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Justification of concurrent engineering environments based on fuzzy mathematics

M.-C. WU†

This paper presents an approach to justify which combination of concurrent engineering (CE) techniques would be most beneficial to a particular company under a given budget constraint. Existing documents of design change are used to evaluate the effectiveness of each prospective CE technique. An algorithm for computing the combined effectiveness of multiple CE techniques is proposed. Fuzzy set theory has been applied to model the data for cost/benefit analysis, which is imprecise due to subjective judgment.

1. Introduction

Concurrent engineering (CE) is widely advocated as a promising technique to enhance competitiveness. The focal point of concurrent engineering is the enhancement of the product design function coupled with a shortening of the lead time for new product introduction. For this, several product design factors such as the manufacturability, assemblability, testability, and serviceability of products, which traditionally are not part of designers' tasks, should now be considered at the product design stage. In essence, concurrent engineering recommends that the function of product design should be enlarged in order to predict and solve these problems as early as possible, which would otherwise appear more troublesome in the downstream stages.

The CE philosophy of early problem solving at the design stage can be economically justified by some empirical findings. Huthwaite (1988) revealed that product design accounts for only 5% of a product's cost; however, it can influence 75% or more of manufacturing costs and 80% of a product's quality performance. This finding is quite consistent with verdicts from two automobile producers. According to General Motors executives, 70% of the cost of manufacturing truck transmissions is determined during the design phase (Whitney 1988). Ford Motor Company estimated that among the four manufacturing elements of design, material, labour, and overhead, 70% of all production savings can be achieved by improving design (Cohodas 1988).

In the past decade, a number of concurrent engineering techniques have been proposed. Examples of these involve the formulation of a multi-functional design team; the use of design handbooks; the use of checklists and structured procedures; the development of computer software for checking the manufacturability to enhance design; and the development of expert systems to facilitate design in satisfying the constraints of other life-cycle factors (Young *et al.* 1992, Jo *et al.* 1993).

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These existing CE techniques are widely varied and most of their reported applications seemingly are limited to specific domains. These techniques may not be equally beneficial to companies which differ in size and the complexity of their product design processes. The decision as to which type or which combination of CE techniques to adopt for a particular company must be made by the management once they have decided to introduce CE techniques.

To aid the decision-making process, this paper proposes an economic justification model for the selection of CE techniques for a particular company. In the proposed justification model, the data for cost/benefit analysis and the effectiveness of CE techniques are estimated by CE experts, which unavoidably are subjective and involve fuzziness. Therefore, fuzzy set theory techniques have been applied to model the vagueness.

2. Fuzzy set theory

The fuzzy set theory used in this research involves three major subjects: fuzzy numbers, linguistic variables, and union operators on fuzzy sets.

2.1. *Fuzzy numbers*

Consider a referential set X with x as its element. A fuzzy subset A of X is defined by a membership function $f_A(x)$ which maps each element x in X to a real number in the interval $[0, 1]$ The function value of $f_A(x)$ denotes the grade of membership, that is, the degree to which element x is in set A. A fuzzy subset is often briefly known as a fuzzy set (Kaufmann and Gupta 1985).

A fuzzy number is a fuzzy subset in R (real line) which is usually represented by a special membership function over a closed interval of real numbers. In this research, a special class of fuzzy numbers known as triangular fuzzy numbers (TFN) developed by Van Laarhoven and Pedrycz (1983) is used. As shown in figure 1, a TFN is in a triangular shape and can be denoted by a triplet (a_1, a_2, a_3) where a_1 can be semantically interpreted as the lower bound, a_2 the most probable value, and a_3 the upper bound, with the membership function defined as follows:

$$f_A(x) = \begin{cases} (x - a_1)/(a_2 - a_1) & a_1 \leq x \leq a_2 \\ (a_3 - x)/(a_3 - a_2) & a_2 \leq x \leq a_3 \\ 0 & \text{otherwise.} \end{cases}$$

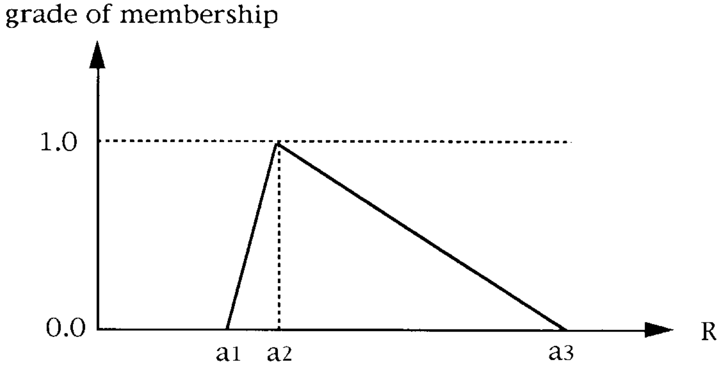

Figure 1. A triangular fuzzy number (a_1, a_2, a_3).

By the extension principle proposed by Zadeh (1965), the addition and subtraction operations on TFNs definitely give a TFN. Multiplication, inverse, and division operations on TFNs do not necessary give a TFN. However, the results of these operations can be reasonably approximated by TFNs (Kaufmann and Gupta 1985) as illustrated below.

