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USE OF DFE METHODOLOGIES AND TOOLS – MAJOR BARRIERS AND CHALLENGES

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ABSTRACT
Products make substantial impact on environment. Product to waste mass generated through out the product lifecycle can be as high as 1:20. Design for Environment (DfE) is an approach to design where all the environmental impacts of a product are considered over the entire life cycle of a product. Early stages of product development are the key for 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 [1, 2]. However, unlike cost and performance, use of environmental criteria and DfE is far from part of mainstream designing [3].

Most DfE tools are conceptual in nature, and there is very little adoption of these in industry. Methods like [4] are useful for specific phases of the lifecycle of a product. However, during product development there is a need to consider the whole lifecycle rather than a single phase of the product.

From descriptive studies we found that there is substantial difference in the environmental impact among products having the same functionality generated during the same design process. Analysis of industrial products shows similar results. This means that design can substantially affect the impact created by a product. Designers in general are not aware of environmental impact as a criterion, and current support is inadequate in terms of integrated, sustainable product development where design and impact estimation are seamlessly integrated.

This paper reviews the state of the art, identifies the requirements for a tool for DfE, and explores potential means for fulfilling these requirements.

Keywords: design for environment, sustainability, lifecycle design, eco-design, lifecycle thinking

1 INTRODUCTION
Products make substantial impact on environment. Product to waste mass generated through out the product lifecycle can be as high as 1:20. Design for Environment (DfE) is an approach to design where all the environmental impacts of a product over the entire lifecycle of a product are considered. Early stages of product development are the key to this because if the environmental impacts of potential designs can be assessed while designing, changes to these designs can be made then and there so as to reduce these impacts [1, 2]. Since over 80% of the product costs are committed during the early stages of product development, design can play a central role in reducing this environmental overloading by products [3]. However, unlike cost and performance, use of environmental criteria and DfE is far from part of mainstream designing [3].

2 OBJECTIVES AND METHODOLOGY
This paper uses review of literature and descriptive studies of design to ask the following questions:

What are the primary reasons for DfE not being a part of mainstream designing? This question is answered mainly using review of current literature focusing on identifying the state of the art in the area of DfE, and using review and analysis of existing methodology and tools for DfE for product analysis and design.

How does this situation change with the availability of information or support for DfE? This is explored through descriptive studies of designers solving design problems with increasing amount of information and support available on DfE. This is also used to understand the specific constraints associated with using information or support for DfE, to better clarify support development needs.

3 LITERATURE SURVEY

The need to consider environment protection is increasing in the industrial product development activities. The main reasons for these are environmental regulations, increasing costs of energy, resources, customer requirements, competitors, company image etc. Previously, effort of companies was limited to treating the waste produced, which is called end of pipe solutions. Afterwards, that interest changed to cleaner production whereby the philosophy changed to reduction of waste and its toxicity and use of waste. The companies eventually realised the need to mitigate the waste and toxicity, which led to design for environment where strategies for reduction of waste and toxicity are applied in the design stage itself so as to prevent its occurrence in later stages of the product life cycle.

A number of guidelines were created for assisting designers in the choice of materials, fasteners, processes, end of life processes etc. These guidelines are meant to aid mainly end of life processes: disassemble, reuse, and recycle. Later the efforts became directed on product life cycle as the basis for thinking, addressing all stages of product life cycle, from material extraction to after-use. There are many collections of general guidelines like [1]. These, however, are unlikely to be directly useful in the day to day product development activities. Considerable effort has been spent in developing Design for X tools for each specific phase of the product life cycle, like Design for manufacture, design for assembly, design for disassembly, design for reuse, design for recycle etc. These tools are developed in isolation, and there is very little or no integration of these tools into the design process.

Development of methods to assist analysis of environmental impact of products is increased and Life cycle assessment (LCA) [5] has emerged as one of the promising methods for carrying out environmental impact analysis of products and systems. LCA consists of four main stages a) Goal and Scope Definition, b) Inventory analysis, c) Impact Assessment and d) Improvement assessment. It does not automatically direct us to optimal designs. There are mainly two types of LCAs: i) full LCA, which requires a lot of time, data and money to carry out, and ii) abridged LCA, which is may not be reliable as we need to know beforehand what to consider and what to remove from the analysis, leading to uncertainty in calculation. The level of uncertainty involved in the calculation should be available with the results, as decision maker makes decisions based on these results which have uncertainty. Use of LCA and estimation of its uncertainty normally requires environmental experts.

