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

DEVELOPMENT OF A METHOD FOR ESTIMATING UNCERTAINTY IN EVALUATION OF ENVIRONMENTAL IMPACTS DURING DESIGN

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ABSTRACT
Life Cycle Assessment (LCA) is currently the most promising and scientifically defendable technique for estimating environmental impacts of a product during its lifecycle. Currently, detailed LCA is critically dependent on high volumes of product specific data, time consuming, often unaffordable and used in the detailed stages of design. Current approximate LCA methods are either incomplete, inaccurate or require prior knowledge of what data is important. There is substantial uncertainty involved in the environmental impact calculations in LCA. Literature suggests that impact estimation results must be accompanied by an estimation of its uncertainty or imprecision, without which the decisions taken could be misleading.

During development of a product, there is often a lack of accurate information about its structure, lifecycle stages, and related environmental impact information. As information about the product lifecycle continues to evolve during development, the assessment method should be such that it incorporates the different levels of abstraction about product information. A key result to be presented in this paper is a preliminary method developed using interval algebra and probabilistic theory taking product structure and lifecycle uncertainties into account. This method helps in estimating impact values of a product proposal in the earlier stages of design by providing an uncertainty value in terms of confidence on the result calculated, with the intention of supporting design decision making.

Keywords: Life cycle assessment, uncertainty, early phases of design, approximate LCA, reasoning about imprecision

1 INTRODUCTION
Life Cycle Assessment (LCA) is currently the most promising and scientifically defendable technique for estimating environmental impacts of a product during its lifecycle. Currently, detailed LCA is critically dependent on high volumes of product specific data, time consuming, often unaffordable and used in the detailed stages of design. Current approximate LCA methods are either incomplete, inaccurate or require prior knowledge of what data is important. There is substantial uncertainty involved in the environmental impact calculations in LCA. Literature suggests that impact estimation results must be accompanied by an estimation of its uncertainty or imprecision, without which the decisions taken could be misleading [1].

2 OBJECTIVES AND METHODOLOGY
The objectives of the paper are to:

1. Understand uncertainty in the context of product lifecycle information in various stages of design. This is done using literature survey and descriptive studies.
2. Develop a method for estimating uncertainty in the results for estimation of lifecycle environmental impacts of a product. This is done by developing a computational method based on approximation analysis theories, and evaluated by benchmarking against current impact estimation tools.

3 LITERATURE SURVEY

Literature [1] on approaches to improve reliability in LCA suggests that uncertainty exists in LCA because of data inaccuracy, data gaps, model uncertainties, choices, spatial and temporal variability, variability between sources etc. Anna E. Björklund in [1] argues that LCA results are usually presented as point estimates, which strongly overestimate the reliability and LCA practitioners' lack systematic approaches for determining data quality and need improved techniques for sensitivity and uncertain analysis. Uncertainty arises due to lack of knowledge about the true value of a quantity. He also stresses the need for estimating and expressing the uncertainty in the data. Even though there are different tools/techniques like classical statistical analysis, Bayesian statistical analysis, interval arithmetic, vague error interval calculations, and probabilistic simulation available for performing uncertainty calculations in different dimensions Björklund in [1] calls for a framework that makes explicit the important aspects of data quality and uncertainty in LCA to the practitioner.

In [2] it is illustrated that in the initial stages of design we need to use the functional parameters, which are functional requirements and constraints for the particular problem, available to estimate environmental impacts of a technical solution, and suggested use of statistical and sensitivity analysis for representing uncertainty. While Literature discusses uncertainty of impact data, there is no discussion on how to calculate and represent the overall uncertainty in the estimated potential impact of a product proposal at any given stage in design with respect to LCA.

In [3] a method is proposed for calculating the uncertainty propagation (if a calculation is performed based on several data points which may be uncertain the uncertainties propagates through the system) in LCAs. It combines approximation formulas like Gauss, Bader/ Baccini and Monte Carlo simulation to estimate the uncertainty. They found some threshold values for each step in impact assessment stage of LCA, which govern the use of particular formulas to estimate uncertainty in those stages.