Addition

$$(a_1,a_2,a_3) + (b_1,b_2,b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3).$$

Subtraction

$$(a_1,a_2,a_3) - (b_1,b_2,b_3) = (a_1 - b_1, a_2 - b_2, a_3 - b_3).$$

Multiplication

$$k \cdot (b_1,b_2,b_3) = (k \cdot b_1, k \cdot b_2, k \cdot b_3)$$

$$(a_1,a_2,a_3) \cdot (b_1,b_2,b_3) \cong (a_1 \cdot b_1, a_2 \cdot b_2, a_3 \cdot b_3)$$

$$\text{if } k \geq 0; a_i \geq 0; b_i \geq 0.$$

Division

$$(a_1,a_2,a_3)/(b_1,b_2,b_3) \cong (a_1/b_1, a_2/b_2, a_3/b_3)$$

$$\text{if } a_i \geq 0; b_i \geq 0.$$

2.2. *Linguistic variables*

Linguistic variables are variables whose values are represented in words or sentences in natural languages, and each linguistic value can be modelled by a fuzzy set (Zadeh 1975/1976). For example, let D be a linguistic variable with the name 'detectability' (the possibility of detecting a design defect by a CE technique), and the set of its linguistic values is {very low, low, medium, high, very high}. Each of these linguistic values is represented by a TFN with its membership functions as shown in figure 2 (Liang and Wang 1991). Rigorously speaking, it is necessary to perform extensive experiments to establish a justified conversion method from linguistic values to fuzzy numbers. In this paper, without the loss of generality, we directly adopt the conversion method proposed by Liang and Wang (1991). Note that these linguistic values are TFNs in the interval $[0, 1]$

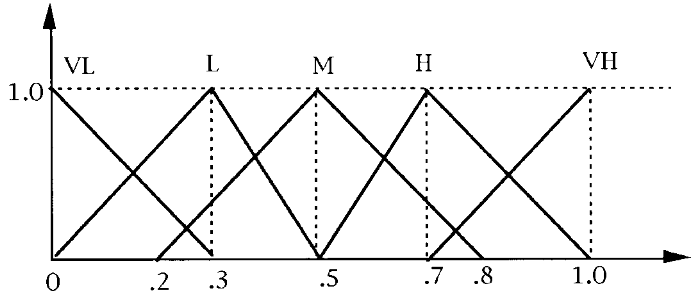

Figure 2. Linguistic values of design defect detectability: 'very low' (VL), 'low' (L), 'medium' (M), 'high' (H), and 'very high' (VH), as represented by triangular fuzzy numbers.

From the figure, the membership function of 'low' is (0.0, 0.3, 0.5). That is, an expression of 'low detectability' denotes that the detectability of the concerned CE technique is between 0.0 and 0.5 and the most probable value is 0.3. Alternatively, if the detectability of a CE technique is exactly 0.2, then it may be described by experts as either 'very low' or 'low', with their grades of membership being equal to 0.33 and 0.66, respectively. Linguistic variables are very useful for experts to give their uncertain justification on the effectiveness of CE techniques.

Note that for any two linguistic values discussed in figure 2, the maximum operation also gives a TFN and can be easily determined by the following formula (Kaufmann and Gupta 1985)

$$(x_1, x_2, x_3) = \mathrm{Max}((a_1, a_2, a_3), (b_1, b_2, b_3)),$$

where $x_i = \mathrm{Max}(a_i, b_i)$.

2.3. *Union operators on fuzzy sets*

The problem of defining a union operation on two fuzzy sets can be stated as follows: Let A and B be two fuzzy sets with membership functions $f_A(x)$ and $f_B(x)$, respectively. If $C = A \cup B$, what is $f_C(x)$?

Several approaches to model the union operation on two fuzzy sets have been proposed in previous literature (Zimmermann 1986). One approach, known as the max-operator, is defined by giving $f_C(x) = \mathrm{Max}(f_A(x), f_B(x))$. This method is quite popular in the application of fuzzy set theory. However, it lacks 'adaptability' in dealing with different contexts. That is, this type of fuzzy set aggregation is independent of the application context, which may be widely varied from a human decision to a medical diagnostic system.

In order to solve the adaptability problem, researchers propose parametric operators to model the union operation of fuzzy sets. One example, known as Yager's union operator, is introduced below (Zimmermann 1986).

$$f_C(x) = \mathrm{Min}\left\{ 1, (f_A(x)^p + f_B(x)^p)^{1/p} \right\}; \quad p \geq 1$$

For $p = 1$, the Yager's union operation becomes the bounded sum; that is, $f_C(X) = \mathrm{Min}\{1, f_A(x) + f_B(x)\}$. For $p \to \infty$, it becomes the max-operator; that is, $f_C(x) = \mathrm{Max}(f_A(x), f_B(x))$. The Yager's union operator is adaptable to different application contexts by varying the value of parameter p. That is, the parameter value p can be interpreted as the degree of conservativeness in evaluating the union operation. The most conservative evaluation is by taking the max-operation ($p \to \infty$), and the least conservative way is by taking the bounded sum ($p = 1$). The larger the p value, the smaller the union result.

In this research, we adopt the parametric notion of Yager's operator to define the combined detectability of two CE techniques. Suppose the detectability of two CE techniques (T_A and T_B) are known with linguistic values (a_1, a_2, a_3) and (b_1, b_2, b_3), respectively. The combined detectability of these two techniques can be interpreted as the union of two individual detectabilities, as denoted by:

$$x = Y_p(a, b)$$

where

Y_p is the union operation with parameter p;
a $= (a_1, a_2, a_3)$;

	VL	L	M	H	VH
VL	(0,0,0.36)	(0,0.30,0.52)	(0.20,0.50,0.80)	(0.50,0.71,1)	(0.70,1,1)
L	*	(0,0.36,0.59)	(0.20,0.52,0.80)	(0.50,0.74,1)	(0.70,1,1)
M	*	*	(0.23,0.59,0.95)	(0.59,0.83,1)	(0.70,1,1)
H	*	*	*	*	(0.74,1,1)
VL	*	*	*	*	(0.83,1,1)

Table 1. Results of performing the proposed union operation on two linguistic values (VL= 'very low', L= 'low', M= 'medium', H= 'high', and VH= 'very high').

b $= (b_1, b_2, b_3)$;
x $= (x_1, x_2, x_3)$, a TFN in $[0, 1]$ and
x_i $= \mathrm{Min}\left\{1, (a_i^p + b_i^p)^{1/p}\right\}$; $p \geq 1$.

