LIFE CYCLE ANALYSIS IN PRELIMINARY DESIGN STAGES

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Abstract: In a design process the product is decomposed into systems along the disciplinary lines. Each stage has its own goals and constraints that must be satisfied and has control over a subset of design variables that describe the overall system. When using different tools to initiate a product life cycle, including the environment and impacts, its noticeable that there is a gap in tools that linked the stages of preliminary design and the stages of materialization. Different eco-design methodologies under the common denominator of the use of a life cycle analysis have been compared in time efficiency of use and in which stages of the life cycle they can be used. A case study was developed by the application of these methodologies to obtain first-hand information and interpretable results to define advantages and disadvantages of the selected methodologies.

Key words: Sustainability, Life Cycle Analysis, Eco-Design, Design Process.

1- Introduction

The product´s life cycle varies dramatically, from processors embedded in disposable consumer goods to applications requiring maintenance and support for decades. Taking into account the complete product life cycle is a design requirement. It covers from the initial product concept, through its operational period, finishing with the replacement with advanced equipment [K2]. The specific concern areas in a life cycle perspective are: an accurate life cycle economic model to guide engineering tradeoffs, taking into account requirements for logistics and support during the product operational period, and other issues regarding to refurbishing/retiring/discarding the system at the end-of-life. Despite the fact that the "life cycle" term has different meanings for various technical communities, the main idea is to expand the traditional engineering emphasis on the "design cycle" to include optimizing utility, profits, and tradeoffs across the entire lifetime of the product being designed. [K1]

2- Design process

Design is an iterative process; since the solution is not found on the first attempt (technical parameters, ergonomics, aesthetics, economics, logistics, legal, etc.). The more is explored about a problem domain (different alternatives being explored), there is a need to start from scratch more than once. This is a core issue when designing in diverse fields such as building, product design and computer system design. Even though design activities within those fields are apparently not related, all of them aim to solve an often ill-specified problem with a solution that suits conflicting goals.

In a typical sequential design process [PB1] (Figure 2), the product is decomposed into systems, each system has its own goals and constraints that must be satisfied, [HG1] [B1] and has control over a subset of the design variables that describe the overall system. [H1] Clearly, a new approach is needed in order to take into account the complex interactions that exist among the disciplinary lines.

Many functions or design constraints are associated with the life cycle and should be considered for a deep understanding of the product, including design stages, inputs and outputs of the system.

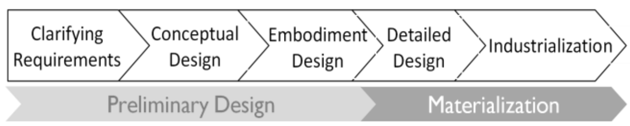


Figure 2: Overview of development of a product´s cycle

It is during the design process when an estimated 60-85% of the product's cost is determined [Z1]. This has led to the increased interest in the activities incorporated in the design process [AB1]. Rapid product development cycles require design methodologies to explore efficiently design spaces to build world wide competent products by reducing costs and environmental impacts, also, improving functionality and quality.

One of the design steps that is least supported, is the transition from early design phases to the final design stages, which is considered a major activity within the design process. [AB1]. This is the transition from vague and imprecise parameters to precise and exact values. In contrast, many design methods only attempt to provide design support in the domain of well defined variables and parameters in which all values used during design must be known with certainty. This certainty restriction limits the utility of these systems to the later stages in the design process.

Imprecision is most noticeable in the early phases of the design process (Figure 3) and has been defined as the choice between alternatives [AO1]. Uncertainty can be described as the cloud of alternatives the designer must consider [LA1]. The concept of this "cloud" is related to the presence of facts that haven't been concretized and will be critical for the product performance. Moreover, is during this stage in where designers might be judgmental because there are no certain variables thus giving their own meaning to them, enhancing the randomness and indeterminacy within the stage [WE1].