Many methodologies have been developed for LCA, like Ecoindicator99, EPS2000, CML2 baseline 2000, which are region-dependent. LCA provides a means of quantifying impacts and improvements and a means of providing additional directions to the design process. There are different indicators for representing environmental impacts, like MIPS (material intensity per unit service), Ecopoint, Ecoindicator developed for specific regions, etc. There are a number of tools available for material selection but there is no classification according to the environmental aspects of the data [6].

Studies by the National Research Council of USA [7] and others [8] conducted on various large scale projects estimate that up to 80% of the life cycle design costs are determined in the first 20% of the design phase or the early conceptual stage of product development.

The other aspect of environmental protection is its management, leading to creation of environmental management systems. In such systems, main focus is to study the organisational, business and strategy-related issues of eco-design, so as to develop methods to accelerate these. The most pressing design need seems to be for technology that can fully integrate life cycle analyses and design methods directly into computer aids. Further it should support product and manufacturing process design with fundamental data and analytic modelling of the technical, economical and environmental impacts of design decisions [9].

There are mainly two types of tools available: *analysis tools* which are useful in finding the areas where the impact is substantial, and *improvement tools* which are useful in finding solutions with which to reduce the impact by helping designer to generate appropriate alternatives.

Major barriers for environmentally oriented product development are listed [10] as: low knowledge of the environmental impacts of specific products, low priority of environmental goals in product design, cost orientation, and lack of methods for early planning. New eco-design tools are needed for early stages to help identify functional, economic or environmental problems and any associated risks [11].

As impact on the environment comes from all phases life cycle phases, we should not omit some life cycle phases as in streamlined LCA as it may not be clear a priori in which life cycle phases the impact will be more for a particular system [12]. It is required to envisage the specific processes present in the specific life cycle phase for impact assessment. The environmental impact of electricity intensive materials (such as virgin aluminium) and production steps will be largely dependent on the geographical location of the supplier [13]. The use of ecodesign tools may lead not only to environmental improvements but also towards options for cost reduction and new innovative directions [14]. Environmental issues can trigger innovation and new solutions for old or new purposes have been reported [15].

An iterative use of LCA during product development has been reported to be advantageous [16]. The criteria for life cycle oriented designing approaches to be successful are a) use of environmental effects as one of the criteria for the selection of the final design, b) focus on functionality of the product, c) being compatible with existing design procedures, d) being easy to use, e) being suitable for teamwork, f) being useful for both analysis and synthesis, and g) being effective (result versus effort) [17].

To summarise, the primary reasons for DfE not being part of mainstream design are found to be the following:

Most of the DfE tools are conceptual in nature and there is very little adoption in the industry. Methods like [4] are useful for specific phases of the lifecycle of a product. But during product development there is a need to consider the whole lifecycle rather than a single phase of a product. Qualitative tools like checklists which are subjective in nature are used in the initial phases, and quantitative tools like LCA, which require enormous amount of data, time and effort, are used in the later stages of design. There is no communication between these tools or their results.

Methodologies like EPS2000 and Ecoindicator99 used for lifecycle impact estimation in LCA are region-dependent. There are streamlined LCA methods available but they require prior knowledge of what to consider and what to leave out. This leads to uncertainty in the calculations and this uncertainty should be represented in the final results.

There are various DfE strategies and guidelines like [1] and [18], but little is said on how to combine and integrate these within the design process with other strategies for trade-off analysis. There is no comprehensive method that can be useful for the whole lifecycle of a product in various stages of its design for both synthesis and analysis.

4 ANALYSIS OF PRODUCTS

4.1 Introduction and Data Collection

From the analysis of products, we found that there is substantial difference in environmental impact between products with the same functionality. Data collected from a number of companies and their sub-contractors on materials, manufacturing and assembly processes necessary for producing six consumer products analysed. The list of products analysed are given in Table 1.

Table 1 List of products analysed with specification and working principle.

