Understanding The Evolution of Information About Product Life Cycle With Respect To Life Cycle Assessment In Design

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ABSTRACT

Products make substantial impact on the environment. Literature suggests that earlier phases of product development can play a major role in reducing these impacts because decisions about how a product will behave during its life cycle stages are constrained by the decisions taken during product development, causing unintended environmental impact. As a result, there is a need to consider the whole life cycle of a product rather than its isolated stages during product development. Life Cycle Assessment (LCA) is currently the most promising technique for estimating environmental impacts of a product during its life cycle. Currently, detailed methods for LCA are critically dependent on high volumes of product specific data, are time consuming and often unaffordable. Current approximate LCA methods are either incomplete, inaccurate or require prior knowledge of what data is important. In this research, our goal is to understand the evolution of product information for all the life cycle phases in different stages of design, and based on these observations, to develop a method for estimating the environmental impact of a product during its life cycle at different stages of its development. During product development, there is often a lack of accurate information about a product's structure and life cycle stages, and related impact information – both temporal and spatial. As information about the product life cycle continues to evolve during development, the assessment method should be such that it incorporates the different levels of abstraction about product information. The paper will discuss the result of descriptive studies undertaken to understand product life cycle information evolution, based on which requirements for the assessment method were identified. Subsequent tasks are design, and implementation of the method, and its evaluation using in-house design experiments to assess its effectiveness and efficiency.

Key words
Life Cycle Design, Life Cycle Assessment, Design for Environment, Sustainable Development, Environmental Impact Assessment

1 INTRODUCTION

Products make a substantial impact on environment. The ratio of product mass to waste mass directly or indirectly produced as a result of the product during its life cycle is about one to twenty **[1]**. These wastes are thrown into the environment in each stage of the product life cycle from raw material extraction to product retirement. The lifecycle principle, where the whole impact of a product across its life is to be examined (from 'cradle to grave') is gaining importance in product development **[2]**. We need to consider environment also as one of the criteria along performance, quality and cost in product development. Environment is gaining importance as an evaluation criterion because of government regulations, competition and customers' requirement.

Traditionally research has been carried out on how to treat the wastes produced, while subsequently the focus shifted to reduction of waste by utilizing the waste produced as by-products. More recently strategy has shifted to eliminate waste in the first place it self and this led to the idea of sustainable development. Sustainable development is defined in the Brundtland report **[3]** as 'development which meets today's needs without placing the ability of future generations to meet their needs at risk'. For sustainable development, design can play a major role as the decisions taken in this stage will affect the later phases of the life cycle.

2 OVERALL IDEA, OBJECTIVES AND RESEARCH METHODS

2.1 Overall Idea

Over all Idea of this paper is to understand the product life cycle information evolution in various stages of design so as to identify the requirements for an environmental impact assessment method for use throughout design.

2.2 Objectives

The objectives are to

- Establish the importance of Design for Environment (DfE)

- Identify shortcoming of current practices
- Understand evolution of product life cycle information
- Identify requirements for the assessment method

2.3 Methodology

In order to establish the importance of Design for Environment, a preliminary literature survey was done, which is used as a basis for a detailed literature survey on current assessment practices, their advantages and disadvantages. Based on these, the requirements of a method to generate, evaluate and select a product proposal in the context of Design for Environment throughout the design process were identified. Product Analysis was carried out on six products to identify the organisation of a product in terms of its sub system, and relationships between these and to understand the information generated. A series of three design experiments were conducted to understand the product life cycle information evolution throughout the design process. The understanding was used to identify the requirements for the assessment method.

3 LITERATURE SURVEY

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 [4, 5]. Early stages of product development are the key in doing this because if we know the environmental impacts of potential designs while designing, we can make changes to these designs then and there so as to reduce their environmental impacts [6]. Since over 80% of the product costs are committed during the early planning and product development stages, design can play a central role in reducing this environmental overloading by products [7].

Life Cycle Assessment (LCA) [8] is the most promising method for estimating environmental impacts of a product during its life cycle [9, 10]. Currently, detailed methods for LCA are critically dependent on high volumes of product-specific data, and are time consuming and unaffordable. Current approximate LCA methods are either incomplete, inaccurate or require prior knowledge of what data is important [11]. LCA tools are not well integrated with other design tools [5]. They are used to validate the design rather than to truly feed into the design process, to shape or steer design decisions [2]. At all stages of design it is necessary to make choices based on various criteria [12]. Consequently, there is a need for an LCA method integrated into the design process that can be applied to early as well as detailed design stages, and that can be driven with generic data available.