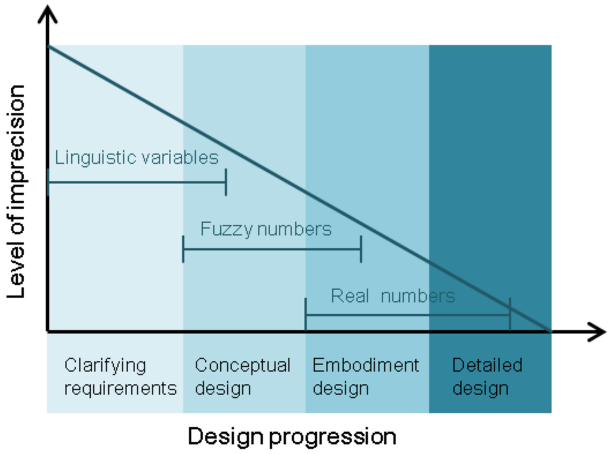


Figure 3: Design stages versus imprecision level [AO1].

3- Life cycle Analysis

The life cycle analysis emerges from the term "sustainable development", that was first introduced in the report of the World Commission on Environment and Development that appeared as Our Common Future in 1987 [HG1]. Since then, sustainable development is steadily defined as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [B1] sustainable development has been adopted as a policy principle by the UN, the EU, many countries, but it has also become a central notion for many designers, engineers, companies, business councils, political parties, etc.

The term sustainability has directed policy makers, environmentalists and industrial decision-makers to a broadened focus in various directions regarding the life cycle of a product**:**

3.1 – Life cycle thinking

Successful and sustainable innovation relies on having a clear understanding of product's impacts and benefits or service throughout the entire life cycle, starting from the sourcing of raw materials and ending up by ultimate disposal at the end of life. It is imperative to consider all stages in the life cycle, not just the ones that go until the company's factory gate [LS1].

Life cycle thinking is sometimes referred to a "cradle to grave" approach, as it follows a product or a service from sourcing of primary materials ("cradle") to ultimate disposal of waste ("grave"). A related term "cradle to cradle" refers to the design of products that can be easily reused or recycled at the end of their useful life. This helps to use resources in a more sustainable way. Moreover, it avoids waste when the use life is over. Therefore, a sustainable approach to design of products is essential, as the product life cycle and its subsequent impacts are determined at this stage, then, it is crucial for the conceptual and architectural stages that all future impacts must be taken into consideration.

"Life cycle thinking" can be translated into sustainability quantitative measurement. Considering the sustainability basis (environmental, social and economic dimensions), examples of such measures are illustrated in Figure 4. In order to life-cycle-thinking be an effective early stage approach tool for the industry, by speeding up the decision making process, designers must completely understand which parameters are meaningful and meaningless for a product's environmental impact. This parameter relevance is found in materials to be used, manufacturing process, measurement shipping, logistics and maintenance. However, evaluation of the environmental performance of these parameters for generating alternatives that improve upon the performance of designs are typically not performed until the design development stage [BF1] and they evolve along the product´s life cycle.

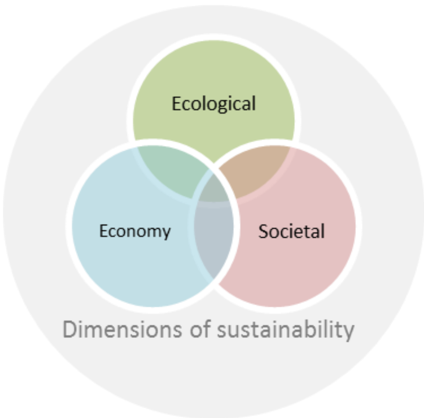


Figure 4: Pillars of sustainability

3.2 – Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a compilation and evaluation of inputs, outputs and potential environmental impacts of a product or service throughout its life cycle. LCA as outlined by International Standards Organization –ISO- [HG1] has been widely applied as a decision support tool to identify the important environmental factors in product systems. Moreover, it is able to compare the full range of environmental effects assignable to products and services in order to improve processes, support policy and provide a sound basis for informed decisions [G1**]**. LCA enables the identification of the most significant impacts and stages within the life cycle which maximum improvements are required to be targeted (Figure 5). This helps to avoid the shift from environmental burdens from one stage to another, as would be the case if the production process was considered in itself.