List of Products	Vacuum Cleaner1 (VC1)	Vacuum Cleaner2 (VC2)	Compressor1 (COM1)	Compressor2 (COM2)	Mixer Grinder1 (MG1)	Mixer Grinder2 (MG2)
Specification	800 w	1300 w	100 w	115 w	550 w	550 w
Working Principle	Universal motor with impeller	Universal Motor with impeller	Single phase Induction motor with reciprocating pump	Single phase Induction motor with reciprocating pump	Universal Motor high rpm	Universal Motor high rpm

A Format (Figure 1) for data collection from companies to help analysis of each product has been established used in data collection. The bill of materials for each product with part names, materials, weights etc. has been collected for material-wise impact assessment.

Product Data Checklist / Template

Level
Name
Manufactured By
Manufacture's Address

Code

Bill of Material Details:

Sl No	Item code	Description	Weight/unit	Quantity	Source				Remarks
					a	b	c	d	
1									
2									
....									
15									

Source Key: Page off
a = In-house
b = outworked Apprised By: Checked By:
c = Imported
d = combination (Name in BLOCK letters & signature) (Name in BLOCK letters & signature)

Figure 1 Part of product data collection template

Data on description of components, processes, machines, input materials, weights and output substances, by-products, consumables, and energy used are collected for material and process- wise environmental impact assessment, see format in Figure 2.

Process Data Template

Component Name : Code :
Manufacturers Address :
Material Des:

Sl. No.	Process	Machine	Machine Description	Input				Output			Recycled Byproduct	Remarks
				Material	Weight	Consumables & Weight	Energy	Material & Weight	ByProduct & Weight	Energy		

Figure 2 Part of manufacturing process data template

Data on types of assembly, components, assembly processes, and their energy details are collected for assembly-wise environmental impact assessment, see format in Figure 3.

Assembly / Process

Sl. No.	Operation	Components Added	Welding	Pressing	Screwing	Manual	Glueing	Others			Type of Energy	Energy (KW)	Remarks

Figure 3 Part of assembly process template

Data collection on usage with volume of production, sales, emission etc. is carried out using a questionnaire (Figure 4) to help assess environmental impacts in use and retirement phases.

QUESTIONNAIRE FOR LCA OF PRODUCT

Company :		Address :			
Product :		Product Details :			
Kindly answer the following questions and if not applicable please indicate as NA.				Date :	
1. What is the average order quantity of the product/month?					
2. What is the percentage distribution of the product in India?					
3. What are the packing materials used? Give details.					
4. Are there any emissions/effluents as output during manufacture of the pr		Yes		No	
If Yes	a. How are they treated?				
	b. Is there any recycling involved?				
	c. Means of disposal				
5. Are there any buy back policy to take back the product after its life?		Yes		No	
If Yes	a. Give details of method adopted for collection?				
	b. Are the parts reused/ recycled?				
	c. What is the scrap disposal method?				
6. How are shop rejections & Scrap handled?					
7. Are there any Effluent Treatment Plants in the plant?		Yes		No	
8. Any instruction / running details manuals given along with the product?		Yes		No	
9. Do the product need any consumables during its life?		Yes		No	
If Yes	a. What are the consumables?				
	b. Are they provided with the product?				
	c. Are they available in the market?				
10. Do the product have Warranty?		Yes		No	
11. Are the spares available in the market?		Yes		No	
If Yes	a. How are the replaced defective parts handled?				
	b. Is there repair & reuse of these parts?				
	c. How are these scraped?				
12. Are there any emissions during the use of the Product?		Yes		No	
If Yes	a. List the emissions				

Figure 4 Part of questionnaire for usage and after use

A summary of data collected is given in Table 2 with part count, material type count and process type count for each product analysed.

Table 2 Summary of no. of parts, material types, process types

List of Products	VC1	VC2	COM1	COM2	MG1	MG2
Part count	76	66	57	67	66	77
Type of material count	7	9	8	9	12	12
Process type count	14	14	28	32	22	17

4.2 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 [5].

A Life Cycle Assessment study consists of four main activities.

1. **Goal Definition** and Scope consists of specifying the focus of the study. Here the focus is on the raw material, manufacturing, assembly processes and usage.

2. **Inventory Analysis** consists of developing all the inventories necessary in the whole life cycle of the product.
3. **Life Cycle Impact Assessment** (LCIA) consists of assessing the environmental impact of the inventories developed in activity 2. A methodology called Eco-indicator99 is used for LCIA in the project, as it is the most popular method around the world for LCIA. In this methodology 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.
4. **Interpretation** consists of structuring the LCIA results and identifying the important areas that have substantial potential for improvement in terms of reduced environmental impacts.

