e., it is really a challenge), whereas compelling reason has a low information content (i.e., it is indeed a compelling reason).

Table 5.2. State of creative concept (C2).

Propositions		Linguistic *TV*	Numerical *TV*	Requirement (P_R)	*TV*
P21:	C2 is suitable for the perceived need	perhaps true (*pt*)	0.733	C2 should be suitable for perceived need	0.733
P22:	C2 is not suitable for the perceived need	perhaps false (*pf*)	0.267		
P23:	C2 performs well	not sure (*ns*)	0.5	C2 should perform well	0.5
P24:	C2 does not perform well	not sure (*ns*)	0.5		

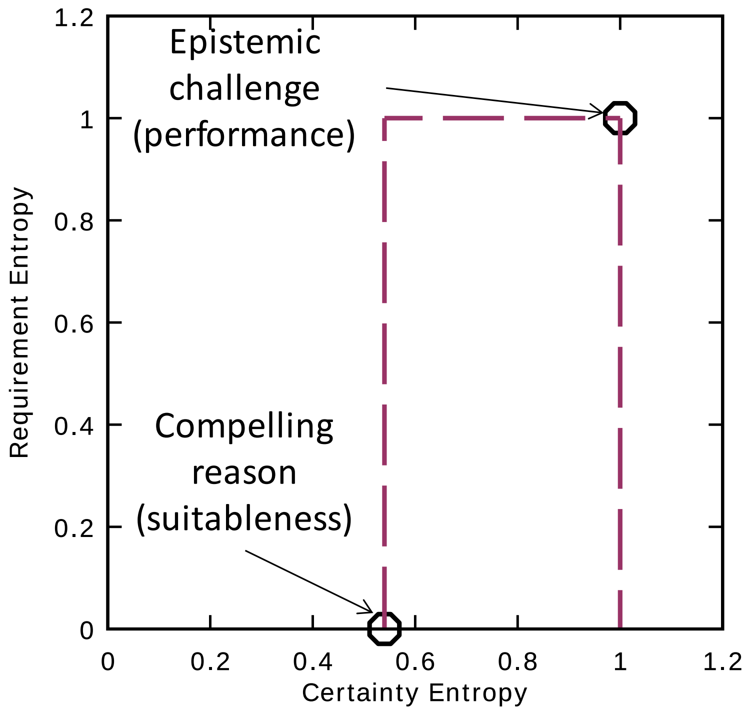

Figure 5.4. Information content of C2.

The overall information content of C2 is high compared to that of C1. Needless to say that the overall information content means here the value of coherency measure (λ) as defined in Chapter 2. This means a creative concept possesses high epistemic information content while being conceived. This information content however should reduce when new knowledge is available, i.e., K4 transforms to K′4 so that the propositions like P23 and P24 exhibit truth value similar to that of P21 and P22.

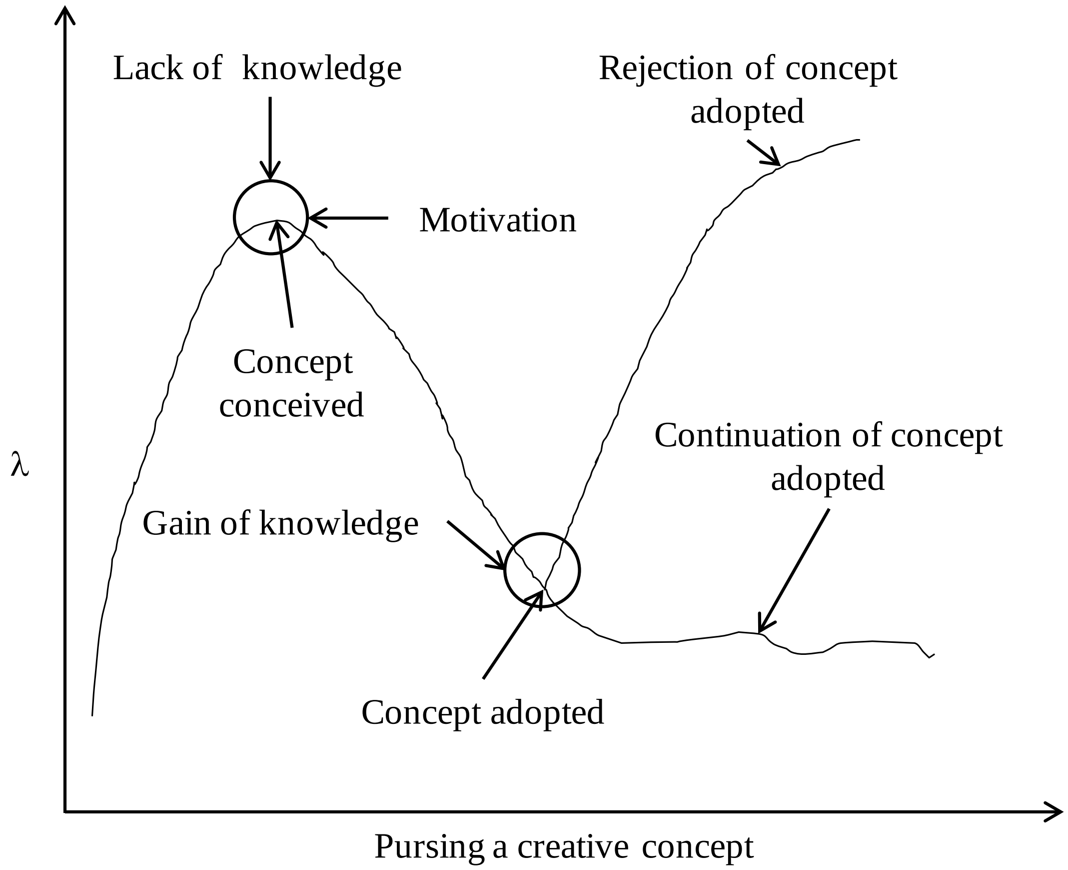

Figure 5.5. The states of a creative concept.