Internationally there are many methods developed like *Design for Energy Efficiency* **[9]**, which are useful for specific phases of the lifecycle of a product. However there is no comprehensive method that can be useful for the whole life cycle of a product in various stages of its design. Even though guidelines **[13]** for various phases exist, the guidelines are sometimes too abstract for designers to know what to do in actual design of their products **[14]**. A critical need for a product developer is a method that can be used to estimate environmental impacts of a product during its whole life cycle, even if approximately, while the designer works through the various stages of its development, so that design changes can be made concurrently to the product proposal to make it more eco-friendly. This is relatively inexpensive since one would be able to do so without having to make, use or dispose off the product to see its environmental impacts and understand the trade-offs available between different product life-cycle phases.

If Design for Environment is only used at a post specification stage, relatively minor environmental changes can be affected and organizations may have difficulty in implementing the principles fully. Most significant reductions in environmental impact can be achieved by implementing Design for Environment at the pre-specification stage of design, which is greatly lacked, tools to support the decision-making process **[12]**.

With the progress in capability of computational tools, it appears beneficial to develop an overall support system for the entire design process. This would involve development of both synthesis and analysis support tools. The utilization of the product life cycle for this task offers good opportunities to achieve an efficient support for both analysis and synthesis **[15]**.

Few tools were found which mapped to iterative changes required in product development and this is an area which needs further research **[16]**. To discourage mass production, mass consumption, and mass waste, we need to establish design methodologies for closed life cycles **[17]**. We need to think about the whole life cycle rather than single phases in all stages of the design so that sustainable development products can occur.

We need to automate the extraction of LCI data elements from product documentation as completely as possible so as make LCA a viable analysis tool during the design process **[18]**. As it takes a huge amount of time and work for LCA, it will be good if we can automate the process of extraction without any extra effort. That is different from the usual working process.

3.1 Life Cycle Assessment

Life Cycle Assessment is a process for evaluating the environmental impacts associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, and for identifying and evaluating opportunities to effect environmental improvements **[8]**. It consists of four main activities.

- **Goal Definition and Scope**

This activity consists of specifying the focus of the study. We have to specify the functional unit; which consists of description of product, life cycle and performance. It is important to compare products with same performance. For example to compare vacuum cleaners the functional unit will be to clean the house (dry, wet) for a period of 5 years.

- **Inventory Analysis**

This activity consists of developing all the inventories necessary for the life cycle phases specified in previous activity. It is the most difficult and time taking activity in this method. For example for vacuum cleaners we need to collect the data of amount of materials used like ABS plastic and the processes used for extraction and transportation, manufacturing, assembly processes used for the component manufacturing, energy required, consumables in the usage phase and the disposal type and path.

- **Environmental Impact Assessment (EIA)**

This activity consists of assessing the environmental impact of the inventories developed in previous activity. There exist different methodologies for calculating EIA of products. For example in Eco-indicator99 [**19]**, the overall environmental impact of a product is shown in a single number that combines the impacts on a) human health, b) eco-system quality, and c) resources.

- **Improvement Assessment**

This activity consists of structuring the EIA results and identifying the areas that have substantial potential for improvement in terms of sustainable development.

3.2 Existing methods for LCA have the following problems:

They require high volume of product specific data and it consumes large amount of time. Existing tools are not integrated with design process, they cannot be used in earlier phases of design and these phases are the key in product development. Designer has to put up extra effort for modelling the life cycle, finding the inventory values which are not in his normal working procedure. Current tools are difficult to apply directly in specific design stage like conceptual phase where we have no data or part of the data required. Existing impact estimation tools are developed in isolation so cannot be used with the current CAD tools directly for analysis. Most tools are conceptual and in actual industry they cannot be used as they are. Do not fulfil designer's requirements like generation, evaluation and selection of product proposals.