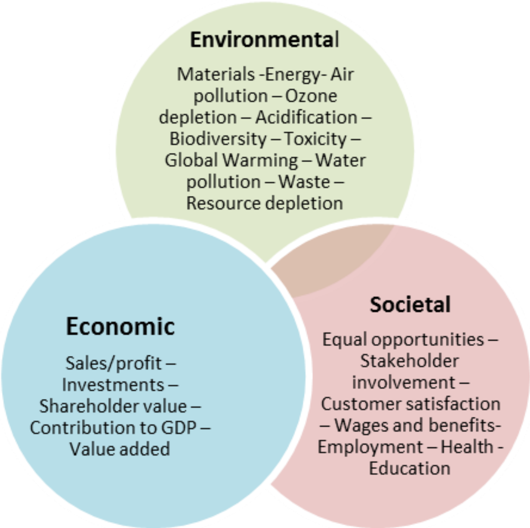


Figure 5: Sustainability issues in the life cycle of a product [AS1].

Such developments have produced an overabundance of concepts, approaches, strategies, policies, models, tools, and indicators. To mention a few, sustainability analysis, technology assessment, life cycle costing, life cycle assessment, green chemistry, and eco-efficiency attempt to provide an answer to questions regarding the sustainability of overall industry, and of the production-consumption system in an even more general sense. [HH1] However, this area has matured to the point that there are international standards to approach towards the problem, including the ISO 14000 series, and in particular ISO 14040 "Life Cycle Assessment"(LCA) [K1]. The main phases of an LCA Methodology [P1] [HG1] are:

• Goal & Scope definition: The goal & scope definition is a guide that ensures the consistent performance of the LCA. In this section, the most important (often subjective) choices of the study are described in detail i.e. methodological choices, assumptions and limitations, particularly with regards to the following topics.

• Inventory analysis: A Life Cycle Inventory (LCI) includes information on all of the environmental inputs and outputs associated with a product or service i.e. material and energy requirements, as well as emissions and waste. The inventory process seems simple enough in principle, in practice however, it is subject to a number of practical issues.

• Impact assessment: The inventory list is the result of all input and output environmental flows in a product system. Nonetheless, a long list of substances is difficult to understand and that is the reason of why a further step is needed, this step is known as life cycle impact assessment.

3.2.1 –LCA principle

There are diverse LCA methodologies that can be applied. They differ according to categories (Energy consumption, toxicity, raw materials, emissions), and they have an impact on their indicator selection and the geographical focus. There are also some “Eco-design” tools and software that use LCA principle to reduce the environmental impact, but LCA has some limitations, which are related to the insufficient transparency of the results, which can hinder the utilization of existing studies as an information source and comparisons. Moreover, LCA does not consider the social and economic impact during the product life cycle (even though the life cycle approach and methodologies can also be applied to these aspects) [P1] and requires the design parameters and extensive knowledge to be developed (dimensional parameters, types of materials, mechanical and thermal parameters, obtaining and manufacturing processes) which are known at each stage of the life cycle and evolve along the cycle.

Even in complete design processes, the use of different policy tools to begin with a product life cycle, including the environment and the possible impacts, there is a gap between tools that link the preliminary and materialization stages. (See Figure7).

DEVELOPMENT CYCLE OF PRODUCTS				
Preliminary design			Materialization	
Clarifying Requirements	Conceptual Design	Embodiment Design	Detailed design	Industrialization
Tools to find a design concept			Tools to define life cycle stages	
PDS	Brainstorming	Functional Analysis	CAD	
	Mood board		Just in time	
	Mind maps	CAD	Formalization	
	Functional Analysis		Physical laws	
	QFD Analogy design		LCA	

