Development of a Framework for Sustainable Conceptual Design

William Bernstein[2], Devarajan Ramanujan[2], Srikanth Devanathan[2],
Fu Zhao[1,2] Karthik Ramani[1,2], John W. Sutherland[1]
[1]Division of Environmental and Ecological Engineering
[2]School of Mechanical Engineering
Purdue University

Abstract

The cost and environmental impacts of a product are largely determined during conceptual design. Most often, due to cost and time limitations, only a limited set of design concepts are carried forward for detailed design. As a result, design concepts generally are biased, lack originality, and are poorly supported. The challenge is made even more difficult when environmental performance is considered as a design factor since very limited experience and knowledge have been accumulated and usually a "life cycle" perspective is missing. Life cycle assessment (LCA) has emerged as the most objective tool available for evaluating the environmental footprint of a product or process, however, LCA is generally not suitable for the concept design stage. This paper explores a new framework for establishing sustainable conceptual designs. Central to our proposed approach is the function-impact matrix, which applies LCA data from similar products to the development of new designs.

Keywords

Conceptual Design, Environmental Sustainability, Function Impact Matrix, Life Cycle Assessment

1 INTRODUCTION

Sustainability is one of the most important challenges faced by modern society [1]. It is now recognized that sustainability embraces three pillars: economic, environmental, and societal sustainability [2]. In terms of environmental sustainability, engineers play an important role, since an engineered product interacts with the environment through energy and material flows at every stage of its life cycle, e.g., raw material extraction, manufacturing, distribution, use, and recycling [3].

One way that engineers can help address the environmental sustainability challenge is by designing products that satisfy user needs while minimizing environmental impacts. To accomplish such a task requires a fundamental change in how products are designed. In addition to product cost and performance during design, environmental impacts across the life cycle must be addressed and accounted for in an integrated manner [4]. The consequences of an expanded scope of factors that must be contemplated during the design process means that an already complicated design process becomes even more complex and difficult.

It is widely known that the cost and environmental effects associated with a product are largely determined during conceptual design. Only after conceptual design is completed, can an engineer undertake detail design and specify the specifications for all the characteristics of a product [5]. Decisions made during conceptual design that raise costs and increase environmental impact cannot easily be undone and rectified during detail design [6].

In terms of the design process, many tools require a wealth of information that is only available following the completion of detail design. For example, finite element analysis requires the dimensions of a product and material specifications. Life cycle assessment tools, which are frequently employed to evaluate environment performance, likewise require a firm understanding of the product and all the life cycle stages associated with it. Thus, LCA cannot be employed during the early design stage since it requires too much data that is not readily available; as a result, LCA is unable to support a holistic approach to ecologically sound idea generation [7]. All too often, concept designs have been based on experience, intuition, or at best, a few simplified calculations due to lack of information [8]. As a result, the choices made and concepts selected are likely to be poorly substantiated and biased. In considering environmental effects across the life cycle, the situation is even worse since very limited experience and knowledge has been accumulated on this issue [9,10].

To provide guidance for concept design, a few design methods have been proposed that may be of assistance: these include such methods as Quality Function Deployment (QFD), functional component analysis, and the Pugh chart. The importance of integrating environmental requirements into these tools is widely recognized [11]. During the past decade, many ecodesign tools have been developed (Here the term 'ecodesign' is used to refer to product design that embraces environmental issues following [12]); however, these tools may be criticized for one of two reasons. They are either too qualitative/subjective, and thus cannot offer definitive solutions (thus requiring a designer to have extensive experience and expertise in order to make a sound decision), or they are too complicated/quantitative, and thus cannot be used during concept design where few specific product details are available [13]. In their present form, design engineers feel that these tools are underdeveloped thus very limited industrial penetration has been achieved [14].

This paper introduces and explores a new conceptual design tool, the function-impact matrix, which will serve as the key component of a sustainable conceptual design methodology. As will be evident, this methodology infuses an environmental life cycle perspective into the early design process. The methodology will be demonstrated through an application where it is applied to the re-design of an alarm clock as a case study.

2 PROPOSED METHODOLOGY

A framework is needed that encompasses the knowledge and information available to a designer at the time of conceptual design in order to make the concepts generated and selected better substantiated and less biased [15]. For sustainable conceptual design, this means to make life cycle environmental impact information available to designers. Traditional tools supporting conceptual design include QFD, Pugh chart, and functional decomposition etc. It has been shown that information and knowledge with regard to requirements, function, behavior, structure as well as attributes, constraints, and objectives can be collected and made available to designers through these tools [15]. Since new designs are generally combinations of existing concepts, the knowledge and information that is needed can be secured through product teardown and benchmarking. The teardown process can reveal the structure, behavior, and functions of competing products [16].

