Tool to incorporate Environmental Costs into Life Cycle Assessment

Senthil Kumaran D [+], S K Ong [+], Reginald B H Tan [++], A Y C Nee [+]

+ Department of Mechanical Engineering

++ Chemical & Process Engineering Center, Singapore

National University of Singapore

ABSTRACT

The objective of this Life Cycle Environmental Cost Analysis (LCECA) model is to include eco-costs into the total cost of the products. Eco-costs are both the direct and indirect costs of the environmental impacts caused by the product in its entire life cycle. Subsequently, this LCECA model identifies the feasible alternatives for cost effective, eco-friendly parts/products. This attempts to incorporate costing into the Life Cycle Assessment (LCA) practice. Ultimately, it aims to reduce the total cost with the help of green or eco-friendly alternatives in all the stages of the life cycle of any product. The new category of eight eco-costs is being included in the cost breakdown structure. The mathematical model of LCECA aims to define the relationships between the total cost of products and the various eco-costs concerned with the life cycle of the products, and determine quantitative expressions between the above said costs. A computational LCECA model has been developed to compare the eco-costs of the alternatives. This model will include a break-even analysis to evaluate the alternatives, sensitivity and risk analysis modules. This model aims at a cost-effective, eco-friendly product as an end result. This LCECA model will be compatible with the existing LCA software tools.

Keywords: Life Cycle, Eco-costs, Life Cycle Assessment, Life Cycle Cost Analysis, Life Cycle Environmental Cost Analysis, Environmental burdens.

1. BACKGROUND – LIFE CYCLE COST ANALYSIS (LCCA)

Early implementation of cost analysis models influences the design changes of the product, and provides explanations of the relationships between cost and design parameters. They contribute to cost reduction by identifying high cost contributors. However, there are many features of a product that can be studied using a LCCA model. The combination of rising inflation, cost growth, reduction in purchasing power, budget limitations, increased competition, etc., has created an awareness and interest in the total cost of products, systems and structures. Not only the acquisition costs associated with new systems, e.g., quality management systems and environmental management systems, are rising, the costs of operating and maintaining systems already in use are also increasing rapidly. This is the case of a Life Cycle Costing (LCC) situation subject to the following conditions:

- Poor quality of products, systems and structures in use,
- Engineering changes during design and development,
- Changing suppliers in the procurement system components,
- System production and /or construction changes,
- Changes in logistic support capability,
- Estimating and forecasting inaccuracies, and
- Unforeseen events and problems.

The application of LCC methods during product and system design and development is realized through the accomplishment of Life Cycle Cost Analysis (LCCA). LCCA may be defined as a systematic analytical process for

---

++ Correspondence: chetanbh@nus.edu.sg; Phone: +65 874 6360; Fax: +65 7791936

evaluating various designs or alternative courses of actions with the objective of choosing the best way to employ scarce resources. A typical LCCA framework has been illustrated in Figure 1. The ultimate objective of the LCCA of any product is to provide a framework for finding the total cost of design/development, production, use and disposal of the product with an intention of reducing the total cost. If there are feasible alternative solutions for this specific problem, a decision will be required for the selection of the preferred approach. There should be a formal analysis process that can be followed. Specifically, the need of the analysis has to be defined, and the approach to be established. The appropriate information about each alternative is being generated. Evaluation of each alternative with the help of an evaluation model, and the recommendation of proposed solutions to the problem has to be made.

There are many choices in the selection of a preferred approach for the determination of the total cost of a product, pertaining to its entire life cycle. More elaborate approaches with various different areas of scope have been identified. In respective contents, these approaches have emerged to address specific problems. But no one of the existing LCC methodologies address the environmental costs of the environmental burdens caused by the product/service in its entire life cycle, in the calculation of the total cost of the product/service. Nearly ten available LCC models had been analyzed and the need for developing a model to include the eco-costs in the life cycle costing methodology was understood.

2. REASONS FOR INCORPORATING ECO-COSTS INTO LCA

Life Cycle Assessment (LCA) was developed to meet the specific needs raised by organizations trying to embrace the protection of the environment in the Product development and improvement. LCA provides the mechanism for measuring the criteria or indicators that will demonstrate the environmental performance or acceptability of a product to the marketplace. But it cannot find out the costs of the same in terms of economic terms. Basically this model intends to incorporate the environmental costs into the LCA of any product. These costs can be avoided or reduced through pollution prevention (P2) activities such as product design, materials substitution, process re-design etc. This model attempts to prescribe a life cycle cost model to estimate as well correlate the effects of these costs in all the life cycle stages of the product.