In the **Inventory Analysis activity** the tasks carried out included the construction of product structure, where all parts of a product are grouped into sub-assemblies. A part of the product structure made for a compressor is shown in Figure 5.

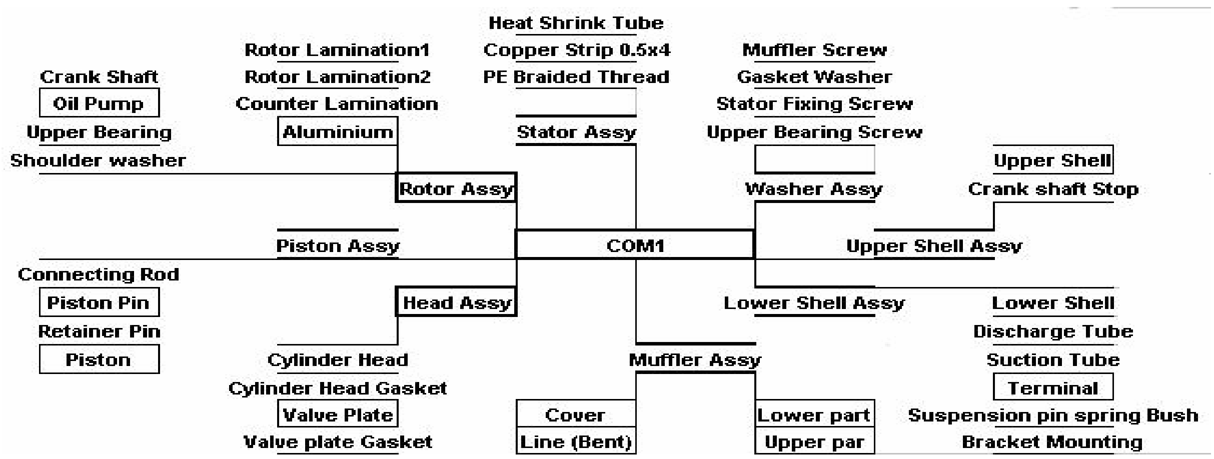

Figure 5 Product structure

The next step was to add details about the features, material and processes used in each component of the product to the component structure to form the process structure (Figure 6) for the product.

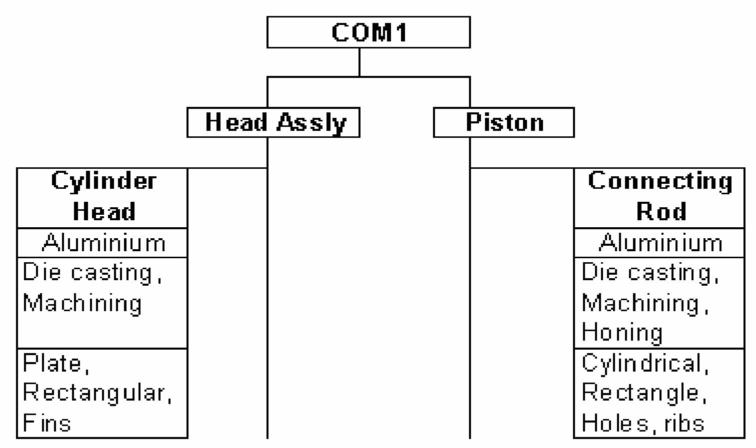

Figure 6 Process structure

In **LCIA activity**, all materials in a product are grouped together in terms of material type and the overall impact per material type is calculated. After that materials are grouped under each sub-assembly and the overall impact for each sub-assembly is calculated. Subsequently manufacturing and assembly details are added to the material details of each sub-assembly and the overall impact for the material and production stages is calculated. Later usage details are also added and the overall impact for material, production and usage stages is calculated for each sub-assembly. The final results of this assessment (against three life cycle stages) are shown in Figure 7–12 below.