Figure 5.5 illustrates the states of a creative concept in terms of overall information content λ. As seen from Fig. 5.5, the Information Axiom (minimize the information content of design (Suh 1998)) does not hold as such for creative concept. Sometimes the information content should be minimized, sometimes it should be maximized. In addition, due to the lack of knowledge the information content of a creative concept jumps to its peak. At the same time, if motivating factors called compelling reason and epistemic challenge prevail, then a creative concept is conceived. When a substantial amount of knowledge becomes available, the information content of the conceived concept should go down significantly. In this case, the conceived concept becomes a part of C-K mapping, i.e., the concept is adopted as a key solution. Otherwise, the creative concept should be abundant and a new course of direction should be explored.

5.3. Results and discussions

This section describes the results of how a creative concept (an engine for Mars exploration) has been differentiated from an ordinary engine (an existing fossil-fuel based engine) using the method described in the previous section. At the beginning the C-K mapping takes the form of the map shown in Fig. 5.6.

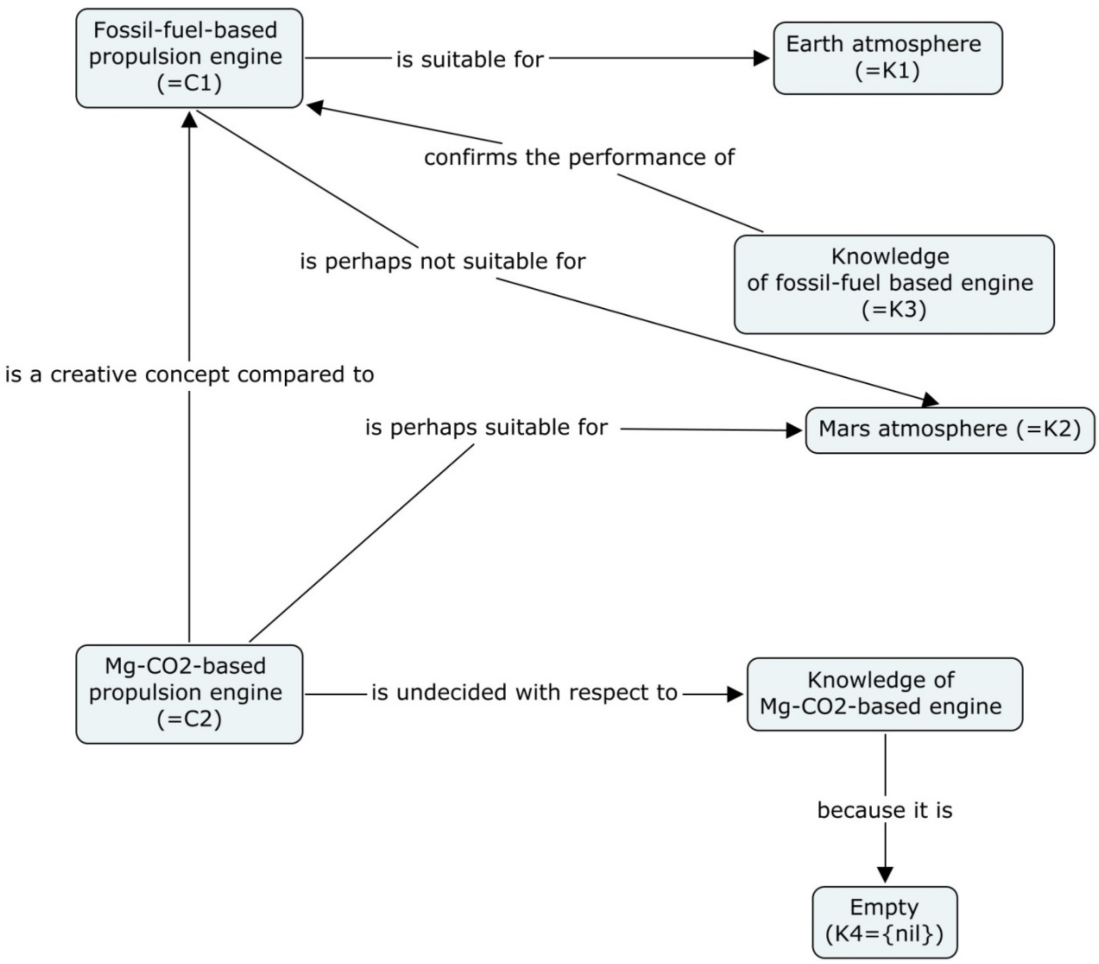

Figure 5.6. C-K mapping of a creative key solution for Mars exploration.

As seen from Fig. 5.6, two solutions C1 = Fossil-fuel based propulsion engine and C2 = Mg-CO_2 based propulsion engine have been considered. C1 is suitable for earth whereas C2 is suitable for Mars. The performance of C1 is known whereas the performance of C2 is quite unknown. This implies the propositions and their truth values as shown in Table 5.3. The information contents of C1 (fossil-fuel based propulsion engine) and C2 (Mg-CO_2 based propulsion engine) can be expressed by the information contents shown in Fig. 5.3 an Fig. 5.4, respectively because of the settings in Table 5.1 is similar to that of Table 5.3 for C1 and in Table 5.2 is similar to that of Table 5.3 for C2. Therefore, Mg-CO_2 based propulsion engine is a creative concept and it can be pursued further.