3.3 Requirements of proposing method:

The problems with the existing methods will become the requirements of the proposed method. The method should work with the generic data available like the common materials, approximate product structure etc. It should be inline with designer's working process. Method can be used in early as well as later stages of product design. There should not be any extra effort needed from the designer, the data has to be automatically generated from the product structure. It should be integrated with current CAD tools so that designer will not feel any discomfort. Method should help in generation, evaluation and selection of the product proposals, because it is iterative process. It has to be integrated with other analysis tools also to reduce time and data duplication. It should allow to access environmental performance of product based on available data. The tool should be computer based as designers willing to work on computer because of ease.

4 PRODUCT ANALYSIS

First the products on which analysis has to be carried out have been identified. The list of products with specifications and working principles is given in Table.1. Two products of the same type have been considered for comparison purposes. The main intention was to compare the environmental impact' within the category. From this analysis we also came to know the relationships between shape, material and manufacturing processes which can be used for generic databases.

Table.1.Product List

List of Products	Vacuum Cleaner1 (VC1)	Vacuum Cleaner2 (VC2)	Mixer Grinder1 (MG1)	Mixer Grinder2 (MG2)	Compressor1 (COM1)	Compressor2 (COM2)*
Specification	800 w	1300 w	550 w	550 w	112 w	110 w
Working Principle	Universal motor with impeller	Universal motor with impeller	Universal motor with high rpm	Universal motor with high rpm	Single phase Induction motor with reciprocating pump	Single phase Induction motor with reciprocating pump

5 DESIGN EXPERIMENTS

A series of three design experiments were conducted in order to obtain a general understanding of the design process as well as to investigate the information evolution in design process with respect to product life cycle.

5.1 Main design stages

The following main design stages were observed which are similar to [**20**]**:**

i. ***Task clarification***, where requirements of the design are specified. Fig.1. shows the part of the transcription of one of the design experiment in the task clarification phase, where the subject is specifying the requirements.

7.44	S1	privacy is not there in gymasium
7.52	S1	privacy is not there means lot of people are feeling, feeling what
8.03	S1	feeling shy of going there, body building exercise probably
8.09	S1	why they don't do exercise wearing the full dress (smile) strange
8.15	S1	current equipment occupies lot of space ok
8.28	S1	and usually are not portable
8.34	S1	these are problems with current equipment
8.39	S1	so the requirements are external requirements, some are constratints
8.46	S1	apart from the solution of the problem, requirements are that
8.52	S1	it should be easily setupable
9.07	S1	it should be setup easily and portable
9.12	S1	and should help in complete workout of the body
9.27	S1	ya
9.29	S1	first of all the thing is that whether we really achieving that

Fig.1. Part of the transcription in the task clarification phase

ii. ***Conceptual Design***, where ideas, spatial layouts and sub-assemblies are specified. Fig.2 shows the part of the transcription at conceptual stage and Fig.3 shows the sketch of an assembly 'handle' at one particular time in the conceptual stage.

11.23	S1	I will write down problem solution
11.32	S1	one is
11.35	S1	one is manual for yoga and this can be customized
11.48	S1	may be I can have a software where you can give problem what are problems you have and you get some output with postures animation and you give some ways to do it and it is proved by many rishis and thousand years of research more that that yoga is very good for healthy and body and not this we are going to copy form british and american guys that we have to do with some rod put springs against it and do some strange exercises which has no meaning after all and we have to wait for one month to see some output I think it has not proved that by doing this exercises your heart is good your teeth are good means your health is good
12.4	S1	but if I see lot of yogic exercises expecially we see madhurasan, we see bakasan we see what else lot of others is there first of all manually is a good option
13.02	S1	now let us think in the other way what can be done

Fig.2. A portion of transcription in the conceptual stage

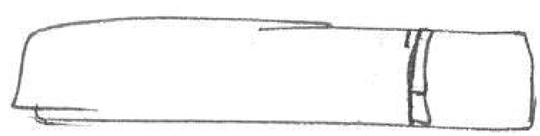

Fig.3. Sketch of an assembly 'handle' in the conceptual stage

iii. Embodiment Design, where interface details are sub systems were specified. Fig.4 shows the sketch of an assembly 'handle' in the embodiment stage.