The goals of this model are,

- To identify the various eco-costs concerned with every life cycle stage of the product,
- To find out the relationships betwe en them and the total cost of the product,
- To develop a life cycle cost model to assess as well compare the existing product with its alternatives,
- To incorporate cost into the eco-design of the products.

The importance of incorporating environmental costs into life cycle analysis, can be understood by the following statements:

- Hidden and unaccounted environmental costs hinder efficient environmental management systems. Without environmental cost information, well-informed decisions on environmental management and investments cannot be made (EPA, 1995) [17].

- Companies and facilities also recognise that initiatives such as proper materials and waste management, efficient process and product design, energy efficiency, and recycling can be both profitable and environmentally preferable (Ditz, 1995).

- International Standards (like ISO) now require companies to develop Environmental Management Systems (EMS). Conformance with ISO 14001specification document has strong potential for becoming a de-facto requirement for conducting trade, both domestically and internationally. Procedures and tools that carefully track environmental costs and impacts will greatly assist organisations in meeting the monitoring and performance measurement requirements of ISO 14000. US federal facilities are now required, under Executive Order 12856, to apply Life Cycle Assessment (LCA) and Total Cost Assessment (TCA) principles to the greatest extent practicable when estimating pollution prevention opportunities (EPA, 1995) [17].

- In the environmental field, Life Cycle Costing (LCC) has come to mean all the costs with a product system throughout its life cycle, from materials acquisition to disposal. Where possible social costs are quantified; if this is not possible, they are addressed qualitatively (EPA, 1995) [17].

- The life cycle considerations in the DIS (1998) have been left intact: "The objective of reducing environmental impacts and not merely transferring impacts across stages of the product life cycle is best served by considering the whole product life cycle when setting environmental criteria… Any departure from this comprehensive approach or selective use of restricted environmental issues shall be justified."

- In a prospective, comparative LCA, the objective of study is the environmental impacts of a potential product substitution. Product substitutions may occur anywhere in the life cycle, from raw material substitutions, over substitutions in the production and use stages, to substitutions between alternative waste handling options (Weidema, 1998).

- The aim of measuring the environmental impacts of a vacuum cleaner (or any white product) was to establish clear priorities, which would need to be addressed in the design process. This was not a comparative study attempting to compare the environmental advantages of one vacuum cleaner over the another, but rather a life cycle impact analysis of a single machine in order to define a baseline for life cycle improvement analysis (Matthew Simon, 1996).

- According to the ISO standard ISO/TC207/SC5N143 on Environmental Management, LCA has a main challenge to find new ways to incorporate costs of resources to produce the product, the costs of transformation that reflects the environmental impacts associated and costs of disposal into it [18].

3. DEVELOPMENT OF THE LCECA MODEL

The objective of this proposed LCECA model is to include eco-costs into the total cost of the products. Eco-costs are both the direct and indirect costs of the environmental impacts caused by the product in its entire life cycle. Subsequently, this LCECA model identifies the feasible alternatives for a cost effective, eco-friendly design of parts/products. Ultimately, it aims to reduce the total cost with the help of green or eco-friendly alternatives in all the stages of the life cycle of any product.

3.1 Conceptual model

The development of the LCECA model assumes the guidelines from the LCCA methodology presented by Fabrycky and Blanchard[1]. A new generic cost structure has been additionally included with the cost breakdown structure of the above- mentioned model. This new category of eco-costs includes:

- Cost of effluent control,
- Cost of effluent/waste treatment,
- Cost of waste disposal,
- Cost of implementation of Environmental Management Systems,
- Costs of Eco-Taxes,
- Costs of rehabilitation (in case of environmental accidents),
- Costs of energy, and
- Cost savings of recycling and reuse strategies.

The methodology of LCECA is given in Figure 2. As a first step, any product from a particular product family can be selected. Then, a disassembly of the product has been performed. For every part, a cost card has been prepared. This card consists of all the cost details pertaining to that part. Development of a suitable cost model and the identification of the feasible alternatives are performed simultaneously. Various checklists can be used to ensure the eco-friendly nature of the alternatives. These checklists have been prepared on the basis of multiple environmental criteria such as disassembly, material recycling, product reuse, use of renewable energy, minimization of hazardous materials, increase in product durability, use of eco-friendly packaging, saving resources, eco-friendly disposal, etc., relevant to the life cycle design of the product. On the basis of the calculated environmental impact indices (EII), priorities can be made for the selection of suitable alternatives.