Note that the union operator defined above is different from the Yager's operator (the Yager's union operation of two TFNs may not be a TFN). Yet, some good properties of the Yager's operator are also held by the proposed operator. That is, for $p = 1$, the combined detectability is the bounded sum of the two individuals; for $p \to \infty$, the combined detectability is the maximum of the two individuals (i.e. $x_i = \mathrm{Max}\left\{a_i, b_i\right\}$ when $p \to \infty$); the larger the p value, the smaller the combined detectability.

By the above formula, for $p = 4$, the union results of any two linguistic values representing detectability can be calculated as shown in table 1. From the table, it can be seen that the combined detectability intuitively shows a reasonable ranking. The better a combination, the higher the combined detectability. For example, the combined detectability of 'M' and 'M' is less than that of 'M' and 'H'.

Alternatively, a direct application of Yager's union operation on the linguistic values in figure 2 may give a confusing result. For example, Yager's union operation on 'medium' and 'very high' detectabilities gives a combined detectability in an interval $[0.2, 1.0]$ which implies that the combined use of two CE techniques is less effective than only using the technique with 'very high' detectability.

The proposed union operation can be extended to simultaneously manipulate multiple linguistic values as shown below.

$$x = Y_p(a_1, a_2, \ldots, a_n)$$

where

a_i $= (a_{i1}, a_{i2}, a_{i3})$;
x $= (x_1, x_2, x_3)$, a TFN in $[0, 1]$ and
x_j $= \mathrm{Min}\left\{1, \left(\sum_{i=1}^{n} a_{ij}^p\right)^{1/p}\right\}$; $p \geq 1$.

3. Classification of concurrent engineering techniques

Most CE techniques by definition aim to solve the design and manufacturing problems or some other product life-cycle factors concurrently. This is not always the case as the following examples demonstrate.

3.1. *DFM/DFX software*

A typical example is the use of a DFM (design for manufacturability) software, which can quickly and automatically provide the manufacturability information for a particular design. The information then provides a feedback to designers for improving their designs. The iterative process of improving and verifying design by DFM software has been claimed to be a concurrent engineering technique. Rigorously speaking, such a process is a ‘fast feedback’ mechanism rather than a ‘concurrent’ system because the two tasks (verifying and modifying designs) are independently performed.

In the discipline of concurrent engineering, the concept of DFM has been generalized to DFX (Design for X), where the X is a life-cycle factor which could be manufacturability (Anjanappa *et al.* 1991, Shankar and Jansson 1993); assemblability (Boothroyd 1982, Runciman and Swift 1985), reliability and maintainability (Grassman and Rodriguez 1989). Most of the DFX software is intended to highlight the undesirable attributes of a particular design from the perspective of the product life-cycle factor X, and provide designers with feedback information for the improvement of the designs. Likewise, each of these CE techniques can be recognized as a ‘fast feedback mechanism’.

3.2. *Multi-functional teams*

The earliest CE technique is the use of multi-functional teams. This approach advocates the formulation of a design team consisting of designers and individuals from all other related functional areas. Team members are selected for their ability to contribute to the design of product and processes by early identification of potential problems and timely initiation of actions to avoid costly rework (Goldhar and Jelinek 1990). This approach can be traced back to the 1940s where Ford Motor Company successfully implemented this technique in developing military hardware for World War II (Ziemke and Spann 1993).

The essence of the multi-functional team approach can also be recognized as a ‘fast feedback mechanism’. That is, comments about a prototype design from the perspective of manufacturing and other life-cycle factors can be directly given by the team members. Such a feedback mechanism would be much faster than the traditional way of placing individual team members in separate functional departments in the organization. In other words, this technique improves the information flow– hence fast feedback.

3.3. *Quality function deployment*

QFD (quality function deployment) can be considered to be a CE technique by providing a framework for facilitating the effective communication between the product designers and other functional departments (Oakland 1993). Through QFD, the priorities of customer demands investigated by the marketing department can be transformed into that of design specifications for designers, and further into that of manufacturing specifications for manufacturing engineers. By the use of QFD, each functional department would explicitly know its interactions with other departments, either upstream or downstream, and then have a ‘global view’ about the development of a product.

The role of QFD in the concurrent engineering platform is as a ‘feed-forward’ mechanism rather than a feedback one. That is, the benefit of using QFD would appear *before* the design of a product rather than after its completion. The integrated information revealed by QFD provides the designer with better understanding about the constraints from other functional departments. Therefore, undesirable design attributes would be noted beforehand and be avoided during the design process.

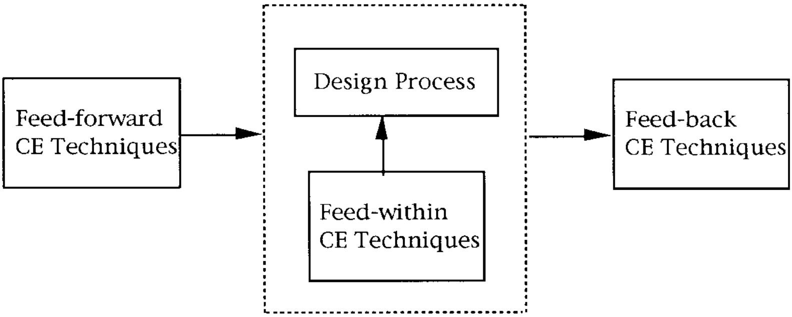

Figure 3. Flowchart of selecting CE environments.

