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A METHOD FOR EVALUATION OF PRODUCT LIFECYCLE ALTERNATIVES UNDER UNCERTAINTY

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ABSTRACT
Decisions made in the preliminary stages of product development typically have a substantial impact on the product. In each stage of product development, we need to take decisions, by evaluating multiple product alternatives based on multiple criteria. 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. There is a need for a method that can aid in decision making by supporting quantitative comparison of alternatives to identify the most promising alternative, under uncertain information about the alternatives. 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 with non crisp values. 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 evaluation, life cycle design, weighted average, interval arithmetic

1 INTRODUCTION
Decisions made in the preliminary stages of product development typically have a substantial impact on the product. In each stage of product development alternative product proposals 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 most promising alternative. Comparative evaluation of alternatives is essential in designing. Classically, quantitative comparative evaluation requires 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 one another.

During product development, designers often must carry out evaluation 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, 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. Approaches are available for estimating the value of a proposal under uncertainty for a single criterion [2], and for comparative evaluation of alternative proposals that uses these values and associated estimations of uncertainty [3]. These are useful in comparative analysis of alternatives using crisp values but the proposed method is useful in comparative analysis of alternatives using range of values (approximate), which are common with uncertain information. These require understanding the issues in comparison with point-interval values and interval-interval values.

2 OBJECTIVES AND METHODOLOGY

The objectives are to:

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

2. Develop a method for integrating these, for each proposal, into a single interval value representing its worth against all criteria considered, and developing its associated uncertainty in interval. 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 require 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" [4]. Thus the goal of engineering design is to "automate the tedious, analyze the intuitive, and communicate the experiential" [4].

Preliminary design is inherently imprecise, and has enormous economic importance. Much of the cost of a design is determined by preliminary decisions [5], 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 stages 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 [6]. There are different methods available for decision making in design. Some of these are discussed in this section.

In [1, 7, and 8] 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 a weak point of these methods. Cardinal methods like the weighted objectives method, the additive value function are quantitative in nature. These methods are useful in decision making under certainty. But in the initial stages of design, information is uncertain, and different or modified methods are needed to support decision making.

Methods such as the Method of Imprecision (MoI) [9, 10], which is developed using fuzzy set theory as the basis, or the Methodology for the Evaluation of Design Alternatives (MEDA) [9] 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 [9 and 10] 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 stage, a designer does not have enough information, it is not clear how to use and represent this in the final estimation.

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 [11].

Interval approaches have been proposed as an alternative basis for decision making under imprecision. Boettner and Ward [12] 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 [12].

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 [13, 14]. 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 [15]. 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 stages of design. The most important design decisions are made at the initial stages. The initial stages of the design process consists of concept generation, initial evaluation etc. Information available about the product in these stages 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 DISCUSSION

From descriptive studies conducted by us, we observed the following four stages in design with reference to time and related information, details can be found in [16].

In the ***0 – 20 % of design time*** information 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.

In the ***20 – 50 % of design time*** information 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. Here the component shapes and material classes are thought of as 'classes' rather than 'instances' of specific class (such as the main material class).

In the ***50 – 70 % of design time*** information is related to specifying relationships between components, subassemblies, local configuration of subsystems, and for evaluating solutions.

In the ***70 – 100 % of design time*** information is used in fortifying all components with exact shape, dimensions, tolerances, material and process details, with exact relationships.

We need to understand the information which is required for evaluation using various criteria, e.g., 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 development 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, components in turn consist of features. Thus, there are different levels at which alternative product proposals may have to be compared: a) complete product proposals, b) different subsystems within a proposal or across different proposals c) different components within a 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, a designer may have none or only part of this information. Based on the information available, a designer has to calculate the worth of a product at a particular state of development of the product, and therefore a method that is meant to supporting this activity ought to be able to help the designer carry out the calculation, but also estimate the accuracy of the calculated result, so that decisions and tradeoffs can be made in an informed manner.

