INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

A METHOD FOR COMPARATIVE EVALUATION OF PRODUCT LIFE CYCLE ALTERNATIVES UNDER UNCERTAINTY

Srinivas Kota[1] and Amaresh Chakrabarti[1]

[1]IDeaSLab, Centre for Product Design and Manufacturing, Indian Institute of Science, Bangalore, India

ABSTRACT
Decisions made in preliminary stages of the design will have greater impact on the later stages of the product development. In each stage of design, we need to evaluate alternatives based on multiple criteria. There is a need for a method that can aid in decision making by supporting quantitative comparison of available alternatives to identify the best alternative, under uncertain information about alternatives. Classical evaluation methods like weighted objectives method assumes certainty about information available during product development. However, designers often must evaluate under uncertainty. Often the likely performance, cost or environmental impacts of a product proposal could be estimated only with certain confidence, which may vary from one proposal to another. While one proposal may be a minor modification of a known product, another might have large areas of uncertainty due to its being substantially novel. In such situations, the classical approaches to evaluation can give misleading results. A method called *confidence weighted objectives method* is developed to compare the whole life cycle of product proposals using multiple evaluation criteria under various levels of uncertainty. It is compared with normal weighted objectives method and found to be better since it estimates the overall worth of proposal and confidence on the estimate, enabling deferment of decision making when decisions cannot be made using current information available.

Keywords: uncertainty in design, decision making, multi-criteria analysis, life cycle design, weighted average, life cycle thinking

1 INTRODUCTION
Decisions made during preliminary stages of the design will have greater impact on the later stages of product development. In each stage of design the alternatives must be evaluated, based on multiple criteria. There is a need for a method that can aid in decision making by supporting quantitative comparison of available alternatives to identify the best alternative. Comparative evaluation of alternatives is essential in designing. Classically, quantitative comparative evaluation needs three kinds of information [1]:

- criteria for evaluation
- relative weights of these criteria, and
- estimated value of each alternative with respect to each criterion.

The alternatives can then be compared:

- against a single criterion: by comparing the values of the alternatives for that criterion
- against all criteria: by integrating the values for all criteria (say as a weighted sum) for each alternative, and then comparing the integrated values with each other.

During product development, designers often must do this under uncertainty. For instance, the likely performance, cost or environmental impacts of a product proposal could be estimated only with certain confidence which may vary from one proposal to another. While one proposal may be a minor modification of a known product, another might have large areas of uncertainty due to its being substantially novel. In such situations, the classical approaches to evaluation could give misleading results.

This is particularly true for doing trade-off analyses between performances, cost and environmental impacts of alternative product proposals, especially at the less detailed stages of development, where some aspects of these characteristics are known but with less confidence. While approaches are available for estimating the value of a proposal under uncertainty for a single criterion [2], a method for comparative evaluation of alternative proposals that uses these values and associated estimations of uncertainty is currently missing.

2 OBJECTIVES AND METHODOLOGY

The objectives are to:

1. Develop a method for comparative evaluation of proposals for given, uncertain values for a single criterion.

2. Develop a method for integrating these, for each proposal, into a single value representing its worth against all criteria considered, and developing its associated uncertainty. This, together with the method in Step 1 can then be used for comparative evaluation, under uncertainty, of alternative proposals against multiple criteria.

3 LITERATURE SURVEY

Design involves the conception of something new to satisfy a need. Design involves creativity (the generation of alternative solutions) and decision (choice among those alternatives). Many of the repetitive tasks in design are being done using the assistance of computers to save time. Routine tasks can be accomplished more quickly and efficiently through computation, and the results can be as good as those that the most experienced and talented individuals can deliver; the designer's time is better spent on questions that merit creative thinking. Although there is interaction between creativity and analysis, and enumerating more alternatives is not the only way to solve design problems, it is generally advantageous to consider a larger set of alternatives, to "increase the size of the design space" [3]. Thus the goal of engineering design is to "automate the tedious, analyze the intuitive, and communicate the experiential" [3].