3.4. *Mathematical programming*

Some studies adopt a mathematical programming approach to model the concurrent interaction of product and process factors. A typical example is given by Dowlatshahi (1992). In his model, the objective function is described by utility values which reflect the combined significance of some product life-cycle factors such as durability, performance, manufacturability, reliability, and safety and the constraints involve manufacturing cost and total budget. The solution space of alternative designs is assumed to be well defined, and the optimal design can be identified by solving an integer programming model.

Compared with previously mentioned CE techniques, the mathematical programming approach is relatively more 'concurrent'. The design and other life-cycle factors are concurrently modelled in an analytical way and an optimal solution can be determined. However, the merits of such an approach are based on an implicit assumption–all constraints or concerns from other functional departments can be precisely quantified so as to validate their mathematical relationships. Such an approach is mostly used in determining the values of some design variables.

The essence of applying mathematical programming to CE can be seen as a 'feed-within' mechanism; that is, designers use such techniques during the design process. In a feed-back mechanism, the constraints from other product life-cycle factors are established after the completion of a design, in a feed-forward mechanism, the constraints are established before the start of a design (figure 3).

3.5. *Constraint-based programming languages*

Another CE technique for modelling the constraints of product life-cycle factors to facilitate design activities is the use of constraint-based programming languages. A typical example of this approach is given by Young *et al.* (1992). In their work, design activities are regarded as searching design alternatives which satisfy constraints of product life-cycle factors. The life-cycle constraints, which could mutually interact, are modelled by a network, by virtue of sharing variables. A valid design alternative can be automatically generated by the system, which is represented by a set of variable values that satisfy each constraint of the network.

Compared with the mathematical approach, the constraint-based programming technique is effective in providing more flexibility and ease for users to model their constraints. However, the optimal solution is not necessarily provided since there is no criterion for the justification. The essence of constraint-based programming can be seen as a 'feed-within' mechanism.

3.6. *Other CE techniques*

There are other methods which have been well-known for some time, but can be acknowledged as CE techniques. Examples of these involve group technology (GT), design by using handbook, and design verification by checklist. Each of these CE techniques can be classified into one of the above three types of checking whether its application is in the stage of before-design, within-design, or after-design. We can therefore categorize various CE techniques into three types: feed-forward, feed-within, and feed-back.

4. Selection of the appropriate CE environments

It is necessary to have a systematic approach to justify the cost/benefit of any CE environment. By a CE environment, we mean the use of one or several CE techniques in a particular design situation. Such a systematic approach is proposed following the steps shown in figure 4.

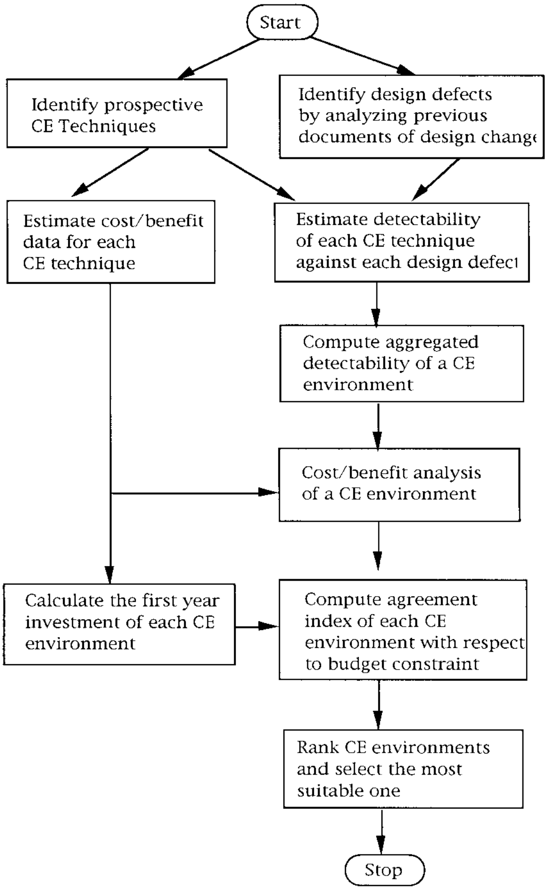

Figure 4. Relationship between feed-forward, feed-within, and feed-back techniques.

4.1. *Estimating the detectability of individual CE techniques*

In practice, documents of design change are generally available in a company to serve as a communication medium to inform the designers how to change their designs. Some of these documents may be issued as a result of demand change, while some others may be issued because of the existence of design defects. The concrete examples of design defects recorded in the documents can be used to interview relevant experts to evaluate the effectiveness of a CE technique. A survey question can be designed as follows.

> If a CE technique (T_i) is used to improve the existing design process, what is the possibility of finding or avoiding a particular design defect (D_j) which was recorded in a document of design change?

The interviewed experts are requested to give their evaluation through a designed rating scale, {'very low', 'low', 'medium', 'high', 'very high'}. The possibility of finding or avoiding a design defect is a linguistic variable, which is briefly known as *detectability*. And the above five ratings are linguistic values with membership functions as shown in figure 2.