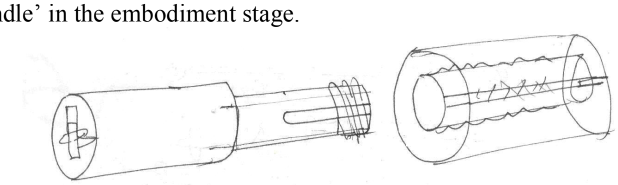

Fig.4. Sketch of an assembly 'handle' in the embodiment stage

iv. Detailed design, where detail dimensions, materials and manufacturing tolerances are specified. Fig.5 shows the detailed drawings of one component of the 'handle' in the detailed design stage.

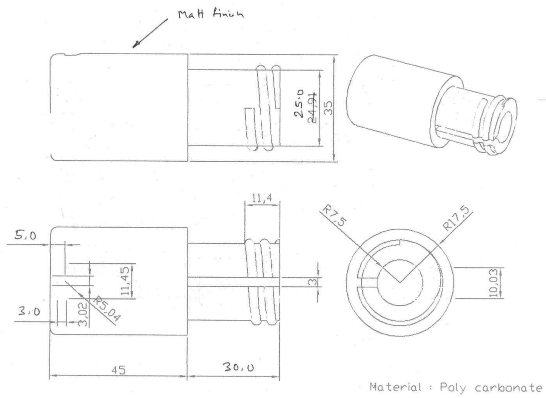

Fig.5. Final drawing of one component of the 'handle' in the detailed design stage.

The activities performed by the designer and the resulting information are discussed in the next two sections.

5.2 Activities performed by designer

The types of activities performed by the designer during the design process are listed below. The intended support should allow a designer to do the above listed activities with ease and in a short time.

a) ***Product version definition***: It is the specification of a concept. For example, in one experiment, the designer sketched four sketches first and then said that these together constitute his first version of the product. After modifying and deleting some of these sketches and evaluating them, he reduced these to three assemblies and said this was his second version. Fig.6 shows the version definitions as sketched by the designer.

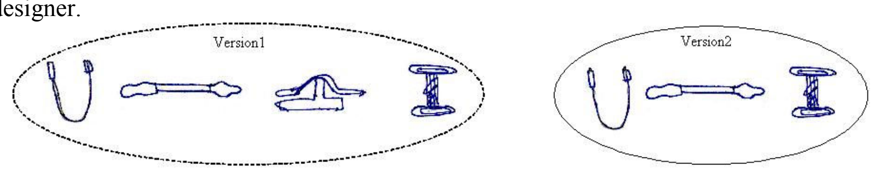

Fig.6. Version Definition

b) ***Addition and subtraction of physical objects/information***: This entails addition or removal of components or features from an existing assembly or component. For example, first the designer drew a skipping rope and to this he added two foot-clamps, see Fig.7. This figure shows the activity of adding components to an earlier assembly. Fig.8 shows the activity of material addition to a component.

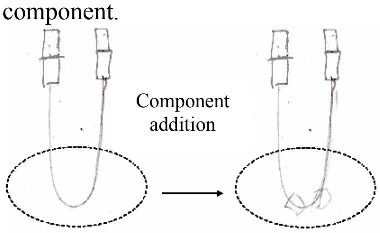

Fig.7. Component addition

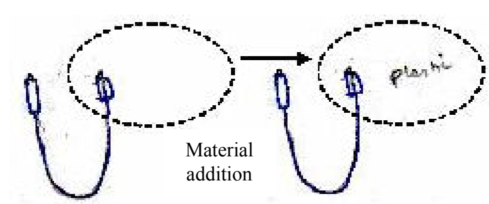

Fig.8. Material addition

c) ***Addition and subtraction of relationships between objects***: In this activity, relationships between objects are specified or removed. For example, the designer in Fig.9 initially drew the two boxes attached without specifying any relationship between them (left of the figure). After this, he added the detail of how the components were exactly related (right of the figure). Fig.9 shows this activity of addition of relation (thread) between the two parts of the handle assembly.

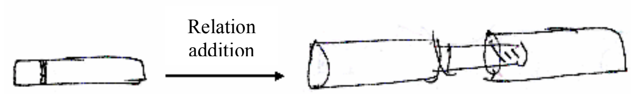

Fig.9. Relation addition

d) ***Substitution of object/information***: This activity is a combination of two activities; subtraction of already available object/information and addition of new object/information. For example, in a single activity, the designer removed the rope and modified the handle part. Fig.10 shows the substitution of an object (rope).