Preliminary design is inherently imprecise, and has enormous economic importance. Much of the cost of a design is determined by preliminary decisions [4], which are often informal and rely on imprecise information. Research is done in engineering, in design theory, in multi-objective optimization, and in multi-criteria decision making to consider simultaneously different attributes for decision making. Most often, the parameters used in these are taken with complete certainty. However, in preliminary phases of design the parameters are uncertain, so we need to consider this uncertain nature of the parameters while evaluating alternatives and making decisions.

The development of explicit design evaluation procedures has been recognized as a crucial step toward development of a more formal theory and methodology of design [5]. There are different methods available for decision making in design. Some of these are discussed in this section.

In [1, 6, and 7] there is mention about different methods used for evaluating product concepts. Ordinal methods like heuristic decision rules, satisfying alternatives, elimination by aspects, new product profiles, the datum method, paired comparison, rank correlation, the majority rule, the Copeland rule, the rank-sum rule, the lexicographical rule, Pugh's concept selection method or decision matrix method are qualitative in nature, and aggregation is the weak point in these methods. Cardinal methods like the weighted objectives method, the additive value function are quantitative in nature. All these methods are useful in decision making under certainty. But in the initial phases of design, information is uncertain and different or modified methods are needed to support decision making.

Methods such as the Method of Imprecision (MoI) [8, 9] which is developed using fuzzy set theory as the basis, or the Methodology for the Evaluation of Design Alternatives (MEDA) [8] which is developed by using utility theory as the basis, discuss about tradeoffs that are necessary between multiple criteria in iterative design under uncertainty. In [8 and 9] for iterative design, designer-preferences on design parameters are coupled to performance parameters, and using different ways of aggregation these are put together. A set of coupled parameters that have a high degree of preference will be selected for the next step as good candidates. However, if at any specific stage, a designer does not have enough information then how to use and represent this in the final estimation is not discussed.

It is accepted that many aspects of design evaluation are highly subjective in nature, particularly in the preliminary stages. Several designers might rationally differ in their preferences for alternatives, based on the economic, institutional, manufacturing, and engineering considerations specific to their situation [10].

Interval approaches have been proposed as an alternative basis for decision making under imprecision. Boettner and Ward [1l] built a Mechanical Design Compiler that uses a labelled interval calculus to determine which components in a design catalogue are feasible with respect to algebraic constraints on real variables. Other approaches to representing imprecision in design include using utility theory, implicit representations using optimization methods, matrix methods such as Quality Function Deployment, probability methods, and necessity methods. These methods have all had limited success in solving design problems with imprecision [11].

During product development, there is a need to consider the whole life cycle of a product rather than only single isolated phases. In other words, it is necessary to design the whole life cycle of the product [12, 13]. Early stages of product development are the key in doing this because if we know the potential life cycle value of alternatives while designing, we can make changes to these then and there so as to improve them [14]. Since over 80% of the product costs are committed during the early planning and product development stages, design has the central role in deciding the behaviour of products throughout its life cycle, with respect to multiple criteria.

It is necessary to develop tools to assist the designer in the initial phases of design. The most important design decisions are made at the initial phases. The initial phases of the design process consists of concept generation, initial evaluation etc. Information available about the product in these phases is often approximate and there is a need for a tool for representing, manipulating, and evaluating approximate or uncertain descriptions of initial design proposals. These tools should be useful from initial to detailed stages of design, support designers to evaluate more alternatives in less time, and provide more information on the performance of each alternative to enable better decision-making.

4 METHOD DEVELOPMENT

From descriptive studies conducted by us, we observed mainly the following four stages in design with reference to time and related information.

Information in the ***0 – 15 % of design time*** was related to identification, analysis and selection of design problem and tasks. It is mainly in this stage that designers worked around the specification given, and tried to identify the problem and its requirements.

Information in the ***15 – 40 % of design time*** is related to finding the principles, global configuration (main assemblies, function etc) of the concept, generating, associating the ideas with the existing ones and primary evaluation. For example while solving a problem for exercising equipment, a designer thought of existing products like, skipping rope etc. Here the component shapes and material classes are thought of as ‘classes’ rather than ‘instances’ of specific class (such as the main material class).