Methods like [4] have been developed for estimating impacts, taking into consideration inventory data uncertainties in a particular domain. They argue that fuzzy intervals and numbers are more informative and closer to human judgements and perceptions than crisp numbers, thus improving the pertinence and the interpretation of the results.

In [5] the results of the survey of LCA studies to know how the uncertainty is taken care of in practice are given. They found that LCA results are subject to many sources of uncertainty. This is due to uncertainties introduced by methodology such as lack of site-specific data and the aggregation of data over different spatial and temporal scales. It should be imperative that studies should include an explanation of the uncertainties that arise during the impact assessment phase of LCA.

Andreas Ciroth et. al. in [6] and [7] showed that the geographical and technological differences in life cycle inventory data are important sources of uncertainty in LCA for processes in waste incinerators.

In [8] a tentative rule of thumb is given that quantifies difference in impact scores necessary to obtain significant results in product comparison concerning impact categories of global warming, acidification, eutrophication and photooxidant creation. They suggest that LCI and LCIA data providers should supply quantitative uncertainty information including correlation estimates for individual parameters.

In [9] authors discuss about the different statistical distributions of data in LCA and a way of converting one type to another as needed for calculations. They emphasise that interpretation of uncertainty information in data and results is an indispensable part of sound decision making and should be an integral part of the analysis itself.

In [10] authors talk about requirement of a framework on modelling data uncertainty in life cycle inventories. They represent uncertainty as data inaccuracy and lack of specific data which in turn are divided into complete lack of data and lack of representative data. They suggest that more importance be given to the parameters which cause the largest spread in the model outcome. It is highly recommended to implement in current LCA software the various tools dealing with data uncertainty.

Uncertainty assessment is required for better decision support, transparency, quality competition but it is not undertaken in LCA studies normally because of additional effort required and lack of methods.

During development of a product, there is often a lack of accurate information about its structure, lifecycle stages, and related environmental impact information. As information about the product lifecycle continues to evolve during development, the assessment method should be such that it incorporates the different levels of abstraction about product information.

4 DESCRIPTIVE STUDIES

We propose mainly four categories and fourteen sub-categories of uncertainty in information with respect to LCA in design. The four categories of uncertainty are uncertainty in structure definition, uncertainty in lifecycle definition, uncertainty in data quality, and uncertainty in methodological choices. The subdivisions of the categories are given below.

1. Uncertainty in *structure definition* is be subdivided into
   - *Uncertainty in subsystems definition (all, some, none)*
   - *Uncertainty in components definition (all, some, none)*
   - *Uncertainty in relations definition (all, some, none)*

2. Uncertainty in *lifecycle definition* is subdivided into
   - *Uncertainty in material phase (extract, produce, distribute)*
   - *Uncertainty in production phase (manufacture, assembly, storage)*
   - *Uncertainty in distribution phase (package, load, transport, unload))*
   - *Uncertainty in usage phase (install, use, maintain, repair, replace)*
   - *Uncertainty in afteruse phase (collect, transport, disassemble, reuse, recycle, disposal)*

3. Uncertainty in *data quality* is subdivided into
   - *Uncertainty in temporal relevance (current, old, too old)*
   - *Uncertainty in spatial relevance (local, national, continental, other)*
   - *Uncertainty in source (single source, multiple sources)*

4. Uncertainty in *methodological choices* is subdivided into
   - *Uncertainty in temporal relevance (current, old, too old)*
   - *Uncertainty in spatial relevance (local, national, continental, other)*
   - *Uncertainty in comprehensiveness (all, some, none)*

At any point of time, uncertainty in information available is a combination of these individual uncertainties. We need to identify what information is required in all dimensions to accurately calculate the environmental impact 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, the uncertainty in an impact estimation is assessed.