Table 5.3. The states of ordinary and creative concepts.

C1 = Fossil-fuel based propulsion engine					
Propositions		Linguistic *TV*	Numerical *TV*	Requirement (P_R)	*TV*
P11:	C1 is suitable for Mars exploration	mostly false (*mf*)	0.1	C1 should be suitable for Mars exploration	0.1
P12:	C1 is not suitable for Mars exploration	perhaps true (*pt*)	0.733		
P13:	C1 performs well	mostly true (*mt*)	0.9	C1 should perform well	0.9
P14:	C1 does not perform well	mostly false (*mf*)	0.1		
C2 = Mg-CO_2 based propulsion engine					
Propositions		Linguistic *TV*	Numerical *TV*	Requirement (P_R)	*TV*
P11:	C2 is suitable for Mars exploration	perhaps true (*pt*)	0.733	C2 should be suitable for Mars exploration	0.733
P12:	C2 is not suitable for Mars exploration	perhaps false (*pf*)	0.267		
P13:	C2 performs well	not sure (*ns*)	0.5	C2 should perform well	0.5
P14:	C3 does not perform well	not sure (*ns*)	0.5		

If C2 (Mg-CO2 based propulsion engine) is pursued further new knowledge can be gained (K4 transforms to K′4). Figure 5.7 shows the state of K′4.

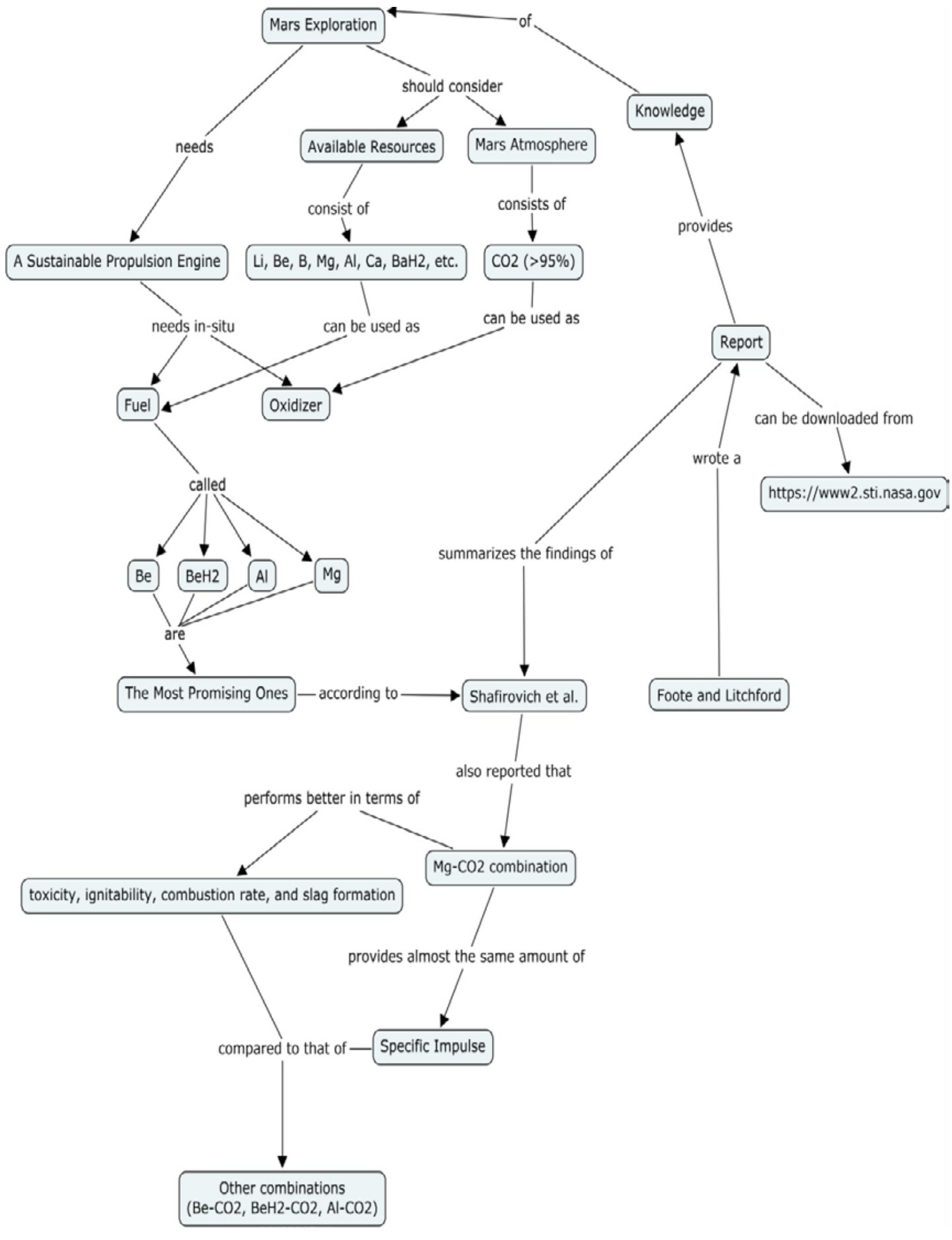

Figure 5.7. When K4 transforms to K′4.