Suppose there are n CE techniques $(T_1, T_2, \ldots, T_n)$ which are considered to be introduced to a particular company. These n CE techniques would form m or $2^n - 1$ alternatives of CE environments, $(A_1, A_2, \ldots, A_m)$, where

$A_t = (a_{t1}, a_{t2}, \ldots, a_{tn})$;
$a_{ti} \in \{0, 1\}$
if technique T_i is included in alternative A_t
then $a_{ti} = 1$
otherwise $a_{ti} = 0$

By analysing the documents of design change issued in the past z years, k design defects $(D_1, D_2, \ldots, D_k)$ can be identified. Through a survey of experts, the detectability of each CE technique can be determined and denoted by a vector $\underline{E_i} = (E_{i1}, E_{i2} \ldots, E_{ik})$, where E_{ij} is a TFN which represents the detectability of CE technique T_i against design defect D_j. Note that the detectability of technique T_i against design defect D_j under environment A_t can be represented by b_{tij}, where $b_{tij} = a_{tj} \cdot E_{ij}$.

4.2. *Estimating cost/benefit data of the individual CE technique*

The annual cost of utilizing a CE technique involves two major cost items and can be described as follows:

$$C_i = O_i + h_i / r_i,$$

where

C_i is the annual cost of utilizing CE technique T_i
h_i is the installation cost of CE technique T_i
r_i is the years of depreciation for the installation cost h_i
O_i is the annual operation cost of CE technique T_i.

The h_i, r_i, and O_i values can be estimated by relevant personnel by requesting them to give the lower bound, the most probable value, and the upper bound. And the cost of utilizing CE techniques can be denoted by a vector $\underline{C} = (C_1, C_2, \ldots, C_n)$, where $C_i = (C_{i1}, C_{i2}, C_{i3})$, a TFN, represents the annual cost of utilizing technique T_i.

Likewise, the loss saving (benefit) of finding or avoiding a design defect can be modelled by a vector $\bar{S} = (S_1, S_2, \ldots, S_k)$ where $S_j = (S_{j1}, S_{j2}, S_{j3})$ is a TFN, which represents the amount of loss saving due to the detection of design defect D_j.

4.3. *Computing aggregated detectability of a CE environment*

In a CE environment, the quality of a design alternative is first influenced by the feed-forward techniques, then by the feed-within, and finally by the feed-back ones (figure 3). Based on the sequential processing characteristic, we propose a hierarchical structure for computing the aggregated detectability of a CE environment as illustrated in figure 5.

Let $\bar{U}_t = (u_{t1}, u_{t2}, \ldots, u_{tk})$ be a vector of TFNs, where u_{tj} represents the aggregated detectability against design defect D_j under CE environment A_t. Referring to figure 5, the procedure for computing the aggregated detectability (u_{tj}) can be explained below. Note that in the following presentation, groups G_1, G_2, and G_3 represent the set of feed-forward, feed-within and feed-back techniques respectively.

Step 1. Compute the aggregated detectability of group G_1:

$$g_{1tj} = Y_{p1}(b_{t1j}, \ldots b_{tij}, \ldots, b_{tnj}), \ \forall T_i \in G_1,$$

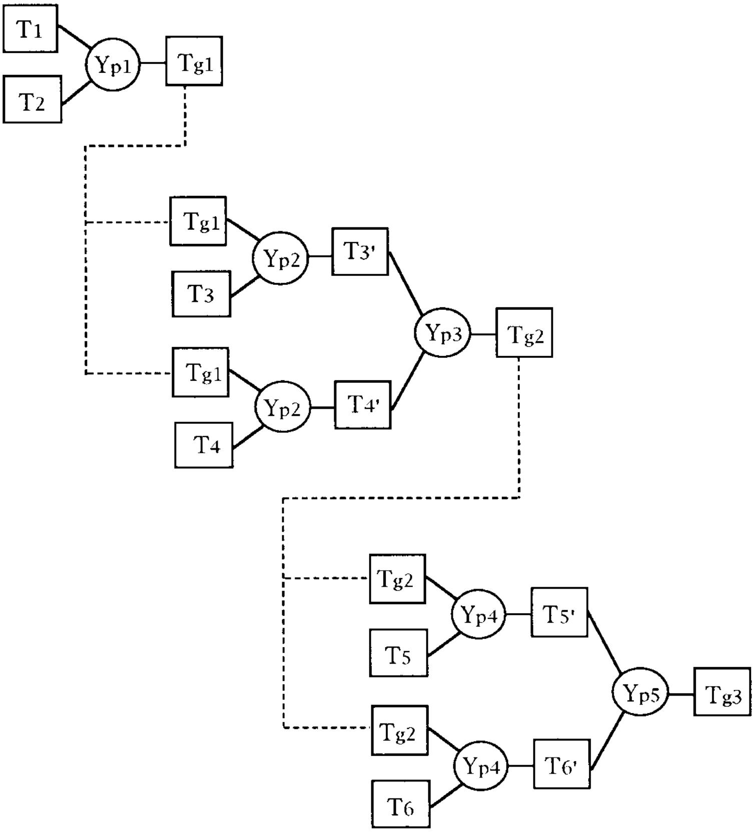

Figure 5. Hierarchical structure for determining the aggregated detectability of a CE environment. Y_{pi} is an adaptable union operator with p_i as the parameter value.

where

g_{1tj} is the aggregated detectability of group G_1 against defect D_j under environment A_t,

b_{tij} $= a_{tj} \cdot E_{ij}$, the detectability of technique T_i against design defect D_j under environment A_t,

Y_{p1} is the proposed union operator with parameter p_1.