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

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

- Establish the criteria based on which a product is to be evaluated (chosen by the designer).
- Estimate the level of uncertainty in the following dimensions (given below).

Product Structure: Uncertainty about the structure of the product is related to its subsystems, components and interfaces between these. For example, at a particular stage of development of a product, it may be known that there are three subsystems in the product, but the interfaces between them may be unknown. Figure 1 shows the product, its subsystems and how they are related to one another.

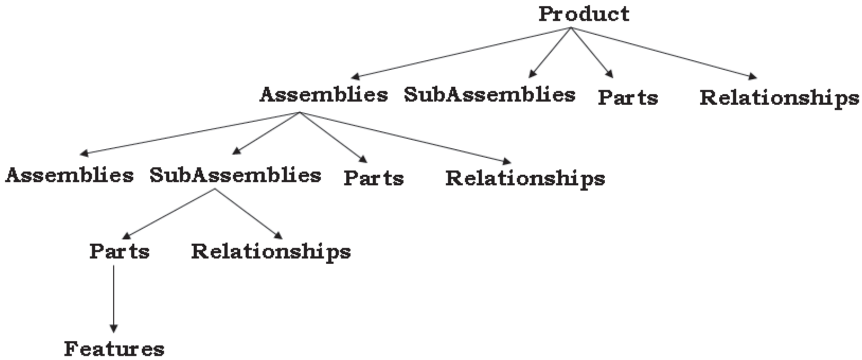

Figure 1 A product and its subsystems

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 within each of these: extraction, manufacturing and transportation in the material phase, manufacturing and assembly in the production phase, packaging and transportation in distribution phase, use, maintenance and repair in the usage phase, and reuse, recycle and disposal in the after-use phase. For example at one stage we may have information only about the material of a component, and not about its other phases. Figure 2 shows the Life cycle phases of a product system.

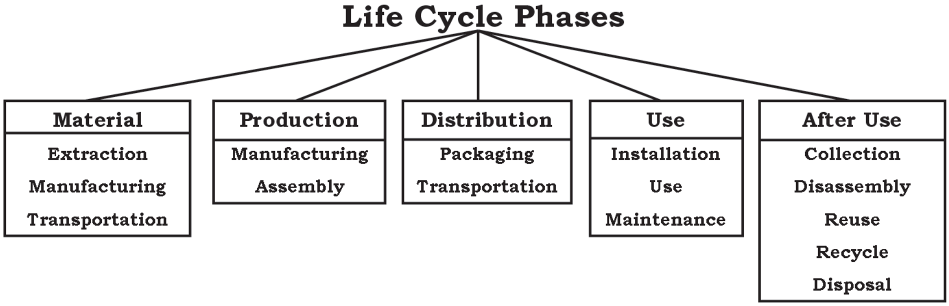

Figure 2 Life Cycle phases of a product system

Information: This uncertainty is related to the difference between amount of Information required in different dimensions and the available information in those dimensions. Based on this the uncertainty related to a specific attribute for specific or individual life cycle phases are estimated.

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 three components. The maximum amount of information that 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 their relationships, related assembly processes, usage processes of these components and their relationships, and after-use details of the three components and their relationships. However, currently we have only a part of this information, so any evaluation of the product based on this information should have a confidence below certainty (100%) because of the incompleteness of information at this state of the product.

