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Epistemic Uncertainty Study of the Conceptual Phase of Product Development by Multi-valued Logic and Information Content

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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 study describes logical approaches for making decisions in conceptual phase of product development. In particular, the emphasis is given on such issues as customer needs and creativity. Multi-valued logic and information content from the context of epistemic uncertainty have been used for the sake of computation.

Keywords: Product Development, Customer Needs Assessment, Sustainability and Creativity.

1. Introduction

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 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.

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. Thus, 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 (Dieter and Schmidt 2009, Ullman 2009, Ulrich and Eppinger 2004, 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).

2. Methodology

A methodology is presented in this section regarding quantify method of the different uncertainty issues in product development.

2.1 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:

$$I(FR) = -log\left(\frac{1}{S}\right) \tag{2.1}$$

In equation (2.1), *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. 2.1.

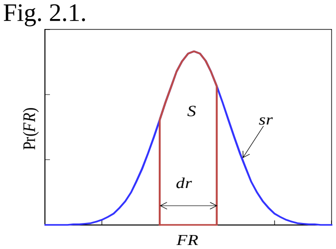

Figure 2.1. Definition of information content for systems design.

In particular, CE is defined as follows:

$$CE = \frac{\sum_{i}^{n} I_c(TV(Pi))}{n} \tag{2.2.1}$$

This means that *CE* is the average epistemic information content, I_c(.), of *TV*(*P*1),...,*TV*(*Pn*). The epistemic information content I_c(.) is determined as follows:

$$I_c(TV(Pi)) = max\left(0, min\left(\frac{TV-0}{0.5-0}, \frac{1-TV}{1-0.5}\right)\right) \tag{2.2.2}$$

Figure 2.2 illustrates I_c(.). As seen from Fig. 2.2, epistemic information content of the truth value of a proposition is a tent function in the universe of discourse of [0,1].

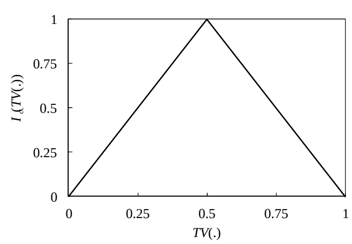

Figure 2.2. Epistemic information content.

The following function can be used to measure *RE* (Ullah 2005a):

$$RE = max\left(0, min\left(1, \frac{a - TV(P_R)}{a-b}\right)\right) \tag{2.2.3}$$

$$a = max(TV(Pi) \mid i = 1,\dots,n) \quad b = min(TV(Pi) \mid i = 1,\dots,n)$$

The procedure to determine the *TV*(P_R) from *TV*(*P*1),...,*TV*(*Pn*) shown in Ullah 2005a is used in this paper. A typical nature of RE is illustrated in Fig. 2.3 corresponding to a = 0.9 and b = 0.05.

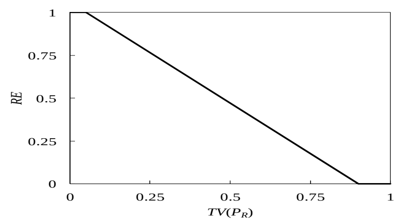

Figure 2.3. A function to determine requirement entropy.

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:

$$\lambda = e + f + g + h + (f - e)(h - g) \qquad (2.2.4)$$

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. 2.4. This way decisionmaking can be carried out in conceptual phase of product development.

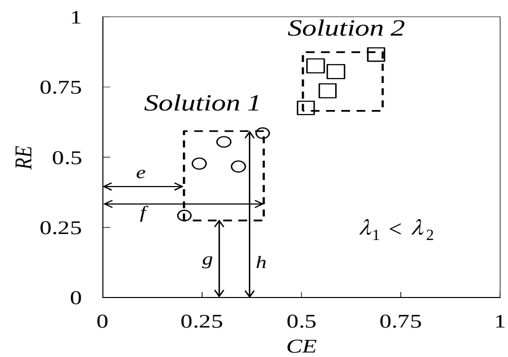

Fig. 2.4. Decisionmaking using two-dimensional information content.

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 as described in Fig. 3.1-3.3 ?

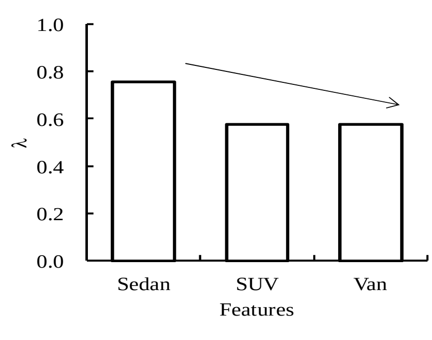

Figure 3.1. Reduction in overall information content for could be included.