As seen from Fig. 5.7, for Mars exploration, a propulsion engine is needed that should use *in-situ* fuel and oxidizer. Given the fact that Mars atmosphere consists of more than 95% CO_2, it (CO_2) can be used as an oxidizer, even if it is an unusual choice. This necessitates a particular type of fuel either metals (Be, Mg, Al, Li, Ca, etc.) or their hydrates (e.g., BeH_2, MgH_2, etc.). The fundamental studies conducted by Shafirovich et al. 1992, 1993 have revealed that the fuels, namely, Mg, Al, Be, BeH2 are probably the most useful fuels when CO_2 acts as the oxidizer. It has also been found that Mg-CO_2 combination produces almost the same amount of Specific Impulse (an important performance measure of propulsion devices) compared to that of other combinations (i.e., Al-CO_2, Be-CO_2, and BeH_2-CO_2). In terms of other important performance measures (i.e., combustion characteristics, such as toxicity, ignitability, combustion rate, slag formation, etc.) Mg-CO_2 combination produces relatively better result.

Table 5.4. States of C2 and C2 based on C-K mapping in Fig. 5.7.

Propositions		Truth Values		Requirement (P_R)
P1	C2 is *acceptable* in terms of Specific Impulse	*pt*	0.733	An engine should be acceptable in terms of Specific Impulse
P2	C2 is *not acceptable* in terms of Specific Impulse	*mf*	0.1	
P3	C3 is *acceptable* in terms of Specific Impulse	*mt*	0.9	
P4	C3 is *not acceptable* in terms of Specific Impulse	*mf*	0.1	
P5	C2 is *acceptable* in terms of toxicity, ignitability, combustion rate, slag formation, etc.	*mt*	0.9	An engine should be acceptable in terms of toxicity, ignitability, combustion rate, slag formation, etc.
P6	C2 is *not acceptable* in terms of toxicity, ignitability, combustion rate, slag formation, etc.	*mf*	0.1	
P7	C3 is *acceptable* in terms of toxicity, ignitability, combustion rate, slag formation, etc.	*mf*	0.1	
P8	C3 is *not acceptable* in terms of toxicity, ignitability, combustion rate, slag formation, etc.	*pt*	0.733	

C2 = Mg-CO_2 Propulsion Engine, C3 = Y-CO_2 Propulsion Engine, Y $\in$ {Be, BeH_2, Al}

Given the C-K mapping in Fig. 5.7, is it possible to show that the information content of concept C2 (Mg-CO2-based propulsion engine) has come down significantly? An answer to this question is needed to make sure the effectiveness of the transformation of knowledge from K4 to K′4. Otherwise, new knowledge (K′4) does not add any value to key solution determination process.

To answer the question, as set of propositions P1,…,P8 and two alternatives C2 (same as before) and C3 (=Y-CO_2-based propulsion engine, Y is either Be or BeH_2 or Al) are considered. The propositions and their truth values are listed in Table 5.4. Needless to say that the truth values of the propositions listed in Table 3 reflect the facts in Fig. 5.7.

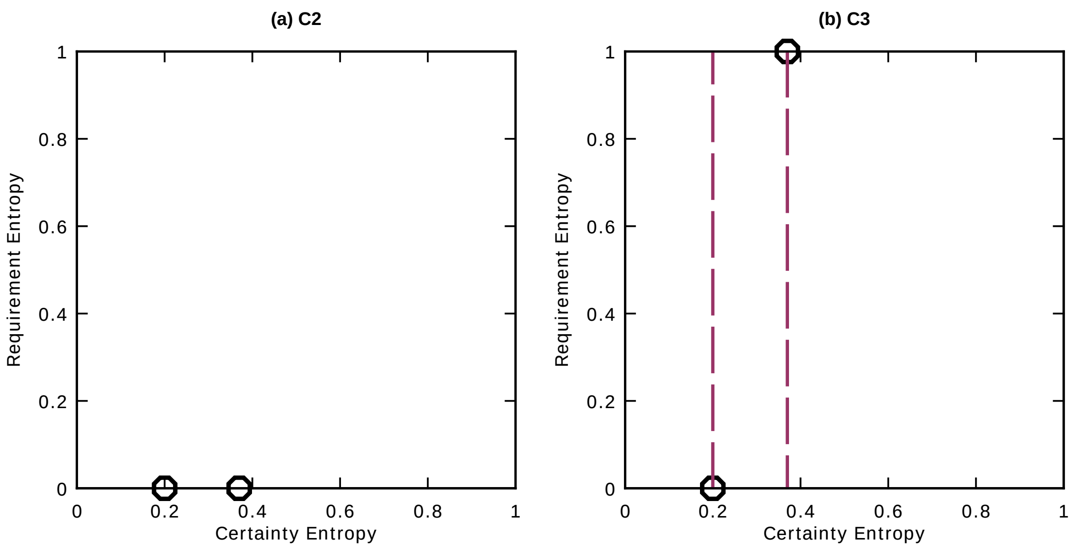

Figure 5.8. Information content of C2 and C3 based the settings in Table 5.4.

The information content in terms of Certainty and Requirement Entropies (*CE*,*RE*) are determined by using the same methods used in the previous section. The results are shown in Fig. 5.8. C2 has information contents (0.37,0) and (0.2,0) for {P1,P2} and {P5,P6}, respectively. The overall information content of C2 is now equal to 0.57. On the other hand, C3 has information content (0.2,0) and (0.37,1) for {P3,P4} and {P7,P8}, respectively. The overall information content of C3 is equal to 1.74. Thus, C2 is preferred over C3, as the key solution to develop a propulsion engine for Mars exploration, the decisionmaking now underlies "minimization of information content," i.e., the process holds the Information Axiom (Suh 1998).

Therefore, the results described in this section hold the scenario described in Fig. 5.5. In synopsis, creativity is first controlled by the maximization of information content in presence of such motivating factors as compelling reason and epistemic challenge and then by the minimization of information content in presence of new knowledge.