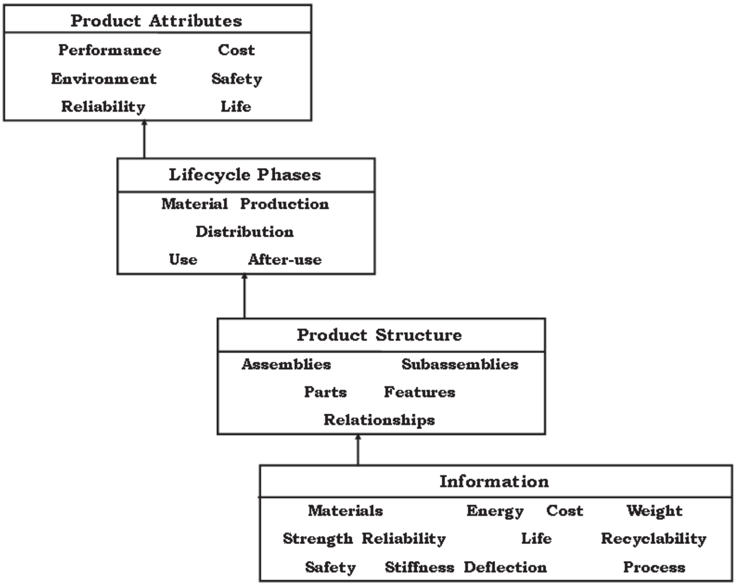

Figure 3 Uncertainty Propagation

Figure 3 shows the uncertainties in different dimensions and their links to the product attributes. The uncertainty in the information dimension can be interms of lack of details regarding material selection, kind of energy used, life of the product, and the details about the processes required etc. The uncertainty in Product Structure dimension can be interms of knowing the availability of assemblies, subassemblies, parts, relationships and features at that particular state with the details about the information domain and the uncertainty in the Lifecycle Phases dimension are considering individual phases, material, production, distribution, use and afteruse or combination of these for the elements of the product structure. The respective combined uncertainty is propagated to the respective attributes of the product lifecycle.

Figure 4 shows our proposed framework through which design is intended to be carried out by a designer. It consists of design stages; Task Clarification, Conceptual Design, Embodiment Design, and Detail Design. In each stage a designer would Generate, Evaluate, Modify and Select the Requirements and Solutions, for the product's lifecycle that consists of material, production, distribution, use and after-use.

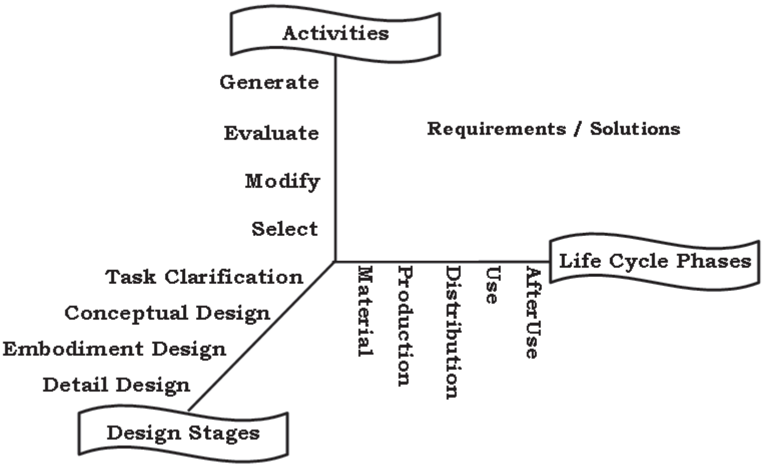

Figure 4 Framework of Lifecycle Design

It is in this context that a method is developed to estimate uncertainty in evaluation of environmental impacts during design [2]. Here the issues in comparing the alternatives using the ***confidence weighted objective method*** (***CWOM***) [3] involving both point and interval values are discussed and the previous method [3] is extended for incorporating point-interval, interval-interval comparisons also with the point-point comparisons. The method has two steps (each discussed in subsequent sections):

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

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

5 DEVELOP A METHOD FOR EVALUATION OF A SINGLE CRITERION USING INTERVAL (RANGE) VALUES

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: There can be three types of scenarios

Pessimistic Scenario: The assumption in this case is that the values of attributes will go up as the confidence increases and hence the degree of effectiveness is reduced. Selection is based on proposals with the highest degree of effectiveness. We compare maximum values for maximum confidence

- $E_{a1}>E_{b1}$, $C_{a1}>C_{b1}$: 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 upper 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 and each addition leads to decrease in the degree of effectiveness), E_{a1} is likely to decrease less than E_{b1}. Hence B's degree of effectiveness is going to decrease further and hence we can select A as our choice.
- $E_{a1}>E_{b1}$, $C_{a1}<C_{b1}$: 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 we can not make any decision here we need more information to decide.
- $E_{a1}>E_{b1}$, $C_{a1}=C_{b1}$: 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.