The CBS of LCECA includes a new classification of costs called eco-costs. Each of the eco-cost categories has a definite cost relationship. The elements of eco-costs are added to the relevant cost categories of the other major costs such as research and development costs, production costs, operation and maintenance costs and disposal costs. After this CBS has been defined, the cost model for facilitating the life cycle economic evaluation is developed. The developed hypothetical cost model is a hybrid of the LCCA and Activity Based Costing (ABC) models. This hybrid model can be either a simple series of parameters or complex set of subroutines depending upon the selected product or system for analysis. It is a comprehensive model that includes all relevant factors and reliable in terms of consistency. The model represents the life cycle dynamics of a product being evaluated, and remains sensitive to the relationships of key input parameters. It can be used for evaluating the overall product requirements as well as the individual component requirements. It is designed to be simple for allowing timely implementation. It permits the modifications to be made to incorporate additional capabilities by expanding certain facets of the CBS.

3.2 Cost Break down Structure (CBS) of the Eco-costs

$\mathbf{T_c}$ = total cost of the product or part

$\mathbf{C_1}$ = cost of the effluent control
= $\mathbf{C_{11} + C_{12} + C_{13}}$, where

$\mathbf{C_{11}}$ = cost of the effluent control system implementation
$\mathbf{C_{12}}$ = cost of the effluent control system operation
$\mathbf{C_{13}}$ = cost of the effluent control system maintenance

$\mathbf{C_2}$ = cost of the effluent treatment
= $\mathbf{C_{21} + C_{22} + C_{23}}$, where

$\mathbf{C_{21}}$ = cost of the effluent treatment system implementation
$\mathbf{C_{22}}$ = cost of the effluent treatment system operation
$\mathbf{C_{23}}$ = cost of the effluent treatment system maintenance

$\mathbf{C_3}$ = cost of the effluent disposal
= $\mathbf{C_{31} + C_{32} + C_{33}}$, where

$\mathbf{C_{31}}$ = cost of the effluent collection
$\mathbf{C_{32}}$ = cost of the effluent transportation
$\mathbf{C_{33}}$ = cost of the effluent land fill or increnation

$\mathbf{C_4}$ = cost of environmental management systems
= $\mathbf{C_{41} + C_{42} + C_{43} + C_{44}}$, where

$\mathbf{C_{41}}$ = cost of implementation of environmental management systems
$\mathbf{C_{42}}$ = cost of operation of environmental management systems
$\mathbf{C_{43}}$ = cost of maintenance of environmental management systems
$\mathbf{C_{44}}$ = cost of certification for environmental management systems

$\mathbf{C_5}$ = cost of the Eco-penalties*

* Eco- penalties include country or product specific eco- taxes, levy etc.

$\mathbf{C_6}$ = cost of rehabilitation
= $\mathbf{C_{61} + C_{62}}$, where

$\mathbf{C_{61}}$ **=** cost of all damages like health disorders, accidents
$\mathbf{C_{62}}$ **=** cost of production losses caused by the damages

$\mathbf{C_7}$ = cost of energy
= $\mathbf{\Sigma\, C_i}$ where i = 1 to n (number of energy systems)

$\mathbf{C_8}$ = cost savings of reuse and recycling
= $\mathbf{C_{81} - (C_{82} + C_{83})}$**,** where

$\mathbf{C_{81}}$ **=** cost of implementation of R^2 strategies
$\mathbf{C_{82}}$ **=** cost of savings of reuse strategies
$\mathbf{C_{82}}$ **=** cost of savings of recycling strategies

3.3 Model Description

This mathematical model aims to define the relationships between the total cost of products and the various eco-rehabilitation costs concerned with the life cycle of the products, and determine quantitative expressions between the above said costs.

The basic assumptions are,

1. The regression equation was assumed to be linear – straight line.
2. There were two types of variables – one dependent total cost and the other independent eco-rehabilitation costs.
3. Data used for the regression and correlation analysis should be considered sample data.
4. Determination of the regression equation has been done by least-squares method, based on these assumptions.