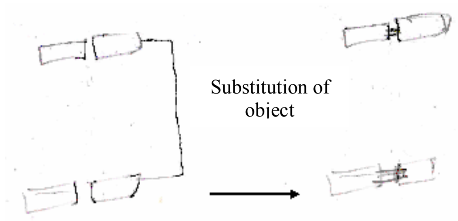

Fig.10. Substitution of objects

e) ***Focus to object or information***: In this activity, a designer concentrates on a particular object or information. For example, while designing workout equipment for executives, the designer drew a sketch representing a skipping rope with handles. In the next sketch, he drew only the handles without drawing the rope because he wanted to focus on the handle. Fig.11 shows this focus activity.

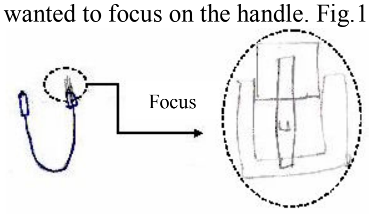

Fig.11. Focus to object

f) ***Defocus from object or information***: Here a designer defocuses, from a focused object or information, by representing the outline. For example, in the defocus activity shown in Fig.7, the designer sketches the details of the handle and then the outline of the handle.

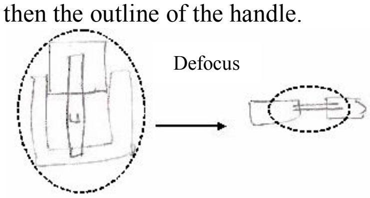

Fig.7. Defocus from object

g) ***Change of the view or focus***: This activity is a combination of two activities; defocusing from the already focused object/information and focusing on others. For example in Fig.8, the designer was initially interested on the internal object (spring) within a rope assembly. Afterwards he changed his point of interest to the outside object (casing)

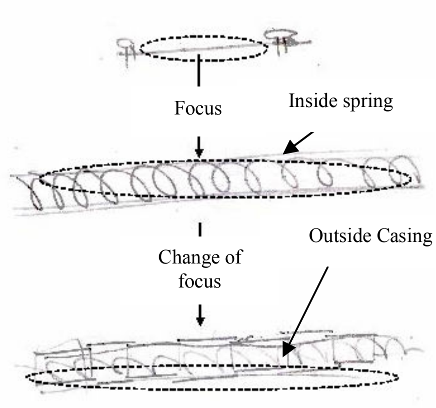

Fig.8. Change of focus

h) ***Change of orientation of the objects***: Here a given object is orientated in a different way as a result of the activity. For example, the designer in Fig.9 initially sketched the object vertically and then changed this to be horizontal.

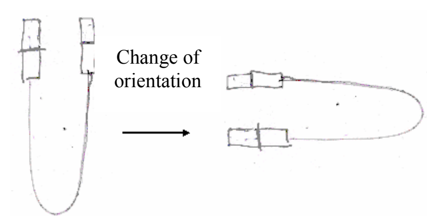

Fig.9. Object rotation

There are some activities that are spoken only, and cannot be represented using drawings or as associations between objects with information. There should be some mechanism for capturing these activities, while allowing a designer to do the activities fast and with ease.

5.3 Evolution of information about product configuration

The information in task clarification phase was about identification, analysis and selection of design problem and tasks. It is mainly in this stage, designer worked around the specification given and tried to identify the actual problem definition and its requirements.

The information in conceptual phase is on finding the principles, global configuration (main assemblies, function etc) of the concept, generating, associating the ideas with the existing ones and primary evaluation. For example while solving a problem for exercising equipment, designer thought of existing products like, skipping rope etc. Here the component shapes and material classes are thought of globally (main material classes etc).

The information in embodiment phase is specifying relations between the components, subassemblies, the local configuration of the subsystems, and evaluating the solutions.

The information in detailed phase is fortifying all components with exact shape, dimensions and tolerances, material, process details with exact relationships.

A summarisation of evolution of product configuration information in all the stages of design is given in Fig.10. The evolved information is above the line and the activities performed by the designer are below the line in the Fig.10.