Information in the ***40 – 80 % of design time*** is related to specifying relationships between components, subassemblies, local configuration of subsystems, and for evaluating solutions.

Information in the ***80 – 100 % of design time*** is used in fortifying all components with exact shape, dimensions, tolerances, material and process details, with exact relationships.

A summarisation of the evolution of product life cycle information with reference to design time is given in Figure 1. The evolved information is above the line (see Figure 1), and the activities performed by the designer are below the line.

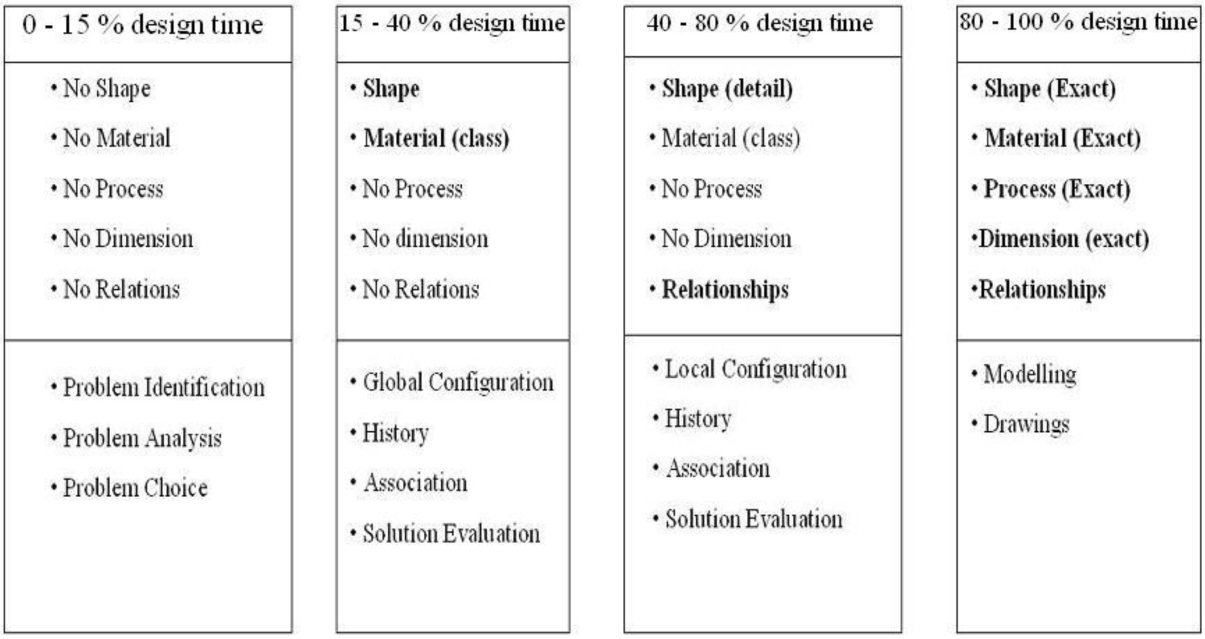

Figure 1 Information Evolution and the activities performed by the designer in design

We need to discover the above information (in Figure 1), which is required for evaluation using various criteria like performance, cost, aesthetics, environment, ergonomics etc., for the whole life cycle of a product system. Availability or lack of information for these categories will be the foundation for assessing the uncertainty involved at different stages of product development. At any point of time, information available will be one, or combination of these. We have to identify what information is required to calculate the value of a product, against a given criterion at a given state of the product, and what information is available in all these dimensions at that particular state of the product. Based on these two, the value and the confidence on the value could be calculated.

Every product concept consists of subsystems that in turn consist of components and interfaces. Thus, there are different levels at which alternative product proposals may have to be compared: a) complete product, b) different subsystems within a proposal or across different proposals c) different components within the proposal or across different proposals. Each of these can be for the whole life cycle or for a single, specific life cycle phase, using a particular criterion or multiple criteria.

In practice, we may have none or only part of this information. So based on the information we have to calculate the worth of a product at a particular state of the product, and therefore any method supporting this should be able to tell the designer something about the accuracy of the calculated result, so that decisions and tradeoffs can be made resulting in an informed manner.