Figure 7: Development cycle of products with tools

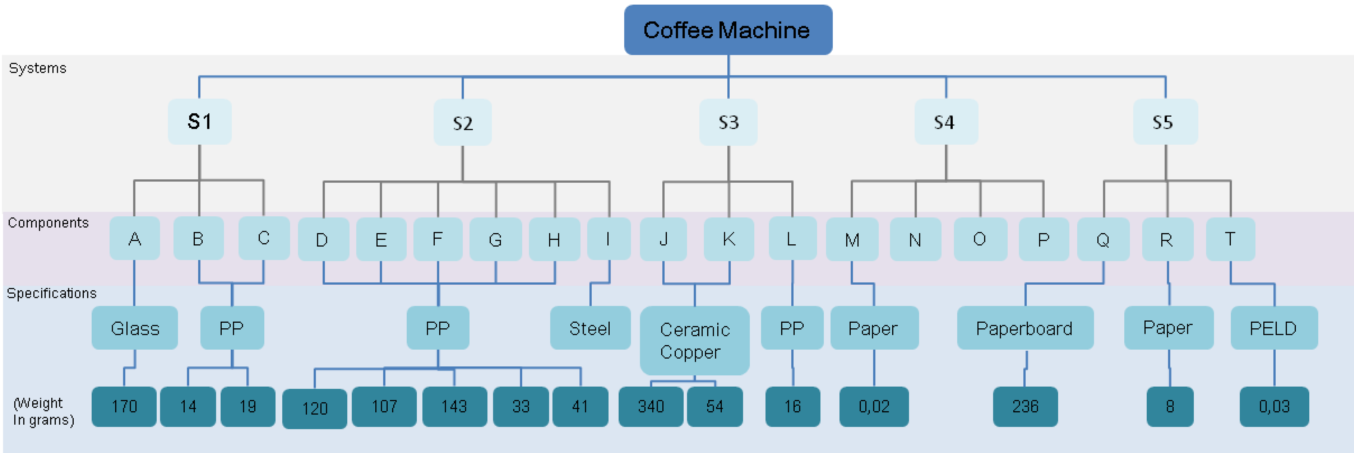
4- Methodological approach

Several eco-design methodologies were chosen from a set of methodologies using LCA as a common denominator. These methodologies have been compared (quantitative and qualitative) and analyzed in order to know which stages during the entire life cycle can they be used in.

A case study was made for the implementation of methodologies, in order to get firsthand experience and have interpretable results throughout the design process to find the advantages and disadvantages of the selected methodologies.

It’s important to take into account the previous knowledge a designer must have in order to develop a specific product, such as a full understanding of the main components, material and available technologies in the context where the product will be developed. Hence, the design practice will be an approximation to a feasible concept.

The methodologies used LCA as a basis for analysing and creating an improved design solution. Nonetheless, it was found that existing tools could be used only after the concept development and product’s architectural design, which means that environmental impacts cannot be measured at the



Systems				Components													
S1	Coffee container	S4	Packaging	A	Glass bowl	D	Filter shell	G	Cover top	J	Heating	M	Paper filter	P	Coffe waste	T	Plastic bag
S2	Body	S5	External Environment	B	Glass top	E	Heating shell	H	Lower top	K	Cable	N	Water	Q	Paperboard		
S3	Heating			C	Handle	F	Body shell	I	Screws	L	Filter	O	Coffee	R	Manual		

Figure 8: Coffee Machine organization chart

early stages of the product's life cycle (Clarifying requirements, conceptual design, and embodiment design).

The analysis was applied to a SAMURAI 6 cups coffee maker (Figure 8) since the chosen methodologies where found to have a void regarding the initial phases of the design process, which grounds the understanding of the LCA being a method that doesn't cover the preliminary design process.

The methodologies used are:

• Eco-indicator 99: Is a quantitative methodological tool that has evolved over time, is one of the most characteristic tools within the LCA. There are numbers that express the total environmental load of a product or process, analysing the product over the life cycle, if the indicator is higher, the environmental impact will be higher. Next to this different design alternatives can be compared [I1]. It is a tool to be used in the search for more environmentally-friendly design alternatives and is intended for the internal use [M1].

• MET matrix: Is a qualitative method that is used to obtain a global view of the inputs and outputs in each stage of the product life-cycle. It also provides a first indicator of aspects for which additional information is required. In developing the MET matrix it is important to consider first all parts that the product has, as its weight in kg, and which processes are used to manufacture the product, also the processes of transport and disposal. This method helps to know if additional information is needed to further establish a prioritization of the elements that the study shows [I1].