5 METHOD DEVELOPMENT

A key result to be presented in this paper is a preliminary method developed using interval algebra [11] and probabilistic theory [12] taking product structure and lifecycle uncertainties into account. This method helps in estimating the impact values of a product proposal in the earlier stages of design and gives an uncertainty value in terms of confidence on the result calculated, which should help in decision making.

Interval measures of estimates for environmental impact of a chosen generic class of material or process, for a given product as a given assembly of components, and a method for combining these estimates into an overall impact measure for a given product are developed.

The measure developed enables the impact value for a given class of materials or processes with given environmental impacts to be taken as an interval of two impact values – the maximum and the minimum possible in the class. Confidence level of an estimate is described using a number between 0 and 1, where 0 specifies no confidence on the estimation while 1 specifies 100% confidence. If for an entity (component or relationship) neither a class nor a specific value is chosen for a given life cycle stage (e.g., material), its impact is taken to be 0 with confidence equivalent to the ratio of number of options in that life cycle stage with zero impact and the total number of options in that stage. If any choice is made, confidence on the value chosen is taken to be 1.

There are two levels of addition possible: addition of impacts of all the components in a product or sub-assembly for a given life cycle stage (e.g., material), and addition of impacts from all life cycle stages. The addition of impacts is carried out using interval algebra, while estimation of confidence level is made using a weighted sum of the individual confidence of impacts, where weighting is done using the impact values. The calculation is performed as follows for the three choices possible:

1. No Material, Production or Assembly, Distribution, Use, AfterUse processes selected

$$Impact\ value_i = 0 \tag{1}$$

$$Confidence_i = \left(\frac{No\ of\ zero\ value\ impact\ items\ in\ database}{Total\ number\ of\ items\ in\ particular\ lifecycle\ database} \right) 100\% \tag{2}$$

2. A Material, Production or Assembly, Distribution, Use, AfterUse process class is chosen

$$Impact\ value_i = [V_{min}\ \ V_{max}\ ] \tag{3}$$

$$Confidence_i = 100\% \tag{4}$$

3. A specific Material, Production or Assembly, Distribution, Use, AfterUse processes is chosen

$$Impact\ value_i = V_i \tag{5}$$

$$Confidence_i = 100\% \tag{6}$$

The aggregation of the confidence of all the processes in a particular life cycle phase is done using the following formula

$$Confidence_{LC} = \left(\frac{NZ}{NZ+Z}\right)\left(\frac{\sum_{i=1}^{NZ} V_i C_i}{\sum_{i=1}^{NZ} V_i}\right) + \left(\frac{Z}{NZ+Z}\right)\left(\frac{\sum_{j=1}^{Z} C_j}{\sum_{j=1}^{Z} C_{j_{max}}}\right) \tag{7}$$

Where

$NZ \rightarrow number\ of\ lifecycle\ processes\ with\ non-zero-impact\ values$

$Z \rightarrow number\ of\ lifecycle\ processes\ with\ zero\ impact\ values$

$V_i \rightarrow impact\ value\ of\ the\ individual\ lifecycle\ process\ i$

$C_i \rightarrow confidence\ on\ impact\ of\ the\ individual\ lifecycle\ process\ i$

$C_j \rightarrow confidence\ on\ impact\ of\ the\ individual\ lifecycle\ process\ j$

$C_{j_{max}} \rightarrow highest\ confidence\ possible\ on\ individual\ lifecycle\ process\ j$

$For\ a\ range\ of\ values\ of\ V_i\ we\ get\ confidence\ in\ range$

The assumptions behind the formula are the following:

- Impact in a given phase of the product life cycle can be estimated by aggregating the impacts from all processes that constitute the phase.
- For a given process, the impact estimated will be either zero or non-zero.
- In either case, there will be some confidence on this number.