Chapter 6
Concluding Remarks

Making decisions, i.e., identifying a key solution (or a set of key solution), in conceptual phase of product development is not only critical but also difficult. It is critical in a sense that around 80% cost of a product is decided by the key solution determination process in the conceptual phase of product development and it cannot be rectified by making adjustments in the downstream of a product lifecycle. It is difficult in a sense that in conceptual phase of product development, the knowledge is very limited and there is an abundance of choice. To shed some light on this issue (decisionmaking in conceptual phase of product development) this thesis poses and answers the following questions:

How to differentiate a creative key solution from a non-creative key solution?

What is the appropriate customer need model?

How to deal with the unknown customer needs?

How to classify the key solutions based on customer responses?

How to deal with the sustainability of materials (used in the product) in key solution determination process?

Nevertheless, the following remarks can be made on the findings:

On the customer needs assessment:

1. One of the ways to identify a key solution to develop a product is to take opinions of customers regarding a set of key solutions.
2. To deal with the intrinsic complexity of customer responses, logical aggregation of customer opinions is a better choice compared to frequency based analysis. This faculty of thought is demonstrated to be true by logically aggregating the field data of customer needs collected from Bangladesh on small passenger vehicles using Kano model.
3. It has been found that a product feature needs to be classified either into a

must be included feature, or into a should be included feature, and or into a could be included feature. The link among these classifiers and Kano evaluations (Must-be, Attractive, One-Dimensional, Indifferent, Reverse, and Questionable) has been established.

4. The multi-valued logic plays an important role in the customer needs assessment. In particular, a two-dimensional information content (in epistemic sense) scheme has been found effective in logically computing the degree of customer satisfaction of a given product feature in terms of must be included, should be included, and could be included.
5. To increase the degree of satisfaction of vehicle users in Bangladesh, it is important to develop SUV- and Van-type passenger vehicles replacing some of the Sedan-type vehicles.

On the sustainability assessment:

1. Sustainability of a product largely depends on the materials used to manufacturing it. Therefore, the material used to manufacture the product become one of the key solutions.
2. To deal with the imprecision associated with the material related sustainability parameters in the conceptual phase of product development, an entity called range compliance has been found effective. The compliance of an sustainability parameter given by a numerical range is determined by calculating its compliance with five fuzzy numbers of the parameters labeled very low, low, moderate, high, and very high.
3. As an example, the imprecision associated with four sustainability parameters namely, CO_2 footprint, NO_X emission, SO_X emission and water usage (i.e., resource depletion) of five classes of hard materials (the materials used to produce abrasive grains of grinding wheel or other material removal tools) based on Alumina, Zirconia, Silicon Carbide, Boron Nitride, and Boron Carbide have been quantified by using the range compliance.
4. The sustainability parameter complying more with very low or low less negative impact on the sustainability, whereas the sustainability parameter

complying more with moderate, high, or very high has high negative impact on sustainability.

5. It is found that Alumina based hard materials have low negative impact followed by Zirconia and Silicon Carbide based hard materials. Boron Nitride/Carbide based materials have the highest negative impact.

On the creativity assessment:

1. To identify a useful key solution in conceptual phase of product development, the product development team members needs to be creative.
2. To differentiate a creative concept from a non-creative concept, Concept-Knowledge mapping as prescribed in C-K theory can be employed.
3. Creative concept means a concept which is undecided when it is being conceived.
4. Conceiving a creative concept is rather a motivation driven process.
5. Information content of a creative concept is high compared to that of a non-creative concept. The information content means here the two-dimensional information content in epistemic sense.
6. When a creative concept is pursued and new knowledge becomes available, the information content should go down significantly. Otherwise, the new knowledge does not add any value to product development process.
7. A non-creative key solution does not exhibit the abovementioned behavior of information content.
8. The effectiveness of the abovementioned approach has been demonstrated by calculating the information contents of two concepts Mg-CO_2 based propulsion engine (a creative concept) and fossil-fuel base propulsion engine (an non-creative concept). It has been found that the Mg-CO_2 based propulsion engine exhibits high information content compared to that of fossil-fuel base propulsion engine for Mars exploration. The information content of Mg-CO_2 based propulsion engine have gone down significantly under the presence of new knowledge.

Bibliography

1. —.CES Selector™ (Version 5.1.0). 2009. Granta Design Limited, UK, http://www.grantadesign.com
2. Altshuller, G. (2001). *And Suddenly the Inventor Appeared: TRIZ, the Theory of Inventive Problem Solving* (Shulyak, L., Trans.). Worcester, MA: Technical Innovation Center.
3. Bellman, R.E. and Zadeh, L.A. (1970). Decision-Making in a Fuzzy Environment, *Management Science*, 17(4), B-141-B-164.
4. Berger, C., Blauth, R., Boger, D., Bolster, C., Burchill, G., DuMouchel, W., Pouliot, F., Richter, R., Rubinoff, A., Shen, D., Timko, M. and Walden, D. (1993). Kano's method for understanding customer-defined quality, *Center for Quality of Management Journal*, 2(4), 3-35.
5. Braha, D. and Reich, Y. (2003). Topological structures for modelling engineering design processes, *Research in Engineering Design*, 14(4), 185–199.
6. Briggs, C. and Little, P. (2008). Impact of Organizational Culture and Personality Traits on Decision-making in Technical Organization, *Systems Engineering*, 11(1), 15-26.
7. Chen, Z. and Ben-Arieh, D. (2006). On the fusion of multi-granularity linguistic label sets in group decision making, *Computers & Industrial Engineering*, 51(3), 526-541.
8. de Bono, E. (1970). *Lateral Thinking: Creativity Step by Step*, Harper & Row, Publisher: NY.
9. Dieter, G.E. and Schmidt, L.C. (2009). *Engineering Design*, Fourth Edition, McGraw-Hill: New York.
10. Donnelly, K., Olds, R., Blechinger, F., Reynolds, D. and Beckett-Furnell, Z. (2004). ISO 14001 – effective management of sustainable design, *The Journal of Sustainable Product Design*, 4(1-4), 43-54.