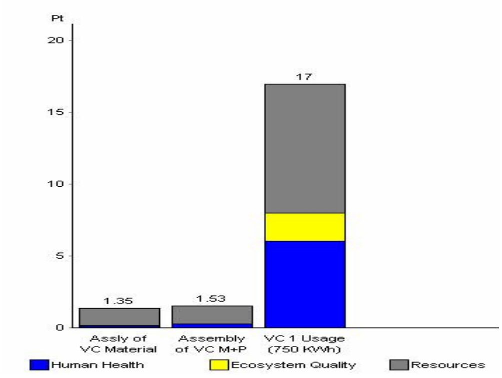

Figure 7 VC1

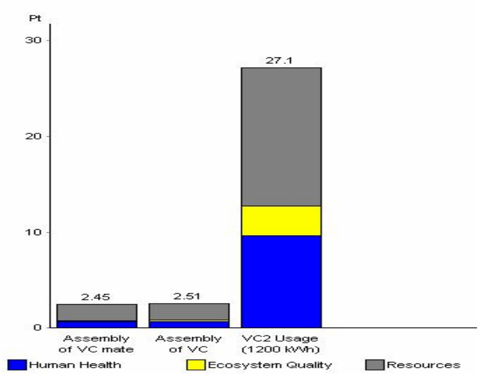

Figure 8 VC2

Figure 7 and 8 show the impacts for various life cycle phases of two vacuum cleaners. The main impact in both the cases is in the usage phase which in these cases is about 10 times more than the material and process impacts combined. Though the vacuum cleaners are of different wattage, after normalizing against wattage their specific impacts are found to be similar. These Impacts are most on resources, next on human health and least on eco-system quality. It is important to note that vacuum cleaners need not be of the high wattages used in the products analysed here. In fact a vacuum cleaner designed and developed in TU Darmstadt in Germany was of 500 Watts and did a similar cleaning job with 1/3 impact of that of VC2.

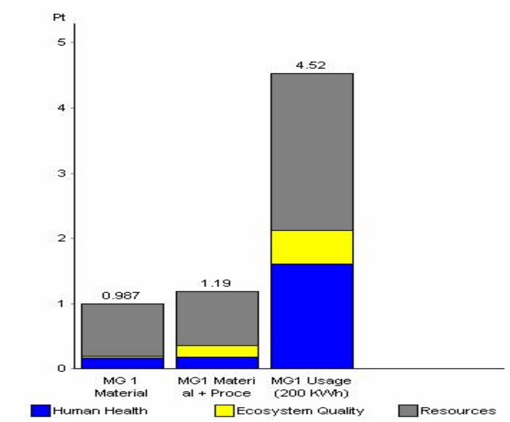

Figure 9 MG1

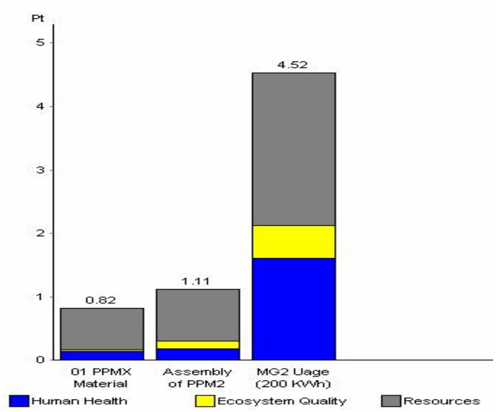

Figure 10 MG2

Figure 9 and 10 show the impacts for various life cycle phases of two Mixer Grinders. The main impact in both the cases is in the usage phase which in these cases is about 4 times more than the material and process impacts combined. The two Mixer Grinders are of the same wattage. These impacts are most on resources, and least on eco-system quality.