Any feasible concept should lead to products that meet the same functionality requirements and satisfy the same constraints. The requirements and constraints are assembled from the needs of all the product stakeholders, e.g., customers, manufacturers, and designers. Any stakeholder may raise environmental sustainability as a design requirement or constraint (yet another perspective is that “the environment” itself may be considered as a stakeholder). Ultimately, however, it is the responsibility of the design engineer to ensure that environmental requirements and constraints are considered and integrated into the design. It is expected that the functions should remain unchanged as long as the environmental requirements become so restrictive that certain functions must change. The environmental effects of a product across its life cycle should drive the creation of new design constraints and objectives. Therefore, for the conceptual design tools to handle environmental requirements and constraints, it is critical to have relationships or mappings developed between functions, behaviors, and structures of a design and its environmental impacts, which is the focus of this paper.

One feasible way to develop such relationships is to conduct LCA on competing/similar products (i.e., benchmarks) on the market. Since it is desired to do this early in the design process when little quantitative information is available, a simplified LCA based on product tear-down and bill of materials (including possible manufacturing processes involved) is considered sufficient. For this work, we will consider the environmental impact of the *i*-th benchmark product as being due to following product stages: i) materials extraction and processing, ii) manufacturing, and iii) use. The product is assumed to consist of a number of components, with each component consisting of a unique material. Each component is processed by *m* manufacturing operations. For the *j*-th environmental impact category (e.g., climate change, ozone depletion, land use, carcinogens, and fossil fuel usage), the environmental impact is:

$$E_{i,j} = \sum_k \left(M_{i,j,k} + \sum_m P_{i,j,k,.m}\right) + U_{i,j} \tag{1}$$

where $M_{i,j,k}$ is the environmental impact for the *k*-th component/material, $P_{i,j,k,m}$ is the environmental impact associated with the *m-th* manufacturing step applied to component *k*, and $U_{i,j}$ is environmental impact due to use of the entire product. This equation may be augmented with environmental impacts for transportation and product end of life management as well.

To facilitate design concept development, a function decomposition is usually conducted. It may be noted that describing a function separate from its implementation is to be avoided since designers will have at least a vague idea of an implementation when they contemplate the function. A meaningful function decomposition cannot be performed without connecting function to structure or form. Function knowledge is often visualized via a hierarchical or procedural function structure diagram, e.g., a function-component matrix. When components are involved in multiple functions, decisions need to be made about how to allocate the structure to the functions. For example, a percentage could be used to express structure-function mapping. That is,

$$\mathbf{FC} = \left[\alpha_{k,n}\right] \tag{2}$$

and

$$\sum_n \alpha_{k,n} = 1,\ \forall k \tag{3}$$

where *FC* represents the function-component matrix with the element $\alpha_{k,n}$ representing the percentage of the component *k* that is to be allocated to the *n*-th function. When combined with Equation (1), Equation (2) defines how the environmental impact of each component is portioned out to each function. Similarly, impacts due to the use of the product can also be distributed by apportioning the relative contribution of each function to product use.

Given this function breakdown, the problem becomes how to utilize the environmental impact of existing products to create an environmentally responsible design. This is made possible by the fact that: i) products are designed to perform certain functions, ii) products achieve functionality by means of their structure and how they are used [17], and iii) environmental impact can be computed using structure and usage information. Given these facts, a relation that connects functional information to the environmental impact data can be established. This allows the environmental impact of each function to be estimated. With the environmental impact of the functions included in the current design available, the functions may be ranked in terms of their impact; this ranking provides a baseline upon which the new design may be improved.

Given these general comments, we propose a new design perspective, the Function-Impact Matrix, which allocates the life cycle environmental impacts to the functions performed by the product. The simplest way to derive the function-impact matrix is by combining Equations 1 and 2:

$$FI = \left[\beta_{i,j,n}\right] = \left[\left\{\sum_k \left(M_{i,j,k} + \sum_m P_{i,j,k,.m}\right) \cdot \alpha_{k,n}\right\} + U_{i,j} \cdot \gamma_n\right] \tag{4}$$

where $\beta_{i,j,n}$is an element within the function-impact matrix *FI*. γ_n is the amount (expressed as a percentage) that function *n* contributes to the overall product functionality (i.e., the use of the product). A main aspect of the function-impact matrix is to identify which product functions are important from an environmental perspective, and which functions need to be re-examined to achieve a better ecodesign.

As a new tool, the function-impact matrix is primarily used to support environmentally conscious concept generation and selection. Generally, the concepts that are selected involve working principles already embodied in other benchmarked products. If this is not the case, i.e., it is proposed to use a new mechanism to realize a function and that mechanism does not exist within the benchmarked/competing products, then the function-impact approach cannot be used directly. Most often, such new mechanisms are “borrowed” from another type of product. An LCA can then be performed on this other product type, and the LCA data can be added to the design model. Thus, new mechanisms can be addressed by expanding the number of products for which LCAs are conducted. So, in general, the function-impact matrix can be used to estimate the environmental impact of any new design.