11. Dubois, D. and Prade, H. (1978). Operations on fuzzy numbers, International *Journal of Systems Science*, 9(6), 613-626.
12. Fang, L., Hipel, K.W. and Kilgour, D.M. (1993). *Interactive Decision Making: The graph Model for Conflict Resolution*, Wiley & Sons: New York.
13. Fiksel, J. (2009). *Design for Environment: A Guide to Sustainable Product Development*, Second Edition, McGraw-Hill: New York.
14. Foote, J.P. and Litchford, R.J. (2007). *Powdered Magnesium—Carbon Dioxide Rocket Combustion Technology for In Situ Mar Propulsion*, NASA Technical Publication, NASA/TP-2007-215077, available from https://www2.sti.nasa.gov.
15. Fukushige, S. Yamamoto, K. and Umeda, Y. (2012). Lifecycle scenario design for product end-of-life strategy, *Journal of Remanufacturing*, 2012, 2:1, doi:10.1186/2210-4690-2-1.
16. Gero, J.S. (2000). Computational Models of Innovative and Creative Design Processes, *Technological Forecasting and Social Change*, 64(2-3), 183-196.
17. Hatchuel, A. and Weil, B. (2009). C-K design theory: an advanced formulation, *Research in Engineering Design*, 19(4), 181-192.
18. Hatchuel. A. and Weil., B. (2003). A new approach of innovative design: an introduction to C-K theory, *Proceedings of the 14th International Conference on Engineering Design Research for Practice* (ICED'03), 19-21 August 2003, Stockholm, Sweden, pp 109–124.
19. Herrera, F. and Herrera-Viedma, E. (2000). Linguistic decision analysis: steps for solving decision problems under linguistic information, *Fuzzy Sets and Systems*, 115(1), 67–82.
20. Higuchi, Y., Wada, N., Nakakubo, T. and Tokai, A. (2012). *Scenario Analysis on the Impact of Diffusion of Next Generation Vehicles on Material Consumption and GHG Emissions*. In: Design for Innovative Value Towards a Sustainable Society (Editors: Matsumoto, M., Umeda, Y., Masui, K. and Fukushige, S.), pp. 599-604, Springer: The Netherland.
21. Hutton, R.J.B. and Klein, G. (1999). Expert Decision Making, *Systems Engineering*, 2(1), 32-45.

22. Inohara, T. and Hipel, K.W. (2008). Coalition Analysis in the Graph Model for Conflict Resolution, *Systems Engineering*, 11(4), 343-359.
23. Kahn, K.B. (Ed.) (2004). *The PDMA Handbook of New Product Development* (Second Edition), Wiley: New York.
24. Kano, N., Seraku, N., Takahashi, F. and Tsuji, S. (1984). Attractive quality and must-be quality, *Hinshitsu*, 14(2), 39-48. (In Japanese).
25. Kazakci, A.O. and Tsoukias, A. (2005). Extending the C-K design theory: A theoretical background for personal design assistants, J*ournal of Engineering Design*, 16(4), 399-411.
26. Keller, L.R., Kirkwood, C.W. and Jones, N.S. (2008). Assessing Stakeholder Evaluation Concerns: An Application to the Central Arizona Water Resources Systems, *Systems Engineering*, 13(1), 58-71.
27. Khozaimy, O., Al-Dhaheri, A. and Sharif Ullah, A.M.M. (2011). A decision-making approach using point-cloud-based granular information, *Applied Soft Computing Journal*, 11(2), 2576-2586.
28. Klien, G.A. (2008). Naturalistic Decision Making, *Human Factors*, 50(3), 456-460.
29. Kobayashi, H. (2006). A systematic approach to eco-innovative product design based on life cycle planning, *Advanced Engineering Informatics*, 20(2), 113-125.
30. Kujawski, E. (2005). A Reference-Dependent Regret Model for Deterministic Tradeoff Studies, *Systems Engineering*, 8(2), 119-137.
31. Noor-E-Alam, M., Lipi, T.F., Hasin, M.A.A. and Sharif Ullah, A.M.M. (2011). Algorithms for fuzzy multi expert multi criteria decision making (ME-MCDM), *Knowledge-Based Systems*, 24(3), 367-377.
32. O'Hagan, A. and Oakley, J.E. (2004). Probability is perfect, but we can't elicit it perfectly, *Reliability Engineering and System Safety*, 85, 239-248.
33. Puccio, G.J., Cabra, J.F., Fox, J.M., and Cahen, H. (2010). Creativity on demand: Historical approaches and future trends, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 24(2), 153-159.
34. Rashid, M.M., Tamaki, J., Ullah, A.M.M.S. and Kubo, A. (2010). A Virtual Customer Needs System for Product Development, *Proceedings of the 2010*

Annual Meeting of Japan Society for Precision Engineering, September 04, 2010, Sapporo, Japan, Pages 53-54.