Average Scenario: The assumption in this case is that the values of attributes will go up as the confidence increases and hence the degree of effectiveness is reduced. Selection is based on proposals with the highest degree of effectiveness. We compare average values for maximum confidence

- $E_{a1}>E_{b1}$, $C_{a1}>C_{b1}$: 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 upper 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 and each addition leads to decrease in the degree of effectiveness), E_{a1} is likely to decrease less than E_{b1}. Hence B's degree of effectiveness is going to decrease further and hence we can select A as our choice.
- $E_{a1}>E_{b1}$, $C_{a1}<C_{b1}$: 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 We can not make any decision here we need more information to decide.
- $E_{a1}>E_{b1}$, $C_{a1}=C_{b1}$: 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.

Optimistic Scenario: The assumption in this case is that the values of attributes will go up as the confidence increases and hence the degree of effectiveness is reduced. Selection is based on proposals with the highest degree of effectiveness. We compare minimum values for maximum confidence.

- $E_{a1}>E_{b1}$, $C_{a1}>C_{b1}$: 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 upper 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 and each addition leads to decrease in the degree of effectiveness), E_{a1} is likely to decrease less than E_{b1}. Hence B's degree of effectiveness is going to decrease further and hence we can select A as our choice.

- $E_{a1}>E_{b1}$, $C_{a1}<C_{b1}$: 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 We can not make any decision here we need more information to decide.
- $E_{a1}>E_{b1}$, $C_{a1}=C_{b1}$: 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.

The outcome for point-point, point-interval and interval-interval comparisons are given for all these scenarios in the following tables for environmental impact or cost where the lowest value needs to be selected.

a) Value and Confidence as single point values for both alternatives:

Table 1 Impact value, confidence and decision for two alternatives (choose low value)

Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision
$V_A > V_B$	$C_A > C_B$	NO	$V_A = V_B$	$C_A > C_B$	A	$V_A < V_B$	$C_A > C_B$	A
	$C_A = C_B$	B		$C_A = C_B$	EQ		$C_A = C_B$	A
	$C_A < C_B$	B		$C_A < C_B$	B		$C_A < C_B$	NO

In Table 1 the first, fourth and seventh columns consists of degree of effectiveness (DOE) and second, fifth and eighth columns consists of confidence of two alternatives and the third, sixth and ninth column gives the choice of alternative to be selected. We have chosen the alternative that has low value. A –represents select alternative A, B – represent select alternative B, EQ – represents both alternatives are equal and NO - represent No selection at this point and need more info for decision.

b) Value and Confidence as point values for one and interval values for other alternative

In Table 2 the first two columns of the nested tables consist of DOE and confidence of two alternatives and the third column of the nested tables show the selected alternative in terms of pessimistic scenario, average scenario and optimistic scenario in first, second and third row respectively. We have chosen the alternative that has low value.