Generally, when sample data are used to estimate multivariate regression equations, it takes the following form:

$$\mathbf{Y_c = a + b_1 X_1 + b_2 X_2 + \dots + b_m X_m}$$

With the fundamental assumptions that every value of the independent variables (X_I), the values of the dependent variable (Y_c) are normally distributed with a variance of σ^2 and also each value of Y is independent of all other values of Y.

Here again,

$\mathbf{Y_c}$ **-** the computed regression value of the dependent variable Y
a - the estimate of Y intercept of the regression line (a constant)
$\mathbf{b_1, b_2, \dots, b_m}$ - the estimates of the slopes of the regression line (of each variable)
n - the number of observations

The constants **a**, $\mathbf{b_1, b_2, \dots b_m}$ in this equation are computed from normal equations. This proposed model utilizes the following terminology:

$\mathbf{T_c}$ = total cost of the product or part
$\mathbf{C_1}$ = cost of the effluent control
$\mathbf{C_2}$ = cost of the effluent treatment
$\mathbf{C_3}$ = cost of the effluent disposal
$\mathbf{C_4}$ = cost of environmental management systems
$\mathbf{C_5}$ = cost of the eco-penalties
$\mathbf{C_6}$ = cost of rehabilitation
$\mathbf{C_7}$ = cost of energy
$\mathbf{C_8}$ = cost savings of reuse and recycling

Now the objective equation is given by,

$$\mathbf{T_c = a + b_1C_1 + b_2C_2 + \ldots + b_8C_8}$$

and the normal equations are,

$$\mathbf{\Sigma T_c = na + b_1\Sigma C_1 + b_2\Sigma C_2 + \ldots + b_8\Sigma C_8}$$

$$\mathbf{\Sigma C_1T_c = a\Sigma C_1 + b_1\Sigma C_1^2 + b_2\Sigma C_1C_2 + \ldots + b_8\Sigma C_1C_8}$$

$$\mathbf{\Sigma C_2T_c = a\Sigma C_2 + b_1\Sigma\, C_1C_2 + b_2\Sigma C_2^2 + \ldots + b_8\Sigma C_2C_8}$$

.

.

.

$$\mathbf{\Sigma C_8T_c = a\Sigma C_8 + b_1\Sigma\, C_1C_8 + \ldots + b_8\Sigma C_8^2}$$

To ensure that there is a relationship between the dependent cost variable and a particular independent variable, the value of ‘b’ for that particular variable should significantly vary from zero. Therefore, multiple regression requires testing of ‘b’ coefficients.

In order to test each ‘b’ value in the multiple regression equation, the error of estimate or error variance has to be calculated. Generally the *standard error of estimate* is given by,

$$\mathbf{S_m = \sqrt{\Sigma\,(T - T_c)^2 / (n-2)}}$$

This can be viewed as a measure of closeness of fit for the regression equation. With this value, it is possible to estimate the standard error of each coefficient of partial regression (S_{bi}). It is given by,

$$\mathbf{S_{bi} = S_m / \sqrt{\Sigma\,(C_i - \overline{C_i})^2}}$$

Next, the null hypothesis $\beta_I = 0$ can be tested using the ‘t’ test for each variable. This test is to determine if there is any relationship between the independent variable $\mathbf{C_i}$ and the dependent variable $\mathbf{T_c}$ in the multiple regression equation.

The expression for the ‘t’ test is given by,

$$\mathbf{t = b_i - \beta_h / S_{bi}}$$

Where β_h is the hypothesised value of β.

After testing the ‘b’ values, the total regression effect of the independent variables on the dependent variable can be found. In other words, there is a way to test the entire equation. This can be accomplished by the use of the analysis of variance to test the null hypothesis $\beta_1=\beta_2=\ldots=\beta_m = 0$.

This ‘F’ test is given by,

$$F = MSR/MSE$$

Where MSR = Mean Square of Regression = SSR/m
MSE = Mean Square of Error = SSE/(n-m-1)

SSR is the sum of squares of regression; SSE is the sum of squares error and ‘m’ is the number of the independent variables.

The total sum of squares, SST is the sum of SSR and SSE.