- The confidence on the aggregate value (for a give phase) will be shared proportionately by the aggregate confidence on zero-value processes and non-zero-value processes.
- The aggregate confidence of the non-zero-value processes is proportional to the number of non-zero-value processes as well as to the value and confidence of each process.
- The aggregate confidence of the zero-value processes is proportional to the number of zero-value processes and the confidence of each process (since the impact value is zero in these cases).
- The equation should reflect the fact that the scale of aggregate confidence should be between 0 and 1, for confidence in the impact value within a phase, aggregate confidence in all zero-value processes, aggregate confidence in all non-zero-value processes, and for an individual process.

The method for estimating the confidence on the total impact value of a product proposal is based on the following proposed formula, where similar assumptions, as in Equation 1, but for zero-impact-value and non-zero-impact-value life cycle phases and overall confidence on impact value for all life cycle phases are made.

$$Confidence_{PP} = \left(\frac{NZ_L}{NZ_L + Z_L}\right)\left(\frac{\sum_{L=1}^{NZ_L} V_L C_L}{\sum_{L=1}^{NZ_L} V_L}\right) + \left(\frac{Z_L}{NZ_L + Z_L}\right)\left(\frac{\sum_{j=1}^{Z_L} C_j}{\sum_{j=1}^{Z_L} C_{j_{\max}}}\right) \quad (8)$$

Where

$NZ_L \rightarrow$ *number of lifecycle phases with non – zero – impact values*

$Z_L \rightarrow$ *number of lifecycle phases with zero impact values*

$V_L \rightarrow$ *impact value of the individual lifecycle phase L*

$C_L \rightarrow$ *confidence on impact of the individual lifecycle phase L*

$C_j \rightarrow$ *confidence on impact of the individual lifecycle phase j*

$C_{j_{\max}} \rightarrow$ *highest confidence possible on lifecycle phase j*

For a range of values of V_L *we get confidence in range*

Example:

Let us take an example in which a product proposal has two components and a relationship, and the impact values (in some appropriate unit) and confidence are specified as given in the Table 1. Here I - impact value and C – confidence. There are mainly six phase considered: material phase (M Phase), production phase (P Phase), assembly phase (A Phase), distribution phase (D Phase), usage phase (U Phase) and afteruse phase (AU Phase). COM1 – Component1, COM2 – Component2, REL – Relation.

Table 1 Three scenarios for a product proposal

		M Phase		P Phase		A Phase		D Phase		U Phase		AU Phase	
	Values →	I	C	I	C	I	C	I	C	I	C	I	C
1	COM1	1	1	0	0			1	1	0	1	1	1
	COM2	1	1	0	0			0	0.5	0	1	0	0.5
	REL					0	0.25						
2	COM1	1	1	0	0.25			1	1	1	1	1	1
	COM2	1	1	1	1			0	0.75	0	1	1	1
	REL					0	0.5						
3	COM1	1	1	1	1			1	1	1	1	1	1
	COM2	1	1	1	1			1	1	1	1	1	1
	REL					1	1						

For the Scenario 1:

$\textit{Impact Value}_{Mphase} = V_{m1} + V_{m2} = 2$

$\textit{Confidence}_{Mphase} = (2/2) \times (1 \times 1 + 1 \times 1) / (1+1) = 1$

$\textit{Impact Value}_{Pphase} = V_{p1} + V_{p2} = 0$

$\textit{Confidence}_{Pphase} = (0/2)(0) + 2/2(0/2) = 0$

$\textit{Impact Value}_{Aphase} = V_{a} = 0$

$\textit{Confidence}_{Aphase} = (0.25) / 1 = 0.25$

$\textit{Impact Value}_{Dphase} = V_{d1} + V_{d2} = 1$

$\textit{Confidence}_{Dphase} = \{(1/2) \times (1 \times 1) / (1)\} + \{(1/2) \times (0.5/1)\} = 0.75$