As designers could require an analysis at any point of time during the design process, the support should be able to calculate the worth based on the complied information currently available and give the value of an alternative with an estimation of its confidence.

We developed a framework for comparative evaluation of product life cycle alternatives under uncertainty. This consists of two evaluation steps.

- Establish the criteria based on which a product needs to be evaluated.
- Find out the level of uncertainty in the following dimensions (given below).

Product Structure: This uncertainty is related to the subsystems, components and interfaces between them. For example we may know that there are three subsystems in the product, but may not know the interfaces between them.

Life cycle phases: This uncertainty is related to the material, production, distribution, usage, after use phases of the product life cycle. There are also sub-phases in these: extraction, manufacturing and transportation in material, manufacturing and assembly in production, packaging and transportation in distribution, use, maintenance and repair in usage, and reuse, recycle and disposal in after use phases. For example at one stage we may have information only about material of the component, and not about the other stages.

Information: Find out the difference between information required and available. Based on this calculate the uncertainty for a specific attribute for specific or individual life cycle phases.

For example, let us say that the information we have about a product is that it has three components and there is one relationship specified between these components. The product state at this point is that the product has two components. The maximum information we can have at this point is the materials of the three components, the relationships between the three components, the manufacturing processes of the three components, the manufacturing processes of the relationships, related assembly processes, after use details of the three components and relationships etc. But currently we have only a part of this information, so any evaluation of the product based on this information should have a confidence well below certainty (100%) because of the incompleteness of information at this state of the product. Figure 2 shows the uncertainties and their links.

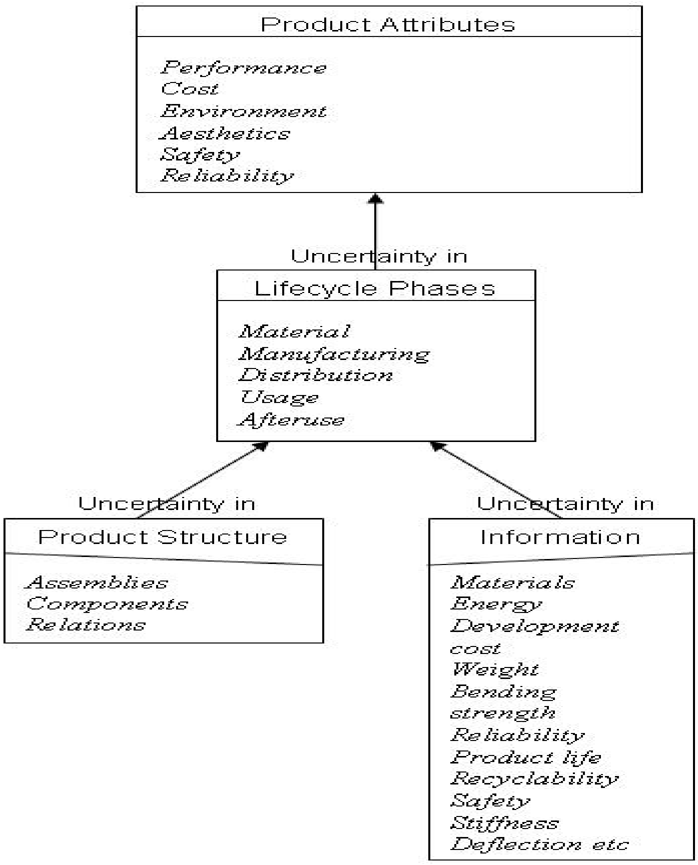

Figure 2 Uncertainty Propagation

A method is developed to estimate uncertainty in evaluation of environmental impacts during design [2]. In this paper a ***confidence weighted objective method*** (***CWOM***) is developed as discussed below.

1. Develop a method for comparative evaluation of Lifecycle proposals for given, uncertain values for a single criterion.

Let there be two product lifecycle alternatives: A, with degree of effectiveness (or value) and associated confidence (E_{a1}, C_{a1}) and (E_{a2}, C_{a2}), and B, with value and associated confidence (E_{b1}, C_{b1}) and (E_{b2}, C_{b2}), each for criteria 1 and 2 respectively. The confidence can be estimated in terms of the degree of difference between the required information and available information.