Step 2. Compute the enhanced detectability of each CE technique in group G_2, due to the influence from group G_1.

$$b'_{tij} = Y_{p2}(g_{1tj}, b_{tij}); \ \forall T_i \in G_2,$$

where

b'_{tij} is the enhanced detectability of technique T_i (in group G_2) against design defect D_j under environment A_t.

Step 3. Compute the aggregated detectability of group G_2, in the presence of group G_1.

$$g_{2tj} = Y_{p3}(b'_{t1j}, \ldots, b'_{tij}, \ldots, b'_{tnj}), \ \forall T_i \in G_2,$$

where

g_{2tj} is the aggregated detectability of group G_2 in the presence of group G_1.

Step 4. Compute the enhanced detectability of each CE technique in group G_3, due to the influence from groups G_1 and G_2

$$b'_{tij} = Y_{p4}(g_{2tj}, b_{tij}); \ \forall T_i \in G_3,$$

where

b'_{tij} is the enhanced detectability of technique T_i in group G_3.

Step 5. Compute the aggregated detectability of environment A_t; that is the aggregated detectability of group G_3 in the presence of groups G_1 and G_2.

$$u_{tj} = g_{3tj} = Y_{p3}(b'_{t1j}, \ldots, b'_{tij}, \ldots, b'_{tnj}), \ \forall T_i \in G_3,$$

where

u_{tj} is the aggregated detectability of environment A_t against design defect D_j.

4.4. *Cost/benefit analysis of a CE environment*

As stated, the design defects are collected from the documents of design change in the last z years. The cost/benefit analysis for the utilization of a CE environment therefore is considered on the basis of this time horizon.

The cost (Q_t) for utilizing a CE environment A_t can be computed as follows:

$$Q_t = \left(\sum_{i=1}^{n} a_{ti} \cdot C_i \right) \cdot z,$$

where

$$a_{ti} = \begin{cases} 1 & \text{if technique T}_\text{i} \text{ is included in the CE environment} \\ 0 & \text{otherwise} \end{cases}$$

C_i annual cost of utilizing technique T_i

z concerned time horizon for the economic justification

n total number of prospective CE techniques.

The benefit (B_t) for utilizing a CE environment A_t can be computed as below.

$$B_t = \sum_{j=1}^{k} u_{tj} \cdot S_j,$$

where

u_{tj} is the aggregated detectability against design defect D_j under CE environment A_t
S_j is the loss saving due to the detection of design defect D_j
k total number of design defects.

Finally, the net benefit (N_t) for CE environment A_t can be formulated as below.

$$N_t = B_t - Q_t.$$

Note that N_t is a TFN. Therefore, to choose the CE environment which has maximum net benefit, a ranking method of fuzzy numbers should be discussed. Many criteria for the ranking of fuzzy numbers have been available in the literature. For ease of computation, one criterion known as a *removal number* is used in this research (Kaufmann and Gupta 1985).

Let A be a fuzzy number. Referring to figure 6, the removal number of A with respect to 0 is defined as the mean of two areas, $R_l(A)$ and $R_r(A)$. $R_l(A)$ denotes the area bounded by left side of A and $x = 0$, and $R_r(A)$ denotes the area bounded by the right side of A and $x = 0$. If A is a triangular fuzzy number (TFN), then the removal

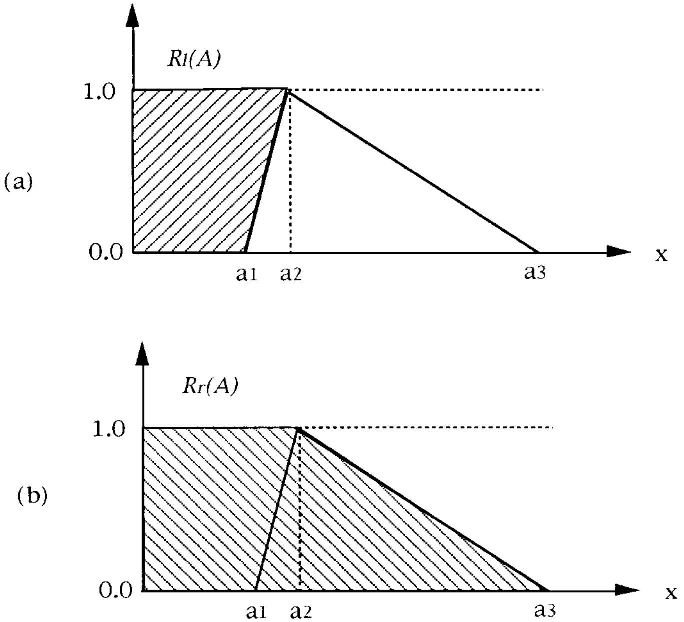

Figure 6. (a) $R_l(A)$: the area bounded by $x = 0$ and the left side of the triangular fuzzy number (a_1,a_2,a_3); (b) $R_r(A)$: the area bounded by $x = 0$ and the right side of the triangular fuzzy number (a_1,a_2,a_3).

number of A, denoted by $\hat{A}$, can be given as follows (Kaufmann and Gupta 1985). The higher the value of $\hat{A}$, the higher rank the fuzzy number A.

$$\hat{A} = \frac{a_1 + 2a_2 + a_3}{4}, \text{ where } A = (a_1, a_2, a_3), \text{ a TFN.}$$

4.5. *Selection of CE environments under budget constraint*

To introduce a CE environment A_t, the investment amount of the first year (I_t) would involve the installation cost and one year operation cost, which can be given below. This investment amount is usually the proposed budget in a proposal for carrying a project.

$$I_t = \sum_{i=1}^{n} a_{ti} \cdot (h_i + C_i).$$

In any budgeting process, it is difficult to develop a total budget with precision. For this reason, a more realistic approach is by modelling the budget threshold by a fuzzy number. Suppose the budget threshold for introducing a CE environment is a fuzzy number L, with its membership function as shown in figure 7a, which shows that a proposed budget between 0 and L_1 is acceptable, and the upper bound of the proposed budget is L_2.