• SIMAPRO: It is a software tool often used in LCA to obtain many of the CO2 impacts [S1]. These factors are critical for converting product component material quantities into embodied impacts. SimaPro is chosen because the software contains impact measurements for many different products materials [BF1]. A limitation of the program is that the software cannot be integrated when going through the preliminary stages of design.

• LiDS Wheel: is a visual tool that allows to contemplate the differences in environmental impacts when two products are being analysed, for that, the tool presents eight major areas of interest to be consider in the design and optimization of a product: Selection of low-impact materials, Reduced use of materials, Techniques to optimize production, Optimizing the distribution system, Reduction of impact during use, Lifetime optimization, System optimization end of life and Development of a new concept [I1].

• Okala Wheel: Is one of the newest qualitative methodological tools. It also has a comprehensive database where the designers base an environmental product improvement in quantitative data. The wheel serves as a powerful brainstorming tool to explore areas of product development or improvement that have not yet been considered [O1].

5- Case study and comparison

In order to apply and compare the different eco design methodologies, a product composed by several systems was chosen. Therefore, it was possible to compare their applicability, time efficiency and usability. In addition, design parameters for each of the methodologies were determined in order to decrease environmental impacts. The study case was made in the following two stages:

5.1 – LCA comparison

The Pugh matrix below (Figure 9) shows which methodologies could be used or not during the different stages of the product life cycle.

Measurement:
(-) The tool provides no solution or decision-making aid at this stage.
(+) The tool provides a solution or decision-making aid at this stage.

				Qualitative			Quantitative		
				Okala Wheel	LiDS Wheel	MET Matrix	Ecoindicators 99	SimaPro	Analysis
Development cycle	Preliminary Design	Clarifying requirements		-	-	-	-	-	A1
		Conceptual design		+	-	-	-	-	A2
		Embodiment design		+	-	-	-	-	
	Life cycle stages	Detailed design	Raw material extraction	+	Δ	Δ	+	+	A3
			Manufacture	+	Δ	Δ	+	+	
		Industrialization	Transport	Δ	Δ	Δ	Δ	+	A4
			Use and Maintenance	+	Δ	Δ	Δ	Δ	A5
			End of Life	+	Δ	-	+	+	A6

Figure 9: Evaluation of eco-design methodologies

(Δ) The tool provides partial solutions or help decision-making at this stage.

Analysis 1 (A1): in “clarifying requirements” stage, from the preliminary design, none of the LCA methodologies provide any tool to obtain a solution or decision-making aids. In addition, it’s noticeable that the LCA has no intervention during the need-searching phase.

Analysis 2 (A2): During the conceptual design stage, Okala gives the designer a number of examples in each stage of the life cycle, which can be taken as a basis to develop a full concept design. In the stage of embodiment design, “Okala” presents a quantitative way to help decision making, easy to use and understand, fast and affordable

Analysis 3 (A3): In both stages: raw materials extraction and manufacturing processes, the Okala, Eco-indicators and Simapro, provides a database that allows to make decisions related to materials and processes selection with lower environmental impact. Also, it allows a comparison over other substitute products. Instead LiDS and MET matrix are tools that don’t even give the designer an aid for making design decisions during these stages; the designer can measure their impact comparing them with old or competitive products.

Analysis 4 (A4): In the transportation stage, the quantitative tools give the designer a numerical data that can guide the decision regarding which transport mode, shipping and logistics is better to use.

Analysis 5 (A5): Okala, is the tool that gives the designer a number of improvement examples for the use and maintenance stages, making it more attractive if a new design concept will be developed and not just a comparison with the competition

Analysis 6 (A6): At the end of life stage; Okala, Ecoindicators and Simapro, offers to the designer a database and examples of appropriate final disposition parameters, also a metric comparison. Instead, MET gives a series of data that can only be used when the product is developed, which makes this tool, purely qualitative and only useful to compare existing designs.

5.2 – LCA Parameters analysis

Then, in order to define the parameters required by each method, a component (S1-A) from the assembly was chosen.