For a single criterion (say 1), the estimated values and confidence for the proposals would be related in one of the following ways:

- $E_{a1}>E_{b1}$, $C_{a1}>C_{b1}$: Here alternative A has a higher degree of effectiveness (or value) with higher confidence than alternative B. In other words, E_{a1} is likely to stay closer in reality to the estimated degree of effectiveness than E_{b1}. If the estimated degree of effectiveness are lower bounds only (e.g., for cost or environmental impact) of the actual degree of effectiveness (which would be the case with imprecise estimations of effectiveness against criteria for which effectiveness is proportional to the number of elements in the dimensions of uncertainty about which information is available), E_{a1} is likely to decrease less than E_{b1}. Hence A must be chosen as B’s degree of effectiveness is going to decrease further. This will hold good also for criteria for which estimated degree of effectiveness are upper bounds only (such as in the case of reliability).
- $E_{a1}>E_{b1}$, $C_{a1}<C_{b1}$: Here alternative A has a higher degree of effectiveness with lower confidence, and as the confidence increases there is a chance of decrease in degree of effectiveness of A so it is difficult to say with the current level of detail which of these alternatives is better. Decision must be postponed till a stage of greater detail, for more detail must be provided for a decision to be taken.
- $E_{a1}>E_{b1}$, $C_{a1}=C_{b1}$: Here A has a higher value with the same confidence and hence must be selected as better. This is similar to a classical situation.
- $E_{a1}=E_{b1}$, $C_{a1}<C_{b1}$: Here both have the same value but A has lesser confidence, which means its degree of effectiveness is likely to come down, and hence B should be chosen.
- $E_{a1}=E_{b1}$, $C_{a1}=C_{b1}$: The two alternatives are equivalent. This is also similar to a corresponding classical case.

2. Develop a method for integrating these, for each proposal, into a single value representing its worth against all criteria considered, and developing its associated uncertainty. This, together with the method in Step 1 can be used for comparative evaluation, under uncertainty, of alternative lifecycle proposals against multiple criteria.

Values for each criterion are integrated into a single value for multiple criteria and its associated confidence is estimated as follows (W_{a1}, W_{b1} are relative weights of criteria 1 and 2; E_{a12} and E_{b12} are integrated values for A and B for both criteria):

The integration is done as a confidence weighted sum:

The overall value for each alternative is calculated using the following formula:

$$E_{a_i} = \sum_{j=1}^{m} \sum_{k=1}^{l} w_{ij} \; X \; e_{ijk} \tag{1}$$

Where

i – identifier for the alternative

j – identifier for the criterion

k – identifier for the lifecycle phase

$$m - total\ number\ of\ criteria$$
$$l - total\ number\ of\ lifecycle\ phases$$
$$e_{ijk} - effectiveness\ of\ i^{th}\ alternative\ j^{th}\ criterion\ k^{th}\ lifecycle\ phase$$
$$w_{ij} - weighting\ factor\ of\ i^{th}\ alternative\ j^{th}\ criterion$$

Its confidence is estimated as follows:

$$C_{a_i} = \frac{\sum_{j=1}^{m} \sum_{k=1}^{l} (w_{ij})(c_{ijk})(e_{ijk})}{\sum_{j=1}^{m} \sum_{k=1}^{l} (w_{ij})(e_{ijk})} \qquad (2)$$

$$Where$$
$$i - identifier\ for\ the\ alternative$$
$$j - identifier\ for\ the\ criterion$$
$$k - identifier\ for\ the\ lifecycle\ phase$$
$$m - total\ number\ of\ criteria$$
$$l - total\ number\ of\ lifecycle\ phases$$
$$w_{ij} - weighting\ factor\ of\ i^{th}\ alternative\ j^{th}\ criterion$$
$$c_{ijk} - confidence\ of\ i^{th}\ alternative\ j^{th}\ criterion\ k^{th}\ lifecycle\ phase$$
$$e_{ijk} - effectiveness\ of\ i^{th}\ alternative\ j^{th}\ criterion\ k^{th}\ lifecycle\ phase$$

This is because the overall confidence for the integrated value is a weighted sum of individual confidence where the weights are proportional to the component of the value affected by the corresponding confidence.