Task Clarification	Conceptual	Embodiment	Detailed
• No Shape • No Material • No Process • No Dimension • No Relations	• **Shape** • **Material (class)** • No Process • No dimension • No Relations	• **Shape (detail)** • Material (class) • No Process • No Dimension • **Relationships**	• **Shape (Exact)** • **Material (Exact)** • **Process (Exact)** •**Dimension (exact)** •**Relationships**
• Problem Identification • Problem Analysis • Problem Choice	• Global Configuration • History • Association • Solution Evaluation	• Local Configuration • History • Association • Solution Evaluation	• Modelling • Drawings

Fig.10. Information Evolution and the activities performed by the designer in design

6 DISCUSSION

There are three main dimensions of uncertainty related to information evolution in design with respect to Life Cycle Assessment:

- ***Uncertainty in information about product structure***

  This uncertainty is related to the ***subsystems***, ***components*** and ***interfaces*** between them. For example we may know that there are three subsystems in the product but we may not know the interfaces between them, and we may/may not know the components in subsystems.
- ***Uncertainty in information about life cycle phases***

  This uncertainty is related to the ***material***, ***production***, ***distribution***, ***usage***, ***after use*** phases of the product life cycle. There are also sub-phases in these: extraction, manufacturing and transportation in material, manufacturing and assembly in production, packaging and transportation in distribution, use, maintenance and repair in usage, and reuse, recycle and disposal in after use phases. For example we will be having information about material of the component only, and then we know information about the material phase only.
- ***Uncertainty in information quality***

  This uncertainty is related to ***temporal***, ***spatial***, ***source***, and ***selection*** in the quality of the information. In temporal sense information may be old or new, in spatial sense information may be applicable to global scenario or local scenario, in source sense information is collected from specific plant or from more plants, and in selection sense selected information is accurate or similar information is selected because of unavailability of information.

At any point of time, information available will be one of these or combination of these. We have to identify what information is required to 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 impact value and confidence value of impact estimation need to be calculated.

Every product concept consists of subsystems that in turn consist of components and interfaces. So, there are different perspectives in which we may want to compare alternate product proposals a) a product, b) different subsystems in the proposal/different proposals c) different components in the proposal/different proposals. Each of these can be with the whole life cycle or for a particular life cycle phase and/or environmental impact category.

For calculating environmental impact, we should know all the inputs from the environment and all the outputs to the environment. In design if we want to calculate the environmental impact of a particular constituent in all its life cycle phases, we should give mass of the materials used, manufacturing processes for that constituent, packaging material mass, manufacturing process, assembly process, material used, transportation type, product mass, distance travelled, energy required in use, auxiliary substances required in use (material, mass), after use stream etc.

In practice, we may have none or only part of this information. So based on the information we have to calculate the impact at that particular instance and therefore should be able to tell the user something about the accuracy of the calculated result, so that decisions and tradeoffs can be made based on the result.

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 two of its components. The product state at this point is that the product has three components. The maximum information we can have at this point are the materials of the three components, the relationships between the three components, the manufacturing processes of the three components, the manufacturing processes of the relationships, related assembly processes, after use details of the three components and relationships etc. But currently we have only a part of this information, so any impact value evaluated based on this information should have a confidence value well below certainty (100%) because of the incompleteness of information at this particular state of the product.

As designers request for any environmental impact analysis at any time in the design process, the support should be able to calculate the impact based on the complied information currently available and give the impact estimation value with an estimation of its confidence level.

7 RESULTS

The results from the research done so far: There are mainly four stages of design; task clarification, conceptual design, embodiment design, and detailed design. In these stages the information about the product (product configuration etc.) changes from abstract for example material of a component as a class to the concrete as a specific material. We also found that designers often evaluate their design with respect to requirements, it's an iterative process. There is a need of a method to incorporate the product information transition. We propose that there are mainly three types of uncertainties with respect to Life cycle Assessment in Design; Product Structure, Life cycle phase, Information Quality.

8 CONCLUSIONS AND FURTHER WORK

The importance of EcoDesign is established for the sustainable development. A critical review of the current practices helped in identifying the shortcomings and defines a path to reduce them. Literature survey, product analysis and in-house design experiments helped in understanding the product life cycle information evolution with respect to Life Cycle Assessment and requirements for the assessment method were identified. Subsequent tasks are design and implementation of the method, and its evaluation using in-house design experiments to assess its effectiveness and efficiency.

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