Correlation analysis can be done, by the determination of the relationships between the variables. These relationships are measured by the following coefficients:

(i) Coefficient of determination (R^2) = SSR/SST
(ii) Coefficient of correlation(R)
(iii) Coefficient of non-determination (K^2) = 1/ R^2
(iv) Coefficient of alienation (K)

Thus, this mathematical model can correlate the various eco-costs with the total cost. It has been converted into a computational model, to compare the costs of the alternatives. This model will include a break-even analysis to evaluate the alternatives, and sensitivity and risk analysis modules. This model can provide both cumulative and individual eco-costs of energy, transportation, packaging, etc. It will be a hybrid cost model using fuzzy sets for its execution. This model aims at a cost-effective, eco-friendly design of the product as an end result.

A case study, namely high pressure cleaner has been selected and LCA of the same has been carried out using Streamlined LCA. Streamlining LCA methods requires that the res earcher make difficult choices as to what to include and what to omit from a study. These choices can relate to the level of specificity, the study's boundaries and other conditions. These choices must be made within certain limits. Streamlining refers to various approaches that have been developed to reduce the cost and effort required for studies using an LCA framework. There is a perspective on how to accomplish this objective, to involve modifying the method used for the study. Most of the Streamlining approaches involve narrowing the boundaries of the study, particularly during the inventory stage; targeting the study on the issues of greater interest; and using more readily available data, including qualitative data.

4.VALIDATION OF THE LCECA MODEL

An existing Streamlined LCA study of a high pressure cleaner has been used for the pilot validation case study. The outputs of this existing LCA study of high-pressure cleaners are used as the inputs for the LCECA computational model. Environmental Impacts that are pertaining to the manufacturing phase of the life cycle of the high-pressure cleaner are only analysed. Data source types include measurements, computations, extrapolations and estimates. Only the "Manufacturing" life cycle stage has been taken for the LCECA study. Only the environmental burdens of this product and the influence of their costs on the total cost are analysed. Cumulative cost estimates of all the eight eco-cost categories are only applied. The cost values used are relative in nature. The cost data obtained from various data sources are applied to the cost estimate expressions of the CBS to find out the respective eco -cost. The Cumulative Environmental Impact Indices are multiplied with the respective costs to get the eight eco-costs.

Equations of the multi-variate regression model were solved by Minitab software initially. LIMDEP 7 is the computational software being used for validating sub-sequent case studies on LCECA application. Iterations on the computational model can impose changes in the application of the model to different products. Relationships between the total cost of the product and all eight eco-costs are found. Significance of each category of the eco-cost has been understood. Same kind of relationships can be found with suitable alternatives so that comparison can be made. Probable alternates are suitably combined to provide less eco-cost and more eco-friendly product.

5. FUTURE DIRECTIONS

This LCECA model will include a Break-even analysis to evaluate the alternatives, in order to determine the points in time when the different alternatives look good. The ultimate decision will be based on the times in the life cycle when one alternate looks better than the other. Decision-makers are typically interested in the full range of possible outcomes that would result from variances in the cost estimates. A Sensitivity analysis permits a determination of how sensitive the final results are to changes in the values of the cost estimates. Sensitivity analysis module involving both single alternative and multiple alternatives can be included in this LCECA model. The lack of certainty about the future changes makes the decision making as the most challenging task to the individual, industry and the federal governments. Under risk the decision-maker works through the assignment of probabilities. Such probabilities may be based on experimental evidence, expert opinion, subjective judgment, or a combination of these. Such a Risk analysis module can be formulated through possible approaches to account for uncertainty can also be included in this model. Validation of this complete LCECA model through variety of case studies, specific to geographic locations is being initiated. Future research has been planned to make this LCECA model compatible with the existing LCA software tools.

REFERENCES

1. Fabrycky W J and Blanchard B S, *Life Cycle Cost and Economic Analysis*, Prentice Hall, Englewood Cliffs, N.J, 1991.

2. Fabrycky W J and Blanchard B S, *Life Cycle Costing: Engineering Handbook*, Section 188, CRC Press, Piscataway, N.J, 1996.

3. Woodward D G, 'Life Cycle Costing – Theory, Information Acquisition and Application, International Journal of Project Management', **Vol 15**, No.6, pp 335-344, 1997.

4. Dahlen P and Bolmsjo G S, 'Life Cycle Costing Analysis of the Labor factor, International Journal of Production Economics', **Vol 46-47**, pp 459-467, 1996.

5. Cobas E, Hendrickson C, Lave L and McMichael F, 'Economic Input Output Analysis to Aid LCA of Electronic Products', *Proceedings of IEEE International Symposium on Electronics and Environment*, pp 273-278, Florida, 1995.