The best solution should be selected based on the following guidelines in Table 1.

Table 1 Guidelines for selection of best alternative using confidence weighted average method

No.	Value	Confidence	Selection
1	$E_a > E_b$	$C_a > C_b$	Here alternative B has lower value with low confidence therefore A must be chosen as B's value can come down as confidence increases.
2	$E_a > E_b$	$C_a < C_b$	Here alternative A has a higher value with lower confidence, and as confidence goes up value comes down so Decision can't be taken so go for greater detail.
3	$E_a > E_b$	$C_a = C_b$	Here A has a higher value with the same confidence and hence must be selected as better. This is similar to a classical situation
4	$E_a = E_b$	$C_a < C_b$	Here both have the same value but A has lower confidence, which means its value is likely to come down, and hence B should be chosen
5	$E_a = E_b$	$C_a = C_b$	The two alternatives are equivalent. This is also similar to a corresponding classical case

5 EVALUATION

Comparison of two alternatives with varying uncertainty (high, moderate, low) has been done. Tables 2-4 show the degree of effectiveness and confidence on three life cycle phases (material, manufacturing, distribution) for three criteria (Cost, weight, Environment impact) for alternative1. If values for all the criteria are uncertain we considered that as high uncertainty, and all the values for all the criteria are certain we considered that as certainty. The numbers in parenthesis beside each criterion name are weight (importance) for that criterion.

Table 2 Values of Degree of Effectiveness and Confidence (high uncertainty)

	Cost (30)		Weight (30)		Environmental Impact (40)	
	DoE	Con	DoE	Con	DoE	Con
Material	6	60	5	40	8	60
Manufacturing	5	50	4	30	5	50
Distribution	3	40	1	20	3	20

Table 3 Values of Degree of Effectiveness and Confidence (moderate uncertainty)

	Cost (30)		Weight (30)		Environmental Impact (40)	
	DoE	Con	DoE	Con	DoE	Con
Material	4	80	2	100	6	80
Manufacturing	4	70	2	100	5	80
Distribution	2	50	1	100	2	60

Table 4 Values of Degree of Effectiveness and Confidence (low uncertainty)

	Cost (30)		Weight (30)		Environmental Impact (40)	
	DoE	Con	DoE	Con	DoE	Con
Material	2	100	2	100	5	80
Manufacturing	3	100	2	100	3	80
Distribution	1	100	1	100	1	90

Tables 5-7 show the degree of effectiveness and confidence on three life cycle phases (material, manufacturing, distribution) for three criteria (Cost, weight, Environment impact) for alternative2.

Table 5 Values of Degree of Effectiveness and Confidence (high uncertainty)

	Cost (30)		Weight (30)		Environmental Impact (40)	
	DoE	Con	DoE	Con	DoE	Con
Material	5	50	5	50	6	40
Manufacturing	5	40	7	40	3	30
Distribution	4	30	4	30	2	40

Table 6 Values of Degree of Effectiveness and Confidence (moderate uncertainty)

	Cost (30)		Weight (30)		Environmental Impact (40)	
	DoE	Con	DoE	Con	DoE	Con
Material	3	75	2	100	5	65
Manufacturing	4	80	3	100	3	70
Distribution	2	75	1	100	2	90

Table 7 Values of Degree of Effectiveness and Confidence (low uncertainty)

	Cost (30)		Weight (30)		Environmental Impact (40)	
	DoE	Con	DoE	Con	DoE	Con
Material	2	100	2	100	3	80
Manufacturing	2	100	3	100	2	90
Distribution	1	100	1	100	2	90

Substituting the values in Tables 2 – 7 in *Eq.1* and *Eq.2* the final values obtained are given in the following table 8.