$\textit{Impact Value}_{Uphase} = V_{u1} + V_{u2} = 0$

$\textit{Confidence}_{Uphase} = (0/2)(0) + 2/2(1+1/2) = 1$

$\textit{Impact Value}_{AUphase} = V_{au1} + V_{au2} = 1$

$\textit{Confidence}_{AUphase} = \{(1/2) \times (1 \times 1)/1\} + \{(1/2) \times (0.5/1)\} = 0.75$

$\textit{Impact Value}_{PP1} = \textit{Impact Value}_{Mphase} + \textit{Impact Value}_{Pphase} + \textit{Impact Value}_{Aphase} + \textit{Impact Value}_{Dphase} + \textit{Impact Value}_{Uphase} + \textit{Impact Value}_{AUphase} = 2+0+0+1+0+1 = 4$

$\textit{Confidence}_{PP1} = (3/6)\{(2 \times 1+1 \times 0.75+1 \times 0.75)/(2+1+1)\}+(3/6)\{(0+0.25+1)/(3)\} = 0.6455 = 64.55\%$

For the Scenario 2:

$\textit{Impact Value}_{Mphase} = V_{m1} + V_{m2} = 2$

$\textit{Confidence}_{Mphase} = (1 \times 1 + 1 \times 1) / (1+1) = 1$

$\textit{Impact Value}_{Pphase} = V_{p1} + V_{p2} = 1$

$\textit{Confidence}_{Pphase} = (½)(1 \times 1) + (½) \times (0.25/1) = 0.625$

$\textit{Impact Value}_{Aphase} = V_{a} = 0$

$\textit{Confidence}_{Aphase} = 0.5/1 = 0.5$

$\textit{Impact Value}_{Dphase} = V_{d1} + V_{d2} = 1$

$\textit{Confidence}_{Dphase} = \{(1/2) \times (1 \times 1) / (1)\} + (1/2) \times (0.75/1) = 0.875$

$\textit{Impact Value}_{Uphase} = V_{u1} + V_{u2} = 1$

$\textit{Confidence}_{Uphase} = (1/2)(1/1) + 1/2(1/1) = 1$

$\textit{Impact Value}_{AUphase} = V_{au1} + V_{au2} = 1 + 1 = 2$

$\textit{Confidence}_{AUphase} = (1 \times 1 + 1 \times 1)/2 = 1$

Impact Value$_{PP2}$ = *Impact Value*$_{Mphase}$ + *Impact Value*$_{Pphase}$ + *Impact Value*$_{Aphase}$ + *Impact Value*$_{Dphase}$ + *Impact Value*$_{Uphase}$ + *Impact Value*$_{AUphase}$ = 2+1+0+1+1+2 = 7

Confidence$_{PP2}$ = *(5/6){(2x1+1x0.625+1x0.875+1x1+2x1)/(7)}+(1/6)(0.5/1) = .8568 = 85.68%*

For the Scenario 3:

Impact Value$_{Mphase}$ = $V_{m1} + V_{m2} = 2$

Confidence$_{Mphase}$ = (1 x 1 + 1 x 1) / (1+1) = 1

Impact Value$_{Pphase}$ = $V_{p1} + V_{p2} = 2$

Confidence$_{Pphase}$ = (1 x 1 + 1 x 1) / (1+1) = 1

Impact Value$_{Aphase}$ = $V_a = 1$

Confidence$_{Aphase}$ = (1 x 1)/ 1 = 1

Impact Value$_{Dphase}$ = $V_{d1} + V_{d2} = 2$

Confidence$_{Dphase}$ = (1 x 1 + 1 x 1) / (1 + 1) = 1

Impact Value$_{Uphase}$ = $V_{u1} + V_{u2} = 2$

Confidence$_{Uphase}$ = (1 x 1 + 1 x 1) / (1 + 1) = 1

Impact Value$_{AUphase}$ = $V_{au1} + V_{au2} = 2$

Confidence$_{AUphase}$ = (1 x 1 + 1 x 1)/ (1 + 1) = 1

Impact Value$_{PP3}$ = *Impact Value*$_{Mphase}$ + *Impact Value*$_{Pphase}$ + *Impact Value*$_{Aphase}$ + *Impact Value*$_{Dphase}$ + *Impact Value*$_{Uphase}$ + *Impact Value*$_{AUphase}$ = 2+2+1+2+2+2 = 11