It started from the need to design the glass bowl for the coffee machine, in order to follow a complete design process. Also, the studied methodologies were applied to detect the parameters required to implement them, and which parameters are known or not.

Most parameters (weight, volume, materials, processes, etc.) are obtained in the detailed design stage (to avoid assumptions and imprecision of design parameters and rework); limiting the methodology application to the early stages of design development.

The following matrix (Figure 10) shows which parameters are required for the application of different methodologies.

Measurement:

(-) The parameter is not required for the application

(+) The parameter is required for the application

After defining the parameters needed to implement the methodologies, it can be seen that in the early stages of product development, these parameters are vague and diffuse [AO1] even some of these parameters are not known yet, (Weight, volume, dimensions, materials) even when based on redesign process.

In a complete new design process the imprecision and ambiguity of the parameters make the design process slower, less time-efficient and more costly, usually forcing the reprocessing.

	Materials	Weight	Volume	Manufacturing Process	Energetic consumption processes	Toxic emissions	Packaging	Transport system	Energy consumption in use	Disposal
Ecoind 99	+	+	-	+	+	-	+	+	+	+
LiDS Wheel	+	+	+	+	-	-	+	+	+	+
Okala Wheel	+	-	-	+	+	-	+	+	+	+
MET Matrix	+	+	-	+	+	+	+	+	+	+
SimaPro	+	+	-	+	+	-	+	+	+	+

Figure 10: Parameters required for the application

6- Further work

Currently, in order to measure the environmental impact according to material selection, the designer might choose between several ways to proceed, to give an example, an existing product data base or a tool that facilitates to carry on with uncertain variables, such as a fuzzy logic tool [AM1]. The importance of this process it's the level of uncertainty that will be found in early stages of the design process, grounding the results according to design variables. Therefore, tackling uncertainty in early stages is not only imperative in order to address user requirements accurately; it also opens a possibility to cover sustainable requirements since the design process begins.

A review of the different methods that aim to solve uncertainty issues, may give a clue of how sustainability can be defined since the task clarification phase within a product design process.

At the beginning of a design process, it is evident that ideas are vague and might vary easily, what makes difficult to find an environmental impact measure of a concept. In contrast, it might be different if the process it's already in the detailed design phase, in where variables such as measures, materials and manufacture processes are already defined. (See figure 11)

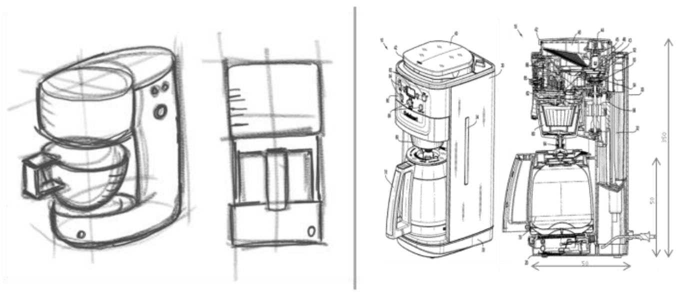


Figure 11: Coffee Machine sketch Vs Coffee Machine technical drawing.

7- Conclusions

A case study analysis was presented in order to show which LCA methodology has the highest contribution to a product's embodied impact by aiding consistently the design process.

They should have participation during early design stages as well, leading to an embodied impact reduction and leave not so important decisions to the design development stage.

The scope of the evaluated methodologies is limited to the constraints and parameters, requiring the knowledge of the previous existing products in the preliminary design and the indicators adaptation. The imprecision of the specific parameters, estimates the value range (materials, dimensioning), among others.

A significant portion of the environmental impacts of the product is determined by the decisions made in the early stages of design. An early stages, there is evidence of an absence of indicators to guide designers on their decision-making.

It has been noticed that during stages where needs are identified, there are not enough general rules that supply adequate information that could reduce the environmental impacts and cost of the final product. In addition, the preliminary design stage should seek to reduce uncertainty by suiting the indicators to easily known general parameters, estimates of intervals and parametric models (a guideline is defined by variables) or grouping linguistic variables.

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