Table 2 Impact value, confidence and decision for two alternatives (choose low value)

Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision
V_A > [V_{Bmax} V_{Bavg} V_{Bmin}]	C_A > [C_{Bmax} C_{Bavg} C_{Bmin}]	NO	V_{Bmax} = V_A > [V_{Bavg} V_{Bmin}]	C_A > [C_{Bmax} C_{Bavg} C_{Bmin}]	A	V_{Bmax} > V_A > [V_{Bavg} V_{Bmin}]	C_A > [C_{Bmax} C_{Bavg} C_{Bmin}]	A	V_{Bmax} > V_A = V_{Bavg} > V_{Bmin}	C_A > [C_{Bmax} C_{Bavg} C_{Bmin}]	A	[V_{Bmax} V_{Bavg}] > V_A > V_{Bmin}	C_A > [C_{Bmax} C_{Bavg} C_{Bmin}]	A	[V_{Bmax} V_{Bavg}] > V_A = V_{Bmin}	C_A > [C_{Bmax} C_{Bavg} C_{Bmin}]	A	[V_{Bmax} V_{Bavg} V_{Bmin}] > V_A	C_A > [C_{Bmax} C_{Bavg} C_{Bmin}]	A
		NO			NO			NO			A			A			A			A
		NO			NO			NO			NO			NO			A			A
	C_{Bmax} = C_A > [C_{Bavg} C_{Bmin}]	NO		C_{Bmax} = C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} = C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} = C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} = C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} = C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} = C_A > [C_{Bavg} C_{Bmin}]	A
		NO			NO			NO			A			A			A			A
		B			B			B			B			B			EQ			A
	C_{Bmax} > C_A > [C_{Bavg} C_{Bmin}]	NO		C_{Bmax} > C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} > C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} > C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} > C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} > C_A > [C_{Bavg} C_{Bmin}]	A		C_{Bmax} > C_A > [C_{Bavg} C_{Bmin}]	A
		NO			NO			NO			A			A			A			A
		B			B			B			B			B			B			NO
	C_{Bmax} > C_A = C_{Bavg} > C_{Bmin}	NO		C_{Bmax} > C_A = C_{Bavg} > C_{Bmin}	A		C_{Bmax} > C_A = C_{Bavg} > C_{Bmin}	A		C_{Bmax} > C_A = C_{Bavg} > C_{Bmin}	A		C_{Bmax} > C_A = C_{Bavg} > C_{Bmin}	A		C_{Bmax} > C_A = C_{Bavg} > C_{Bmin}	A		C_{Bmax} > C_A = C_{Bavg} > C_{Bmin}	A
		B			B			B			EQ			A			A			A
		B			B			B			B			B			B			NO
	[C_{Bmax} C_{Bavg}] > C_A > C_{Bmin}	NO		[C_{Bmax} C_{Bavg}] > C_A > C_{Bmin}	A		[C_{Bmax} C_{Bavg}] > C_A > C_{Bmin}	A		[C_{Bmax} C_{Bavg}] > C_A > C_{Bmin}	A		[C_{Bmax} C_{Bavg}] > C_A > C_{Bmin}	A		[C_{Bmax} C_{Bavg}] > C_A > C_{Bmin}	A		[C_{Bmax} C_{Bavg}] > C_A > C_{Bmin}	A
		B			B			B			B			NO			NO			NO
		B			B			B			B			B			B			NO
	[C_{Bmax} C_{Bavg}] > C_A = C_{Bmin}	B		[C_{Bmax} C_{Bavg}] > C_A = C_{Bmin}	EQ		[C_{Bmax} C_{Bavg}] > C_A = C_{Bmin}	A		[C_{Bmax} C_{Bavg}] > C_A = C_{Bmin}	A		[C_{Bmax} C_{Bavg}] > C_A = C_{Bmin}	A		[C_{Bmax} C_{Bavg}] > C_A = C_{Bmin}	A		[C_{Bmax} C_{Bavg}] > C_A = C_{Bmin}	A
		B			B			B			B			NO			NO			NO
		B			B			B			B			B			B			NO
	[C_{Bmax} C_{Bavg} C_{Bmin}] > C_A	B		[C_{Bmax} C_{Bavg} C_{Bmin}] > C_A	B		[C_{Bmax} C_{Bavg} C_{Bmin}] > C_A	NO		[C_{Bmax} C_{Bavg} C_{Bmin}] > C_A	NO		[C_{Bmax} C_{Bavg} C_{Bmin}] > C_A	NO		[C_{Bmax} C_{Bavg} C_{Bmin}] > C_A	NO		[C_{Bmax} C_{Bavg} C_{Bmin}] > C_A	NO
		B			B			B			B			NO			NO			NO
		B			B			B			B			B			B			NO