6. Cobas E, Hendrickson C, Lave L and McMichael F, 'Life Cycle Analysis of Batteries using Economic Input Output Analysis', *Proceedings of IEEE International Symposium on Electronics and Environment*, pp 130-134, Dallas, TX, 1996.

7. Eversheim W, Neuhausen J and Sesterhenn M, 'Design to Cost for Production Systems', Annals of the CIRP, **Vol 47**, pp 357-360, 1998.

8. Westkamper E and Osten-Sacken D v d, 'Product Life Cycle Costing applied to Manufacturing Systems', Annals of the CIRP, **Vol 47**, pp 353-356, 1998.

9. Bras B and Emblemsvag J, *Designing for the Life Cycle: Activity Based Costing and Uncertainty, Design for X, Concurrent Imperatives*, pp 398-423,Chapman & Hall, UK, 1996.

10. Aseidu Y and Gu P, 'Product Life Cycle Cost Analysis: state of the art review', International Journal of Production Research, **Vol 36**, No.4, pp 883-908, 1998.

11. Pacific NW Pollution Prevention Resource Center, *Report on the Analysis of Pollution Prevention and Waste Minimization Opportunities using Total Cost Assessment: A case study in the Electronics Industry*, Seattle, WA, 1997.

12. Henrik Wenzel, Hauschild M and Alting L, *Environmental Assessment of Products, Vol 1*, Part IV & V, Chapman & Hall, UK, 1997.

13. Frank Werner and Richter K, 'Economic Allocation in LCA', International Journal of Life Cycle Assessment, **Vol 5(2)**, pp 79-83, 2000.

14. Askiner Gungor and Gupta S M, 'Issues in Environmentally Conscious Manufacturing and Product Recovery: a survey', Computers & Industrial Engineering, **Vol 36**, pp 811-853,1999.

15. Hermine Dimitroff- Regatsching and Schintzer H, 'A techno-economic approach to link waste minimization technologies with the reduction of corporate environmental costs: Effects on the resource and energy efficiency of production', Journal of Cleaner Production, **Vol 6**, pp 213-225, 1998.

16. N I Caspersen and Sorensen A, 'Improvements of Products by means of Life Cycle Assessment: High pressure cleaners', Journal of Cleaner Production, Vol 6, pp 371-380, 1998.

17.United States Environment Protection Agency, *An Introduction to Environmental Accounting as a Business management Tool: Key Concepts and Terms*, Washington D. C., 1995.

18. International Standards Organization, *ISO/TC207/SC5N143: Environmental management and ISO 14000, Chapter 6 of the development manual*, Paris, France, 2000.

19. Curran, Mary Ann, *Environmental Life Cycle Assessment*, Chapters 1-4, McGraw Hill, New York, 1996.

20. William H Greene, *LIMDEP Version 7:User Manual*, Econometric Software Inc., Plainview, NY, 1998

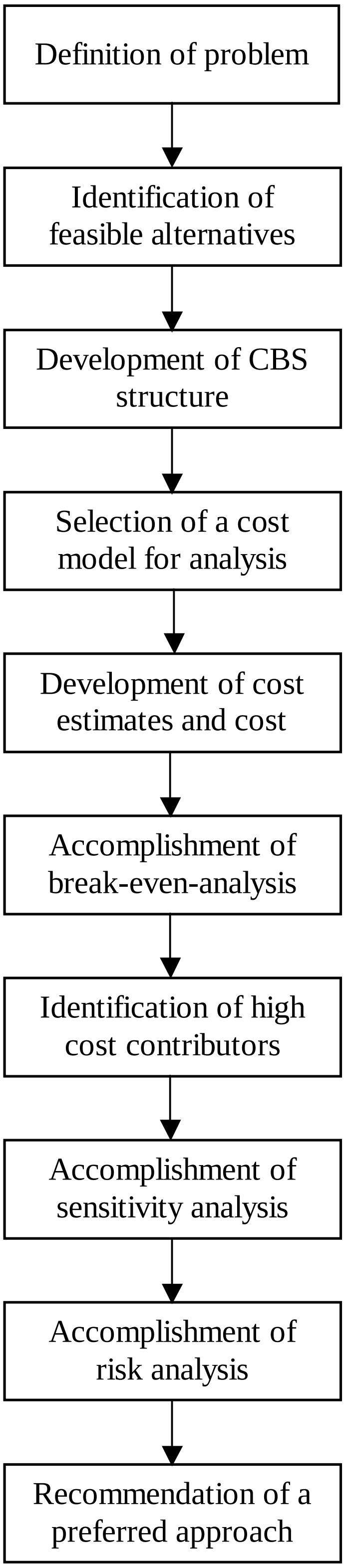

Figure 1. A typical framework of Life Cycle Cost Analysis (LCCA) Procedure[1]