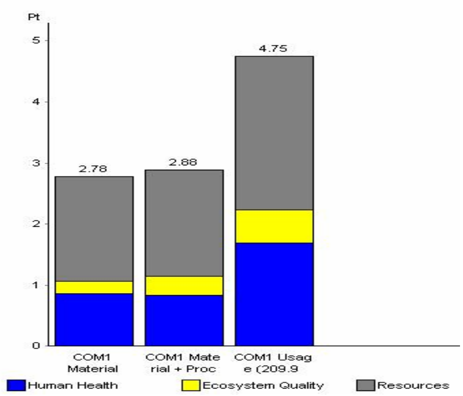

Figure 11 COM1

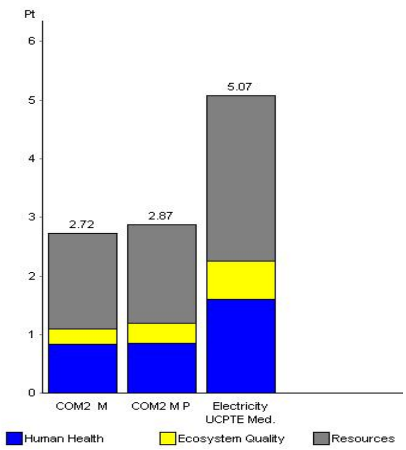

Figure 12 COM2

Figure 11 and 12 show the impacts for various life cycle phases of Compressor1 and Compressor 2. The main impact again is in the usage phase, which in this case is about 1.5 times more than material and process impacts combined. These Impacts are most on resources, next on human health and least on eco-system quality. As can be seen from the variation of relative impact between products of the same kind and products of different kinds, the stages of a product can variously impact environment.

Comparative analysis of the products in pairs is used to identify or conclude the following:

Vacuum Cleaners:

- Ratings are different
- Working principle is the same
- Structures are different
- After normalization there is little difference between the impact.

Mixer Grinders:

- Rating is the same
- Working Principle is the same
- Structure is very similar
- There is little difference in impact as a whole between the two, which is understandable given the high similarity in their structures
- Dismantling of MG2 is easier compared to MG1 because of absence of permanent joints. As a result: energy is saved in dismantling the product, and parts can be replaced or reused without spending much energy.

Compressors:

- Rating are slightly different
- Working Principle is the same
- Structure is different
- There is little difference in the impact as a whole between the two in spite of the difference in structure.
- This is because of the use of copper. In both the compressors, the usage of copper is 1/5th that of mild steel by weight but the overall impact of copper is 8 times more than mild steel, Table 3.

Table 3 Comparison of impact of copper and mild steel in compressor1

Material	Copper	Mild steel
Weight	664.52gm	3212.079gm
Impact	1.78	0.276

Observations across all products analysed are:

- The Impact of materials is greater than impact of processes for most processes and materials involved in these cases
- The impact in the usage phase is more than the impact in the material and process phases combined in these cases.

Interpretation based on the assessment is the last activity. One should be able to identify which materials and processes are particularly environmentally unfriendly, and which phases and why. Hence general observations about relative importance of materials can lead to a drive to reduce impacts in these. Figure 13 shows the environmental impact for 1Kg of some commonly used materials. Some specific observations to note are

- Impact of copper is most on resources, next worst materials being nickel and plastic.
- Impact of lead is most on eco-system quality, next worst materials being nickel and copper.
- Impact of nickel is most on human health, next worst materials being copper and aluminium.
- The overall impact is most from Nickel, next worst materials being copper, Lead and aluminium.

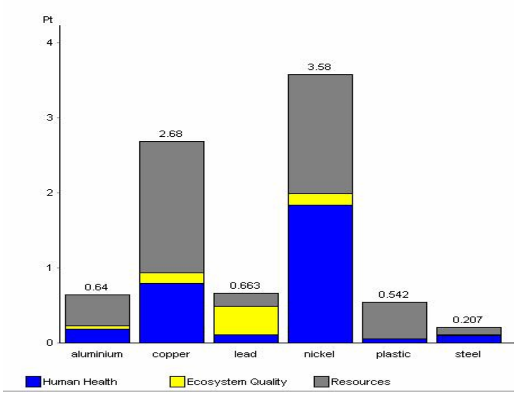

Figure 13 EI for 1Kg of some commonly used materials

5 DESIGN EXPERIMENTS

Design Experiments are conducted in order to evaluate the need for a support for Design for Environment (DfE) and to find answers to the following questions

1. Whether designers generally consider environment as an important criterion in designing.
2. Whether this consideration is bettered by the existence of information or support for DfE.
3. What aspects of general designing must be taken into account while developing support for DfE?

Three experiments are conducted to help answer these questions, each with different support. Details can be found in [19].

The following broad design stages were identified to be present in the design processes observed in the experiments with respect to time.