c) Value and Confidence as interval values for both alternatives

In Table 3 the first two columns of the nested tables consist of values and confidence of two alternatives in the intervals and the third column of the nested tables show the selected alternative in terms of pessimistic scenario, average scenario and optimistic scenario in first, second and third row respectively. We have chosen the alternative that has low value.

Table 3 Impact value, confidence and decision for two alternatives (choose low value)

Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision	Value	Confidence	Decision
	$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	NO		$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	NO		$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	NO		$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}\ C_{Amin}] > [C_{Bmax}\ C_{Bavg}\ C_{Bmin}]$	A
		NO			NO			NO			NO			A			A			A			A			A			A
		NO			NO			NO			NO			NO			A			A			A			A			A
WORST CASE	$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	NO		$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	NO		$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	NO		$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	A		$[C_{Amax}\ C_{Avg}] > C_{Amin} = C_{Bmax} > [C_{Bavg}\ C_{Bmin}]$	A
		NO			NO			NO			NO			A			A			A			A			A			A
		NO			NO			NO			NO			NO			A			A			A			A			A
	$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	NO		$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	NO		$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	NO		$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	A		$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	A		$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	A		$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	A		$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	A		$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	A		$C_{Amax} > C_{Avg} = C_{Bmax} > C_{Amin} > [C_{Bavg}\ C_{Bmin}]$	A
		NO			NO			NO			NO			A			A			A			A			A			A
		NO			NO			NO			NO			NO			A			A			A			A			A
	$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	NO		$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	NO		$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	NO		$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Amax} = C_{Bmax} > C_{Avg}\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A
AVERAGE		NO			NO			NO			NO			A			A			A			A			A			A
		B			B			B			B			B			EQ			A			A			A			EQ
	$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	NO		$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	NO		$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	NO		$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Avg}]\ C_{Bavg} > C_{Amin} > C_{Bmin}$	A
		B			B	$V_{Amax} > V_{Avg} = V_{Bmax} > V_{Amin} > [V_{Bavg}\ V_{Bmin}]$		B	$V_{Amax} = V_{Bmax} > V_{Avg} > V_{Bavg} > V_{Amin} > V_{Bmin}$		B	$V_{Bmax} > [V_{Amax}\ V_{Avg}\ V_{Bavg}] > V_{Amin} > V_{Bmin}$		EQ	$V_{Bmax} > [V_{Amax}\ V_{Bavg}\ V_{Avg}] > V_{Amin} = V_{Bmin}$		A	$V_{Bmax} > V_{Bavg} = V_{Amax} > V_{Avg}\ V_{Bmin} > V_{Amin}$		A	$[V_{Bmax}\ V_{Bavg}] > V_{Bmin} = V_{Amax} > [V_{Avg}\ V_{Amin}]$		A	$[V_{Bmax}\ V_{Bavg}\ V_{Bmin}] > [V_{Amax}\ V_{Avg}\ V_{Amin}]$		A	$[V_{Amax}\ V_{Avg}\ V_{Amin}] = [V_{Bmax}\ V_{Bavg}\ V_{Bmin}]$		EQ
		B	$[V_{Amax}\ V_{Avg}] > V_{Amin} = V_{Bmax} > [V_{Bavg}\ V_{Bmin}]$		B			B			B			B			B			NO			NO			NO			B
$[V_{Amax}\ V_{Avg}\ V_{Amin}] > [V_{Bmax}\ V_{Bavg}\ V_{Bmin}]$	$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	B		$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	B		$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	B		$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	EQ		$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	A		$C_{Bmax} > [C_{Amax}\ C_{Bavg}\ C_{Avg}] > C_{Amin} = C_{Bmin}$	EQ
		B			B			B			B			B			NO			NO			NO			NO			B
		B			B			B			B			B			B			NO			NO			NO			B
	$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	B		$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	B		$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	B		$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	B		$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	NO		$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	B		$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	NO		$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	NO		$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	NO		$C_{Bmax} > C_{Amax} = C_{Bavg} > C_{Avg} > C_{Bmin} = C_{Amin}$	B
		B			B			B			B			B			NO			NO			NO			NO			B
		B			B			B			B			B			B			NO			NO			NO			B
	$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	NO		$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	NO		$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	NO		$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	NO		$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	NO		$[C_{Bmax}\ C_{Bavg}] > C_{Amax} = C_{Bmin} > [C_{Avg}\ C_{Amin}]$	B
		B			B			B			B			B			NO			NO			NO			NO			B
		B			B			B			B			B			B			NO			NO			NO			B
OPTIMISTIC	$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	NO		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	NO		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	NO		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	NO		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] > [C_{Amax}\ C_{Avg}\ C_{Amin}]$	B
		B			B			B			B			B			NO			NO			NO			NO			B
		B			B			B			B			B			B			NO			NO			NO			B
	$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	B		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	EQ		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	A		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	A		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	A		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	A		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	A		$[C_{Bmax}\ C_{Bavg}\ C_{Bmin}] = [C_{Amax}\ C_{Avg}\ C_{Amin}]$	EQ
		B			B			B			B			EQ			A			A			A			A			EQ
		B			B			B			B			B			EQ			A			A			A			EQ