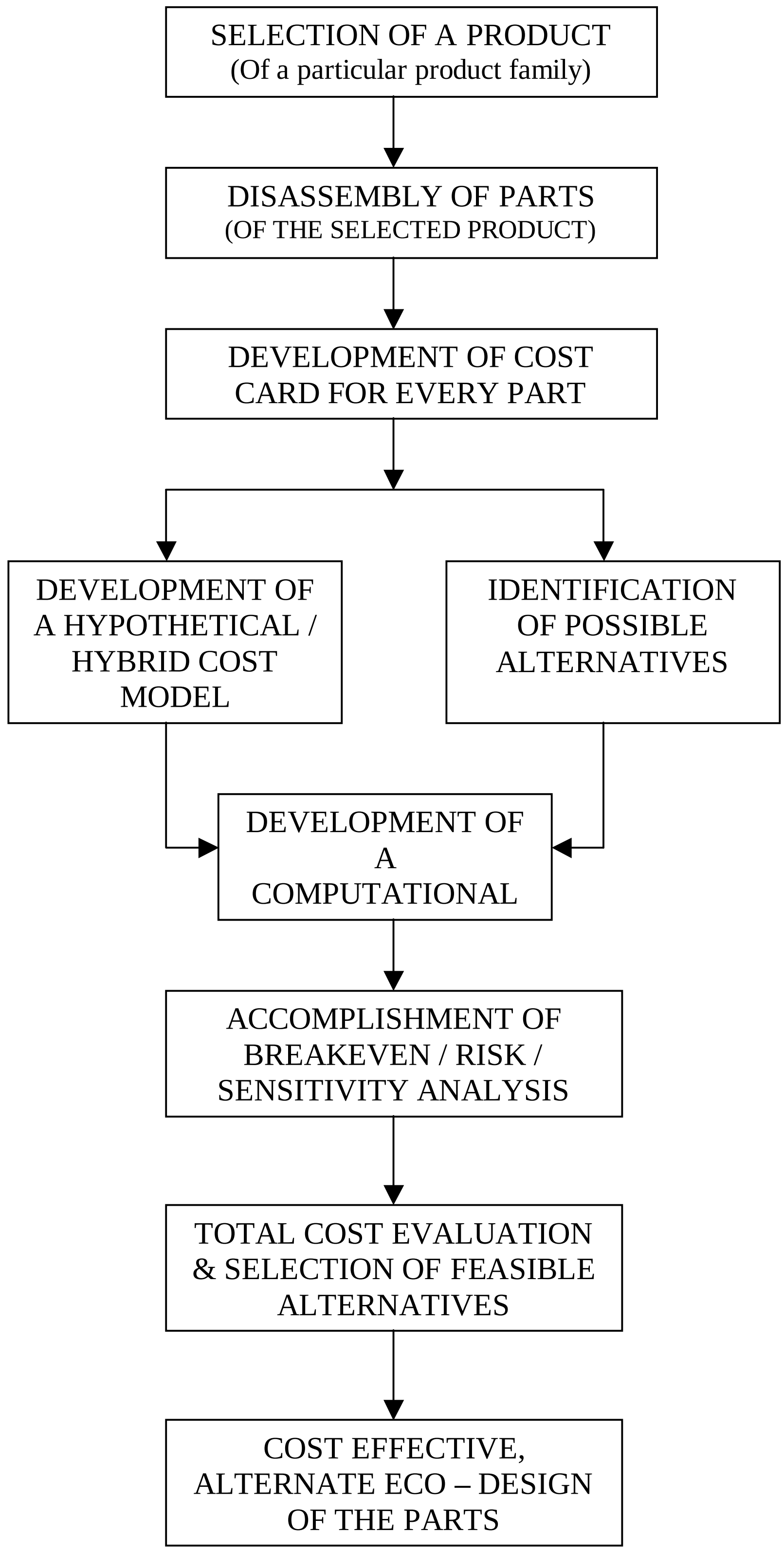

Figure 2. Flowchart of Life Cycle Environmental Cost Analysis (LCECA)