Figure 3.2 shows the value of coherency measure when the requirement refers to "should be included" for Sedan, SUV, and Van. As seen from Fig. 3.2, 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).

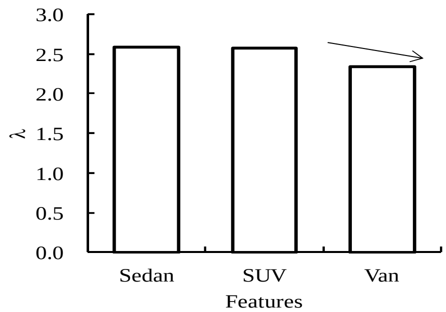

Figure 3.2. Reduction in overall information content for should be included.

Figure 3.3 shows the value of coherency measure when the requirement refers to "must be included" for Sedan, SUV, and Van. As seen from Fig. 3.3, 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. 3.1). This time a great deal of uncertainty (a large value of coherency measure) is associated with the decision.

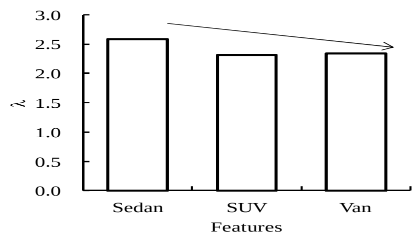

Figure 3.3. Reduction in overall information content for must be included.

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. 3.1). SUV and Van are not that much unexpected surprises to the car users in Bangladesh (Fig. 3.2).SUV and Van must increase the level of satisfaction of car users in Bangladesh but this conclusion possesses a great deal of uncertainty (Fig. 3.3).

4. Creativity Assessment

This section deals with the assessment of creativity in key solutions determination process in the conceptual phase of product development. This section is based on the work of Ullah et al. 2012. 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. 5.1.

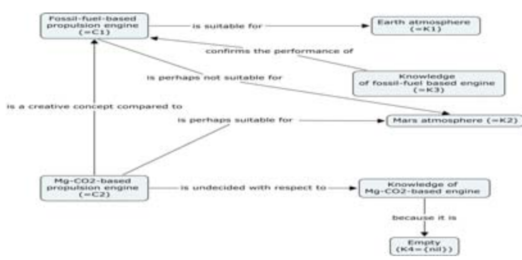

Figure 5.1. C-K mapping of a creative key solution for Mars exploration (Ullah et al.2012)

As seen from Fig. 5.1, 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 5.1.

Table 5.1. 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		

Table 5.2. States of C2 and C2 based on C-K mapping

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}

According to C-K mapping , 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 5.2.

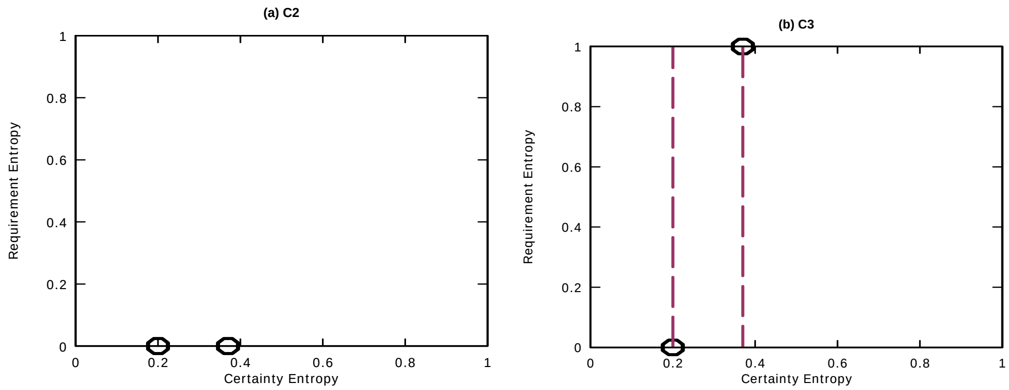

Figure 5.2. Information content of C2 and C3 based the settings in Table 5.2.

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. 5.2. 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).

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.

5. Conclusion

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 paper 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:

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. 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. 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. 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. 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 creativity assessment

To identify a useful key solution in conceptual phase of product development, the product development team members needs to be creative. To differentiate a creative concept from a non-creative concept, Concept-

Knowledge mapping as prescribed in C-K theory can be employed. Creative concept means a concept which is undecided when it is being conceived. Conceiving a creative concept is rather a motivation driven process. 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. 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. A non-creative key solution does not exhibit the abovementioned behavior of information content.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.

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