6 DEVELOP A METHOD FOR INTEGRATING THESE INTO A SINGLE INTERVAL (RANGE) VALUE

Values for each criterion are integrated into a single value for multiple criteria and the confidence is associated with the integral value is estimated as follows.

The integration is done as a confidence weighted sum. The overall value for each alternative is calculated using the following formula:

$$[E_{a_{\max_i}}\ E_{a_{\min_i}}] = \sum_{j=1}^{m} \sum_{k=1}^{l} w_{ij}\, [e_{\max_{ijk}} e_{\min_{ijk}}] \tag{1}$$

Its confidence is estimated as follows:

$$[C_{a_{\max_i}}\ C_{a_{\min_i}}] = \frac{\sum_{j=1}^{m} \sum_{k=1}^{l} (w_{ij})(c_{\max_{ijk}}\ c_{\min_{ijk}})(e_{\max_{ijk}}\ e_{\min_{ijk}})}{\sum_{j=1}^{m} \sum_{k=1}^{l} (w_{ij})(e_{\max_{ijk}}\ e_{\min_{ijk}})} \tag{2}$$

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*

$c_{\max_{ijk}}$ – *maximum confidence of* i^{th} *alternative* j^{th} *criterion* k^{th} *lifecycle phase*

$c_{\min_{ijk}}$ – *minimum confidence of* i^{th} *alternative* j^{th} *criterion* k^{th} *lifecycle phase*

$e_{\max_{ijk}}$ – *maximum effectiveness of* i^{th} *alternative* j^{th} *criterion* k^{th} *lifecycle phase*

$e_{\min_{ijk}}$ – *minimum 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.

One way of confirming a proposal that is clearly the best solution if the choice is same in all scenarios, i.e., worst case, average and optimistic scenarios from the above Table 1, Table 2, Table 3.

5 CONCLUSIONS

A comparative evaluation method is developed for use in multi-criteria decision making involving non crisp values for lifecycle designs of product systems. An understanding is developed on uncertainty related to different dimensions as product structure, lifecycle phases, information using empirical studies and this understanding is used in developing the method and guidelines for evaluation of product lifecycle alternatives under uncertainty. The method is being implemented in a computer based tool and evaluated for its effectiveness.

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