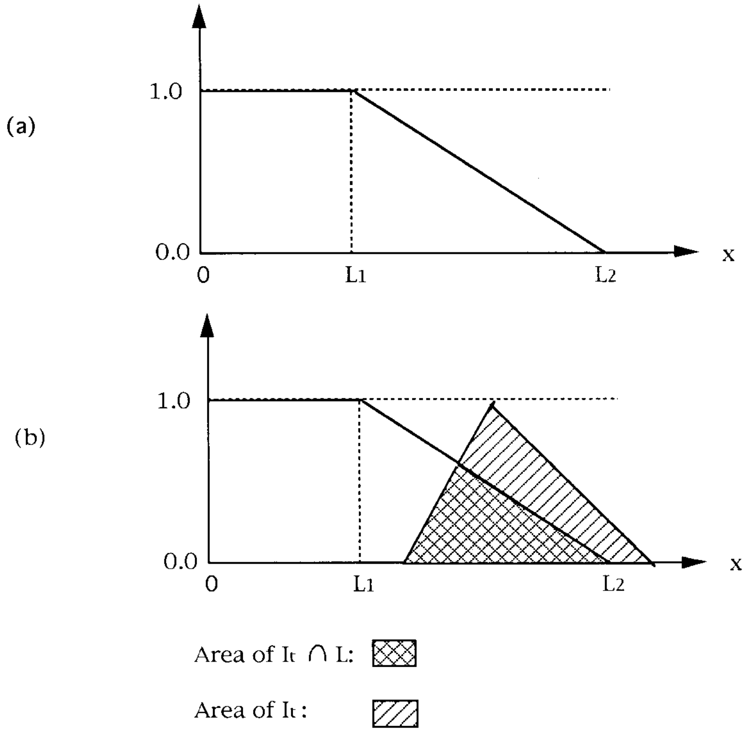

Figure 7. (a) Budget constraint (L) is a fuzzy number; (b) the agreement index of a proposed budget (I_t) against the budget constraint (L).

In this research, an *agreement index* is defined to determine the degree to which the proposed budget (I_t) agrees with the budget threshold (L) (Kaufmann and Gupta 1985). Referring to figure 7(b), the agreement index (x_t) is defined as follows:

$$x_t = (\text{area of } I_t \cap L)/(\text{area of } I_t).$$

A threshold of agreement index, x_0, can be given to determine whether a CE environment (A_t) can be recommended in the sense of budget constraint. That is,

If $x_t \geq x_0$
then $y_t = 1$ (alternative A_t satisfies budget constraint);
otherwise $y_t = 0$ (alternative A_t does not satisfy the budget constraint).

Finally, the most suitable CE environment for the company to introduce can be identified by first sorting out the set of alternatives which satisfy the budget constraint, then selecting the one in the set which has the highest net benefit.

5. Example

In this section, a hypothetical CE environment selection problem is designed to demonstrate the computational process of the proposed approach.

Step 1. Suppose a company intends to introduce CE techniques. After a screening, three CE techniques T_1, T_2, T_3 are identified as candidates, which respectively belong to feed-forward, feed-within, and feed-back types. Relevant experts are invited to estimate the installation cost (h_i), the years of depreciating the installation cost (r_i) and annual operation cost (C_i), and the collected data is as shown in table 2.

Step 2. Documents of design change issued in the last three years ($z = 3$) are analysed and four design defects D_1, D_2, D_3, D_4 are identified. Relevant experts are invited to evaluate the detectability of each prospective CE technique against each design defect, and the result is shown in table 3.

CE techniques	h_i ($\$ \times 10^4$)	r_i (years)	o_i ($\$ \times 10^4$)	c_i ($\$ \times 10^4$)
T_1	(12, 15, 18)	3	(7, 10, 13)	(11, 15, 19)
T_2	(20, 25, 30)	5	(2, 4, 6)	(6, 9, 12)
T_3	(40, 45, 50)	5	(2, 4, 6)	(10, 13, 16)

Table 2. Cost data relevant to example CE techniques.

	Design defects			
CE techniques	D_1	D_2	D_3	D_4
T_1	M	VH	M	L
T_2	H	L	VH	M
T_3	VH	L	H	VH

Table 3. Detectability of example CE techniques against design defects.

S_1	S_2	S_3	S_4
(80, 100, 120)	(120, 150, 180)	(220, 250, 280)	(250, 300, 350)

Table 4. Amount of loss saving due to the finding of design defects ($\$ \times 10^4$).

CE environment	Design defects			
	D_1	D_2	D_3	D_4
$A_1 = (1,0,0)$	(0.2, 0.5, 8)	(0.7, 1, 1)	(0.2, 0.5, 0.8)	(0, 0.3, 0.5)
$A_2 = (0,1,0)$	(0.5, 0.7, 1)	(0, 0.3, 0.5)	(0.7, 1, 1)	(0.2, 0.5, 0.8)
$A_3 = (0,0,1)$	(0.7, 1, 1)	(0, 0.3, 0.5)	(0.5, 0.7, 1)	(0.7, 1, 1)
$A_4 = (1,1,0)$	(0.5, 0.74, 1)	(0.7, 1, 1)	(0.7, 1, 1)	(0.2, 0.52, 0.83)
$A_5 = (1,0,1)$	(0.7, 1, 1)	(0.7, 1, 1)	(0.5, 0.74, 1)	(0.7, 1, 1)
$A_6 = (0,1,1)$	(0.74, 1, 1)	(0, 0.36, 0.6)	(0.74, 1, 1)	(0.7, 1, 1)
$A_7 = (1,1,1)$	(0.74, 1, 1)	(0.7, 1, 1)	(0.74, 1, 1)	(0.7, 1, 1)

Table 5. Aggregated detectability of CE environment alternatives.