35. Rashid, M.M., Ullah, A.M.M.S., Sarker, M.A.R., Tamaki, J. and Kubo, A. (2012). Logical Aggregation of Customer Needs Assessment, *Proceedings of the Fifth International Symposium on Computational Intelligence and Industrial Applications* (ISCIIA2012), Sapporo, Japan, August 20-26, 2012.
36. Rashid, M.M., Ullah, A.M.M.S., Tamaki, J., and Kubo, A. (2011). Evaluation of Hard Materials using Eco-Attribute, *Advanced Materials Research*, 325, 693-698
37. Rasmussen, J. (1993). *Deciding and doing: Decision making in natural contexts.* In: Decision Making in Action, Klein, G., Orasallu, J., Calderwood, R., and Zsambok, C.E. (Eds), Ablex, Norwood, New Jersey, pages 158 - 171.
38. Saaty, T.L. (1980). *The Analytic Hierarchy Process*, McGraw-Hill: New York.
39. Saaty, T.L. (1990). *Multicriteria Decision Making: The Analytic Hierarchy Process*, RWS Publications, Pittsburgh: Pennsylvania.
40. Shafirovich, E.Y., and Goldshleger, U.I. (1992). Combustion of Magnesium Particles in CO2/CO Mixtures, *Combustion Science and Technology*, 84(1), 33-43.
41. Shafirovich, E.Y., Shiryaev, A.A., and Goldshleger, U.I. (1993). Magnesium and Carbon Dioxide: A Rocket Propellant for Mars Missions, J*ournal of Propulsion and Power*, 9(2), 197-203.
42. Shamsuzzaman, M., Ullah, A.M.M.S. and Bohez, E.L.J. (2003). Applying linguistic criteria in FMS selection: fuzzy-set-AHP approach, *Integrated Manufacturing Systems*, 14(3), 247-254.
43. Smith, E.D., Son, Y.J., Palmarini-Piattelli, M. and Bahill, T. (2005). Ameliorating Mental Mistakes in Tradeoff Studies, *Systems Engineering*, 10(3), 222-240.
44. Suh, N.P. (1990). *The principles of design*. Oxford University Press: New York.

45. Suh, N.P. (1998). Axiomatic Design Theory for Systems, *Research in Engineering Design*, 10(4), 189-209.
46. Tomiyama, T., Gu, P. Jin, Y., Lutters, D., Kind, C., and Kimura, F. (2009). Design methodologies: Industrial and educational applications, *CIRP Annals-Manufacturing Technology*, 58(2), 543-565.
47. Ullah, A.M.M.S. (2005a). A Fuzzy Decision Model for Conceptual Design, *Systems Engineering*, 8(4), 296-308.
48. Ullah, A.M.M.S. (2005b). Handling design perceptions: an axiomatic design perspective, *Research in Engineering Design*, 16(3), 109-117.
49. Ullah, A.M.M.S. (2008). Logical interaction between domain knowledge and human cognition in design, *International Journal of Manufacturing Technology and Management*, 14(1-2), 215-227.
50. Ullah, A.M.M.S. and Harib, K.H. (2006). *Zadehian Paradigms for Knowledge Extraction in Intelligent Manufacturing*. In: Manufacturing the Future: Concepts-Technologies-Visions. Editors: Kordic, V., Lazinica, A. and Merdan., M. Pro Literatur Verlag Robert Mayer-Scholz, Mammendorf, Germany, pages 291-308.
51. Ullah, A.M.M.S. and Harib, K.H. (2008). An Intelligent Method for Selecting Optimal Materials and its Application, *Advanced Engineering Informatics*, 22(4), 473–483.
52. Ullah, A.M.M.S. and Tamaki, J. (2011). Analysis of Kano-Model-Based Customer Needs for Product Development, *Systems Engineering*, 14(2), 154-172.
53. Ullah, A.M.M.S., Harib, K.H., Al-Awar, A. (2007). Minimizing Information Content of a Design using Compliance Analysis, *SAE Technical Paper 2007-01-1209*, SAE International: Pennsylvania.
54. Ullah, A.M.M.S., Kitajima, K., Akamatsu, T., Furuno, M., Tamaki, J., and Kubo, A. On Some Eco-indicators of Cutting Tools, *Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference*, June 13-17, 2011, Corvallis, Oregon, USA.

55. Ullah, A.M.M.S., Rashid, M.M. and Tamaki, J. (2012). On Some Unique Features of C-K Theory of Design, *CIRP Journal of Manufacturing Science and Technology*, 5(1), 55-66.
56. Ullman, D.G. (2006). *Making Robust Decisions: Decision Management For Technical, Business, & Service Teams*, Trafford Publishing: British Colombia.
57. Ullman, D.G. (2009). *Mechanical Design Process*, Fourth Edition, McGraw-Hill: New York.
58. Ulrich, K.T. and Eppinger, S.D. (2004). *Product Design and Development*, Third Edition, McGraw-Hill: New York.
59. Umeda, Y. Nishiyama, T., Yamasaki, Y., Kishita, Y. and Fukushige, S. (2009). Proposal of sustainable society scenario simulator, *CIRP Journal of Manufacturing Science and Technology*, 1(4), 272-278.
60. Walley, P. (1991). *Statistical Reasoning with Imprecise Probabilities*. Chapman and Hall: London.
61. Wood, W.H.III. and Agogino, A.M. (1996). Case-based conceptual design information server for concurrent engineering, *Computer-Aided Design*, 28(5), 361-369.
62. Xu, Q., Jiao, R.J., Yang, X., Helander, M., Khalid, H.M. and Opperud, A. (2009). An analytical Kano model for customer need analysis, *Design Studies*, 30(1), 87-110.
63. Yager, R.R. (1978). Fuzzy decision making including unequal objectives, *Fuzzy Sets and Systems*, 1(2), 87-95.
64. Yang, K. (2008). *Voice of the Customer: Capture and Analysis*. McGraw-Hill: New York.
65. Yoshikawa, H. (1981). General Theory of Design Process, *Journal of the Japan Society of Precision Engineering*, 47(4), 405-410. (In Japanese)
66. Zadeh, L.A. (1965). Fuzzy sets, *Information and Control*, 8, 338-353.
67. Zadeh, L.A. (1975). Fuzzy logic and approximate reasoning, *Synthese*, 30(3–4), 407–428.