Confidence$_{PP3}$ = *(2 x 1+2 x 1+1 x 1+2 x 1+2 x 1 + 2 x 1)/(11) = 1 = 100%*

From the three scenarios in the example we can see that as the information about the product proposal increased the confidence on the impact value is also increased. Thus the formula is able to show the uncertainty in the calculated impact value depending on the abstractness of the information about the product proposal. Table 2 shows the summary of impact values and the estimate of confidence on them.

Table 2 Summary of impact values and confidence in three scenarios

	M phase		P phase		A phase		D phase		U phase		AU phase		Total	
	I	C	I	C	I	C	I	C	I	C	I	C	I	C
S1	2	1	0	0	0	.25	1	.75	0	1	1	.75	4	64.55%
S2	2	1	1	.625	0	.5	1	.875	1	1	2	1	7	85.68%
S3	2	1	2	1	1	1	2	1	2	1	2	1	11	100%

This model will be extended in future for information as well as interpretation uncertainty, and different scenarios will be developed using alternative uncertainty modelling approaches for comparison and benchmarking. A preliminary computer aided tool is developed and integrated with CAD to automatically take the information required for life cycle assessment that is available in CAD data about a product, take additional inputs necessary from the user, and estimate impact as well as confidence on the estimate. Figure 1 shows the life cycle information input window. Figure 2 displays the estimated impact values and the confidence on the estimate for a product proposal during a design.