1. ***0 – 15 % time*** was about identification, analysis and selection of design problem and tasks.
2. ***15 – 40 % time*** was on finding the principles, generating global configuration (main assemblies, function etc) of the concept, associating the ideas with the existing ones, and doing primary evaluation.
3. ***40 – 80 % time*** was on specifying relationships between components and subassemblies, creating local configuration of subsystems, and evaluating solutions.
4. ***80 – 100 % time*** was on fortifying all components with exact shape, dimensions and tolerances, as well as with material and process details with exact relationships.

The types of activity performed by designers during their design are a) product version definition, b) addition and subtraction of physical objects/information, c) addition and subtraction of relations between objects, d) combining objects/information, e) evaluation based on behaviour and cost, f) association of objects with information, g) substitution of object/information, h) focusing on objects or information, i) defocusing from objects or information, j) changing of the view or focus, k) rotation of the objects etc. For example, while designing a workout-equipment for executives, a designer drew a sketch representing skipping rope with handles. In the next sketch he drew only handles without drawing the rope because he wanted to focus on the handle. The support that is to be developed should allow him to do the above activities with ease and in a short time.

6 DISCUSSION

From the descriptive studies and literature survey we found that there is substantial difference in the environmental impact among products having the same functionality generated during the same design process. Analysis of industrial products available in the market show similar results. This means that design can substantially affect the impact created by a product. Designers in general are not aware of environmental impact as a criterion, and current support is inadequate in terms of integrated, sustainable product development where design and impact estimation are seamlessly integrated. It is possible to estimate impact to a large extent during early design stages. We also identified the typical activities during designing that must be allowed, supported or taken into account while designing a support for DfE.

We have reviewed a large number of papers, articles and books in order to identify the tool requirements of designers for DfE. The main requirements and a comparison of three major existing methods for different stages of product development based on these requirements are given in Table 4.

Table 4 Comparison of tools for DfE requirements

Tool Requirement ↓		Current LCA Tools	DFE Workbench	Ecodesign PILOT
Proactive	Yes	No	Yes	yes
Support Collaboration	Yes	Yes	Yes	No
Easy to learn, Understand and Use	Yes	No	Yes	Yes
Allow to understand Rationale	Yes	No	No	No
Act as Checklist	Yes	No	No	No
Self Documenting	Yes	No	Yes	Yes
Help in fulfilling specific requirements	Yes	No	No	Yes
Reduce the risk of forgetting important elements in PD	Yes	No	No	No
Reduce total time	Yes	No	Yes	Yes
Computer based	Yes	Yes	Yes	Yes
Facilitate various kinds of communication	Yes	Yes	Yes	No
Store knowledge and experience as know-how backup	Yes	No	No	No
Useful in all stages of design	Yes	No	No	No
No Extra effort for analysis	Yes	No	Yes	No
Integrated to CAD	Yes	No	Yes	No
Trade off between choices	Yes	No	No	No
Uncertainty Analysis	Yes	No	No	No
Standards & Regulations	Yes	No	No	No
Quantitative and Qualitative Evaluation	Yes	No	No	Yes
Analysis & Improvement	Yes	No	Yes	Yes
Consider total life cycle	Yes	Yes	Yes	Yes

From the above table, we can see that a method which fulfils all these requirements should be of substantial support for designers in using DfE in their day to day work. A preliminary prototype for such a method [19] is developed to satisfy part of these requirements, and is planned to be extended to satisfy all these requirements in the future.

The needs identified are:

- Consider lifecycle issues during product development as early and accurately as possible, during design itself, for generation as well as evaluation of alternative product concepts.
- Capture design rationale for future use.
- Calculate and represent uncertainty in lifecycle assessment with respect to design.
- Integrate environmental issues in the design process with other issues.

The steps to fulfil the needs identified are to develop:

- Methods to help generation and evaluation of product proposals in early as well as detailed stage of design.
- Methods to capture evolving product information.
- Methods to estimate environmental impact of a product proposal with imprecise and uncertain information.
- Integration of environmental friendly design strategies with the design process.

7 CONCLUSION AND FUTURE WORK

The main reasons for DfE not being part of main stream designing are established. The requirements of a DfE tool are identified based on analysis of research literature and descriptive studies. Product analysis is done to see the differences between products for the same functionality. Design exercises are conducted to see how support for DfE in design is likely to help in generating and evaluating environmental friendly products. The needs and constraints for a method to support DfE are identified and are being fulfilled using a prototype platform developed which is given in [19].

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