68. Zadeh, L.A. (1997). Toward a theory of fuzzy information granulation and its centrality in human reasoning and fuzzy logic, *Fuzzy Sets and Systems*, 90(2), 111-127.
69. Zadeh, L.A. (2005). From imprecise to granular probabilities, *Fuzzy Sets and Systems*, 154(3), 370-374.
70. Zeng, Y. and Cheng, G.D. (1991). On the logic of design, *Design Studies*, 12(3), 137-141.

Appendix A: Customer Needs Data Collection

Customer needs data has been collected on the some features of small passenger vehicles. The data collection period was January 2012 to April 2012. The data on the 38 features has been collected using the Kano model. The features are listed in Table 3.3. In addition to the data on 38 features, the physiographic and demographic data of the respondents has also been collected, as follows:

Table A.1 shows the demographic questions that have been asked to the respondents in Bangladesh. Needless to say that demographic questions means the questions related the profession, income level, gender, and alike of an individual. The questions related to income of an individual are from the context of Bangladesh.

Table A.1. Demographic questions and answers

Statement		Choose one	Frequency
I am a/n	private service holder	□	14
	government service holder	□	12
	housewife	□	7
	businessperson	□	11
	engineer	□	11
	doctor	□	2
	lawyer	□	12
	student	□	26
	others	□	5
My income is	very high	□	4
	high	□	8
	moderate	□	60
	low	□	28
I am a	Female	□	82
	Male	□	18

The frequencies of the answers are also shown in the last column in Table A.1. On the other hand, Table A.2 shows the psychographic questions that have been asked to the respondents in Bangladesh. Needless to say that psychographic questions means the questions related the life-style and values of an individual. A respondents can choose multiple answers from given options. The frequencies of the answers are also shown in the last column in Table A.2.

Table A.1. Psychographic questions and answers

Statements	Check as many as you like	Frequency
I prefer to drive my vehicle by myself	□□	52
I prefer to hire a driver to drive my vehicle	□□	39
I use my personal vehicle for long trips	□□	35
I always use my own vehicle for commuting to office/school	□□	45
A vehicle is an essential means of transportation for me	□□	53
A vehicle is a luxurious means of transportation for me	□□	21
I prefer environmentally friendly vehicles	□□	60

List of Research Achievements

The following research publications have been submitted to defend the thesis.

1. Md. Mamunur Rashid, A.M.M. Sharif Ullah, Junichi Tamaki, and Akihiko Kubo. (2011). Evaluation of Hard Materials using Eco-Attribute, *Advanced Materials Research,* Volume 325, Pages 693-698 [Trans Tech Publications, Switzerland] [*http://dx.doi.org/10.4028/www.scientific.net/AMR.325.693*]

2. A.M.M. Sharif Ullah, Md. Mamunur Rashid and Junichi Tamaki. (2012). On Some Unique Features of C-K Theory of Design, *CIRP Journal of Manufacturing Science and Technology*, Volume 5, Number 1, Pages 55-66. [Elsevier, The Netherlands] [*http://dx.doi.org/10.1016/j.cirpj.2011.09.001*].

3. Md. Mamunur Rashid, A.M.M. Sharif Ullah, M.A. Rashid Sarker, Junichi Tamaki, and Akihiko Kubo. (2012). Logical Aggregation of Customer Needs Assessment, *Proceedings of the Fifth International Symposium on Computational Intelligence and Industrial Applications* (*ISCIIA2012*), Sapporo, Japan, August 20-26, 2012.

4. Md. Mamunur Rashid, Junichi Tamaki, A.M.M. Sharif Ullah and Akihiko Kubo. (2010). A Virtual Customer Needs System for Product Development, *Proceedings of the 2010 Annual Meeting of Japan Society for Precision Engineering,* September 04, 2010, Sapporo, Japan, Pages 53-54.

Acknowledgments

I am indebted to my doctoral thesis advisor Dr. A. M. M. Sharif Ullah, Department of Mechanical Engineering, Kitami Institute of Technology, Japan, for his encouragement, suggestions, and support throughout this study.

I gratefully acknowledge the suggestions and comments that I have received from my doctoral thesis examination committee members, Professor Jun'ichi Tamaki (Chair), Dr. A. M. M. Sharif Ullah, Dr. Michiko Watanabe, Department of Mechanical Engineering, Professor Toshio Eisaka, and Dr. Fumito Masui, Department of Computer Sciences, Kitami Institute of Technology, Japan.

I also gratefully acknowledge Professor M. A. Rashid Sarkar, Department of Mechanical Engineering, Bangladesh University of Engineering and Technology (BUET), Bangladesh, for accepting me as an exchange student during the period of December 2011 - April 2012 for collecting customer needs data from Bangladesh.

I express my sincere appreciations to the concerned students, staff, and faculty members at the Kitami Institute of Technology, Japan for providing me invaluable assistance during my stay in Kitami.

I am indebted to my employer, The Bangladesh Institute of Management, Dhaka, Bangladesh, and The Ministry of Industries, Bangladesh Government for granting me the study-leave to complete this study.

Last but not the least, I am thankful to my family members for their encouragement and understanding.