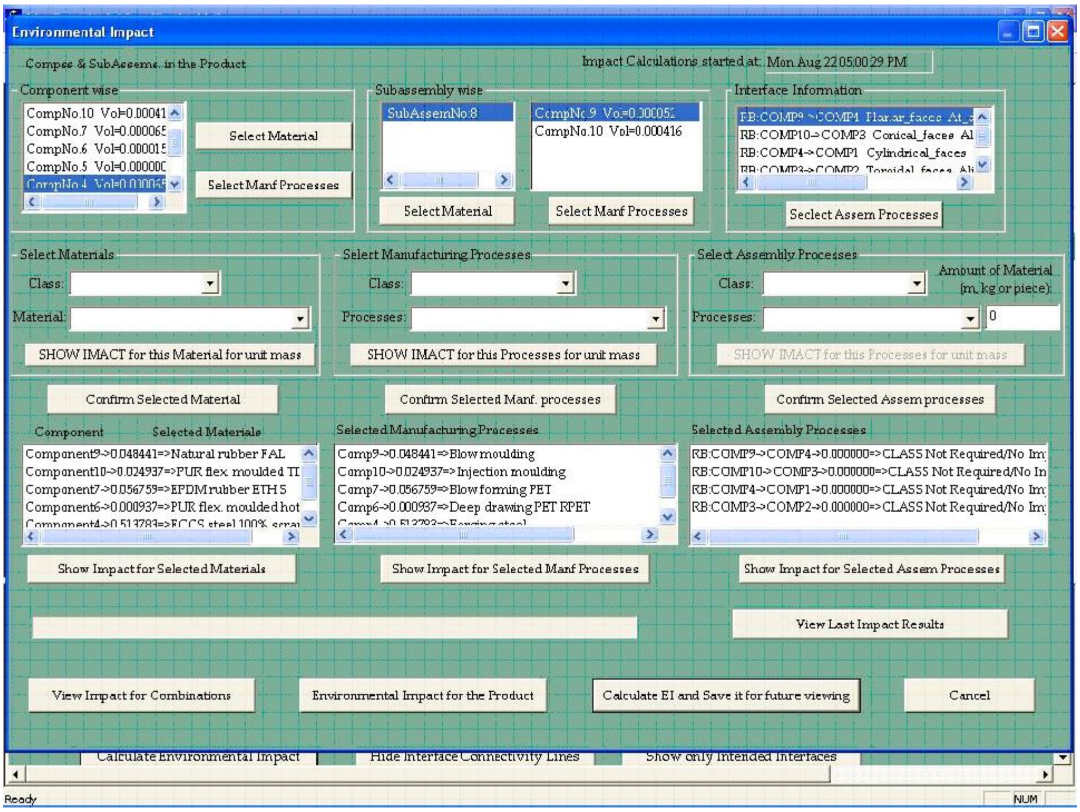

Figure 1 Life Cycle Information input window

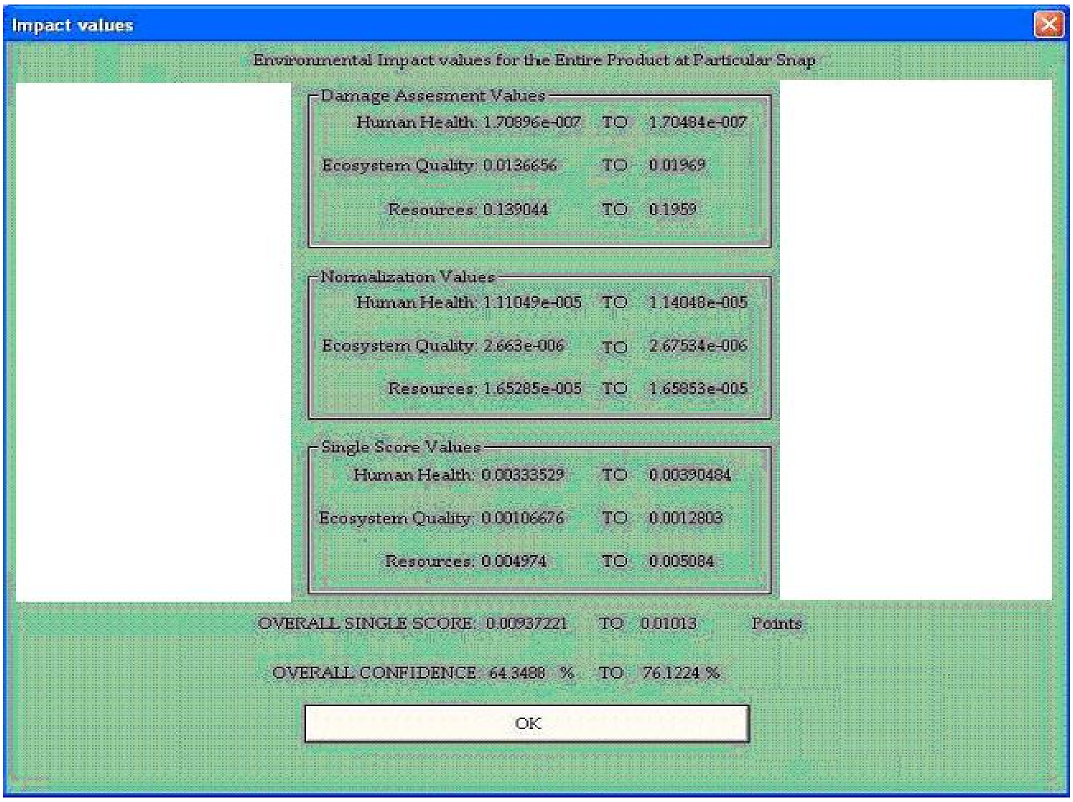

Figure 2 Estimate impact values and associated confidence for a product proposal

This method is evaluated by conducting four design experiments by two designers individually for two separate design problems. For design problem 1, designer 1 used a commercial CAD and Simapro5.1 software, and then would solve design problem 2 using the new tool. Designer 2 worked with the same set of tools in the same order, except solving problem 1 first and then problem 2. The average of the results from the first two experiments was compared with that from the last two – for the number of alternative solution proposals generated, the average percentage of time spent in generating these solutions, the average percentage of time spent in evaluating environmental impacts of these solutions, and the average impact of the final solutions. The result showed using the new software, compared to not using it, led to generation of more alternatives, spending less percentage of time in generating solutions and evaluating their impacts, and creating final solutions with about 25% less environmental impacts. The uncertainty calculated is given as a confidence value on the final impact value in the result, which should be taken into account while making decisions (see Table 3).