Step 3. The amount of loss saving (S_j) due to the finding of a design defect (D_j) has been estimated as shown in table 4.

Step 4. The aggregated detectability for each alternative of CE environment is shown in table 5. The corresponding parameter p values of the proposed union operator are given below. Note that the lower the p value, the higher the corresponding aggregated detectability.

$$p_1, p_3, p_5 \to \infty$$

$$p_2, p_4 = 4.$$

Taking alternative $A_4 = (1,1,0)$ with respect to design defect D_1 as an example, the computing procedure for deriving the results in table 5 is illustrated below. In alternative A_4, technique T_1 and T_2 are utilized, and their detectabilities are 'medium' and 'high' respectively (table 3), and can be represented by two TFNs (0.2, 0.5, 0.8) and (0.5, 0.7, 1) by referring to figure 2. The aggregated detectability of alternative A_4 denoted by (q_1, q_2, q_3), can be computed as follows.

$$q_1 = \mathrm{Min}\left\{1, \left((0.2)^4 + (0.5)^4\right)^{1/4}\right\} = 0.5$$

$$q_2 = \mathrm{Min}\left\{1, \left((0.5)^4 + (0.7)^4\right)^{1/4}\right\} = 0.74$$

$$q_3 = \mathrm{Min}\left\{1, \left((0.8)^4 + (1.0)^4\right)^{1/4}\right\} = 1.0.$$

Step 5. The cost, benefit, and net benefit of each CE environment alternative can be computed as shown in table 6.

CE environment	Q_t (\$ × 10^4)	B_t (\$ × 10^4)	N_t (\$ × 10^4)
$A_1 = (1,0,0)$	(33, 45, 57)	(144, 415, 675)	(111, 370, 618)
$A_2 = (0,1,0)$	(18, 27, 36)	(244, 515, 770)	(226, 488, 734)
$A_3 = (0,0,1)$	(30, 39, 48)	(341, 620, 840)	(311, 581, 792)
$A_4 = (1,1,0)$	(51, 72, 93)	(378, 630, 870)	(327, 558, 777)
$A_5 = (1,0,1)$	(63, 84, 105)	(425, 735, 930)	(362, 651, 835)
$A_6 = (0,1,1)$	(48, 66, 84)	(398, 704, 958)	(350, 638, 774)
$A_7 = (1,1,1)$	(81, 111, 141)	(482, 800, 930)	(401, 689, 789)

Table 6. Cost/benefit analysis of CE environment alternatives.

CE environment	I_t (\$ × 10^4)	x_t	y_t	$\hat{N}_t$ (\$ × 10^4)	Rank
$A_1 = (1,0,0)$	(19, 25, 31)	1.0	1	367	5
$A_2 = (0,1,0)$	(22, 29, 36)	1.0	1	484	4
$A_3 = (0,0,1)$	(42, 49, 56)	1.0	1	566	3
$A_4 = (1,1,0)$	(41, 54, 67)	1.0	1	570	2
$A_5 = (1,0,1)$	(61, 74, 87)	0.96	1	622	1
$A_6 = (0,1,1)$	(64, 78, 92)	0.68	0	*	*
$A_7 = (1,1,1)$	(83, 103, 123)	0.15	0	*	*

Table 7. Investment amount and ranking of CE alternatives (budget threshold is L1 = \$75 × 10^4 and L2 = \$85 × 10^4).

Step 6. The investment amount for each CE environment, and its agreement index can be computed as shown in table 7. Suppose the decision maker set a value of 0.8 as the threshold agreement index. Then alternative A_5 will be selected as the most suitable one in the context. This alternative suggests that CE techniques T_2 and T_3 both be introduced to the company.

6. Concluding remarks

A fuzzy-set theory approach to justify the selection of concurrent engineering (CE) environments has been proposed.

Existing CE techniques are classified into three types: feed-forward, feed-within, and feed-back, which respectively influence the quality of a design process in the following three stages: before-design, during-design, and after-design. This classification is intended to highlight the interacting relationships among various types of CE techniques. That is, the utilization of CE techniques at the upper-stream stage will enhance the effectiveness of CE techniques utilized at the down-stream stage.

Previous documents of design change which denote the existence of design defects are used to evaluate the effectiveness or detectability of each CE technique. The detectability of a CE technique against a particular design defect is modelled by a triangular fuzzy number. An adaptable union operation is proposed for computing the aggregated detectability of several CE techniques.

The benefit of utilizing a CE environment is evaluated based on the aggregated detectability and the amount of loss saving due to the removal of each design defect.

The benefit/cost data of utilizing a CE environment are all modelled by triangular fuzzy numbers; therefore, the net benefit of utilizing a CE alternative is also a triangular fuzzy number.

The annual budget constraint for introducing a CE environment is represented by a fuzzy number. An agreement index is calculated for representing the degree to which a particular CE alternative can be accepted. The CE alternative, whose agreement index satisfies the threshold value and has the largest net benefit, is finally selected as the optimal one.

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