Table 8 Aggregated Degree of Effectiveness and Confidence

	Alternative1		Alternative2		Selection using weighted average	Selection using our guidelines
Uncertainty	DoE	Con	DoE	Con		
High	1360	46.83%	1440	36.80%	A2	Need more detail
Moderate	970	78.35%	850	79.35%	A1	Need more detail
Low	690	90.14%	610	93.44%	A1	A1

From this table we can see that selection using normal weighted average is not consistent with the uncertainty involved with the estimates. Using the proposed method and guidelines seem to provide better consistency. Under the above cases of high or moderate uncertainty, if weighted average method is used, the decisions taken could lead to rejecting potentially better alternatives, unlike using the proposed method, which suggests deferment of judgement in the above cases until more detail to make the judgement was available.

6 CONCLUSIONS

A method is developed for use in multi-criteria decision making for lifecycle designs of product systems. The uncertainty due to different elements is explored and used to develop a method and guidelines for comparative evaluation of alternatives under uncertainty. A comparative analysis is done using the weighted average method (WAM) that is normally used in early stages of design, and the proposed confidence weighted objective method (CWOM). It was found that the proposed method provides more consistency in decision making through the different stages with varying uncertainty.

REFERENCES

[1] Roozenburg N F M, and Eekels K. *Product Design: Fundamentals and Methods*, 1994 (John Wiley & Sons, Chichester)

[2] Srinivas Kota and Amaresh Chakrabarti, Development of a method for estimating uncertainty in evaluation of environmental impacts during design, submitted to ICED07, 2007.

[3] Michael J Scott, Formalizing Negotiation in Engineering Design, PhD Thesis 1999 (California Institute of Technology Pasadena, California).

[4] D. E. Whitney, Manufacturing by design. *Harvard Business Review*, 1988, 66(4), pp.83–91.

[5] Chandrasekran B., A Framework for Design Problem-Solving, Research in Engineering Design, 1989, 1(2), pp.75-86.

[6] Rudolph J Eggert, *Engineering Design*, 2005 (Pearson Prentice Hall, New Jersey)

[7] David G Ullman, *The Mechanical Design Process*, 1997 (Mcgraw-Hill Companies, New York).

[8] K. L. Wood, K. N. Otto, and E. K. Antonsson. Engineering Design Calculations with Fuzzy Parameters. *Fuzzy Sets and Systems*, 1992, 52(1), pp.1-20.

[9] K. N. Otto and E. K. Antonsson. Trade-off Strategies in Engineering Design. *Research in Engineering Design*, 1991, 3 (2), pp.87-104.

[10] Deborah L Thurston, A Formal Method for Subjective Design Evaluation with Multiple Attributes, *Research in Engineering Design*, 1991, 3(2), pp.105-122.

[11] D.D. Boettner and A.C. Ward, Design Compilers and the Labeled Interval Calculus: A Tutorial, *Artificial Intelligence in Engineering Design*, 1992, pp.135-192 (Academic Press).

[12] Schott H., et. al. Sustainable Product Development – A Challenge for Design Science, In *International Conference on Engineering Design, ICED '97, Vol.3*, Tampere, August 1997, pp.665-668 (Tampere University of Technology, Tampare).

[13] Reiner Anderl, et. al. Life Cycle Modelling-A cooperative method supports experts in the entire product life cycle, In *International Conference on Engineering Design ICED '99, Vol.3*, Munich, August 1999, pp.1801-1804. (Technische Universität München, Garching),.

[14] Mueller K, Lampérth M (2001) 'Parameterised inventories for approximate life-cycle

assessment', In *International Conference on Engineering Design, ICED '01, Vol.1*, Glasgow, August 2001, pp. 669-676. (Professional Engineering Publishing, Bury St Edmunds)

[15] G Pahl and W Beitz, *Engineering Design – A systematic Approach*, 1998 (Springer-Verlag).

Contact: Amaresh Chakrabarti,
Indian Institute of Science,
Centre for Product Design and Manufacturing,
Indian Institute of Science, Bangalore - 560012,
India
Phone: +91-80-22933136
Fax: +91-80-23601975
e-mail: ac123@cpdm.iisc.ernet.in
URL: http://cpdm.iisc.ernet.in/people/ac/ac.htm.