Table 3 Comparison of developed method with current methods

Sl. No.		S1 (w/o)	S2 (w/o)	S1 (with)	S2 (with)	Comments
1	Problem	P1	P2	P2	P1	
2	EI of final concept	2.28Pt	1.95Pt	2.44Pt	0.73Pt	Average EI with new support (1.59Pt) less than average EI without using new support (2.11Pt)
3	Confidence	--	--	67.36%	100%	Confidence on the impact value is known with software

6 CONCLUSIONS

With through literature survey and descriptive studies uncertainty in the context of product lifecycle information in various stages of design is understood. Using this understanding a method for estimating uncertainty in the results for estimation of lifecycle environmental impacts of a product is developed and evaluated by benchmarking against current impact estimation tools. Further this computational method will be extended for other uncertainties based on approximation analysis theories and will be evaluated for its usefulness and influence in design.

REFERENCES

[1] Anna E. Björklund, Survey of Approaches to Improve Reliability in LCA, *International Journal of Life Cycle Assessment*, 2002, 7(2), 64-72.

[2] Wim Dewulf and Joost Duflou. ECO-PAS – Estimating the environmental performance of conceptual designs using parametric modelling, In *International Conference on Engineering Design, ICED '03*, Stockholm, August 2003. (Royal Institute of Technology, KTH, Stockholm).

[3] Andreas Ciroth, Gunter Fleischer and Jorg Steinbach. Uncertainty Calculation in Life Cycle Assessments: A combined model of simulation and approximation. *International Journal of Life Cycle Assessment*, 2004, 9 (4), pp.216-226.

[4] Enrico Benetto Christiane Dujet and Patrick Rousseaux. Fuzzy-sets approach to noise impact assessment. *International Journal of Life Cycle Assessment*, 2005 (online first).

[5] Stuart Ross David Evans Michael Webber. How LCA studies deal with unvertainty. *International Journal of Life Cycle Assessment*, 2002, 7 (1), 47-52.

[6] Andreas Ciroth et. al. Geographical and Technological differences in Life cycle Inventories: Shown by the use of process models for waste incinerators Part I. Technological and Geographical differences. *International Journal of Life Cycle Assessment*, 2002, 7(5), 295-300.

[7] Andreas Ciroth et. al. Geographical and Technological differences in Life cycle Inventories: Shown by the use of process models for waste incinerators Part II. Technological and Geographical differences. *International Journal of Life Cycle Assessment*, 2002, 7(6), 363-368.

[8] Georg Geisler, Stefanie Hellweg and Konard Hungerbuhler, Uncertainty analysis in Life cycle assessment: Case study on plant-protection products and implications for decision making. *International Journal of Life Cycle Assessment*, 2005, 10 (3), 184-192.

[9] Reinout Heijungs and Rolf Frischknecht. Representing Statistical Distributions for uncertain parameters in LCA : Relationships between mathematical forms, their representation in Ecospold, and their representation in CMLCA. *International Journal of Life Cycle Assessment*, 2005, 10 (4), 248-254.

[10] Mark A J Huijbregts et. al. Framework for modelling data uncertainty in life cycle inventories. *International Journal of Life Cycle Assessment*, 2001, 6 (3), 127-132.
[11] Moore, Ramon E. *Interval Analysis*, 1966 (Prentice-Hall, Englewood Cliffs).
[12] Walley Peter. *Statistical Reasoning with Imprecise Probabilities*, 1991 (Chapman and Hall, New York).

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