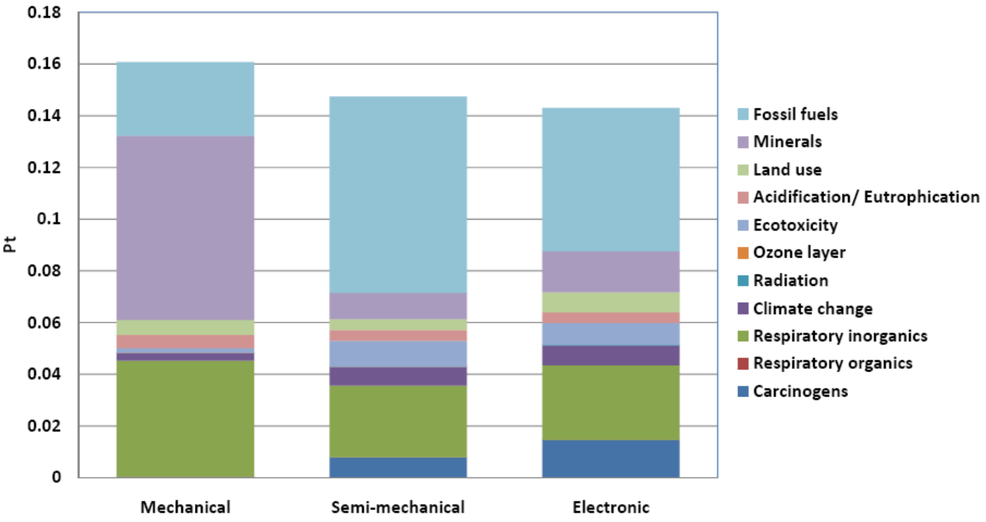

Figure 1. Life cycle environmental impacts of benchmark alarm clocks based on the Ecoindicator 99 method.

To summarize, in order to use the function-impact matrix for sustainable conceptual design, LCA will first be conducted on market leading models for the product of interest using information collected from bills of materials and product tear-downs. Based on functional decomposition, the life cycle environmental impacts will then be allocated to all the sub-functions to support product concept selection. If desired, another LCA may be conducted on the detailed design (once completed) to assess whether the environmental performance predicted by the function-impact matrix is consistent with the detailed LCA. In the following section, results from a case study using alarm clocks will be provided to demonstrate the use of the function-impact matrix design tool.

3 APPLICATION OF THE METHODOLOGY

To demonstrate the use of the methodology, the design of an alarm clock (for reduced environmental impacts) was conducted as a didactic example. Three representative clocks: i) a wind-up mechanical alarm clock, ii) a battery powered mechanical alarm clock, and iii) a battery powered electronic alarm clock were selected as benchmarks. Product tear-down was first conducted on all three clocks. Tables 1-3 show the bills of materials for the three alarm clocks. An LCA was performed using Simapro 7.1 and Ecoinvent 2.0 for all the three alarm clocks. Emissions from the transportation and manufacturing stages are beyond the scope of this LCA. . The end of life stage was also excluded due to a lack of information. Figure 1 shows the overall life cycle environmental impact of the three clocks using the Ecoindicator 99 method. It can be seen that although product weight (and material consumption) decreases significantly as the designs move from mainly mechanical to mainly electric, the environmental impacts remain almost the same. The electronic clock seems to have a smaller impact, which is 10% lower than the mechanical one, but this is very likely within the margin of uncertainties embedded on LCA data. Marginal differences in LCA results among the three clock designs are not unexpected since the product evolution was undoubtedly driven by novelty instead of functionality; environmental performance was almost certainly not a consideration in this evolution.

Table 1. Bill of materials for mechanical clock

Part #	Quant.	Description	Material	Wt. (g)
1	1	Bell	Brass	10.8
2	8	Screws (Cover)	Brass	15.4
3	1	Clock Face Cover	Plastic (PMMA)	6.9
4	1	Top Casing	Plastic (ABS)	7.0
5	2	Side Casing	Plastic (ABS)	14.2
6	1	Bottom Casing	Plastic (ABS)	6.7
7	1	Back Plate	Brass	14.4
8	4	Screws (mech)	Brass	0.7
9	5	Gears	Brass	3.0
10	1	Hammer	Brass/Iron	1.9
11	2	Knobs	Brass	3.8
12	3	Clock hands	Steel	0.3
13	2	Gears with Rods	Steel & Brass	3.1
14	1	Gear	Brass	1.2
15	3	Spring, Washers	Steel	0.3
16	1	Face plate	Steel	2.6
17	1	4 rod inner plate	Brass w/ steel	16.6
18	1	Inner Housing	Brass w/ iron	11.8
19	1	Face Plate Housing	Steel	17.4
20	2	Winders	Brass	5.8
21	1	Small Coil	Spring Steel	2.8
22	1	Big Coil	Spring Steel	8.1
23	1	Small Gear w/ rod	Brass & Steel	2.9
24	1	Big Gear with rod	Brass & Steel	4.7
25	1	Wheel w/ Spring	Brass w/ steel	1.2

Table 2. Bill of materials for electronic clock

Part #	Quant.	Description	Material	Wt. (g)
1	1	Battery Cover	Plastic (ABS)	2.4
2	1	Battery (AA)	Zinc/graphite	23.9
3	2	Screws (Case)	Steel	0.2
4	4	Screws (ESB)	Steel	0.4
5	2	Buttons	Plastic (ABS)	0.3
6	1	Snooze Button	Plastic (ABS)	1.1
7	1	Top Cover	Plastic (ABS)	10.4
8	1	Front LCD Cover	Plastic (ABS)	11.4
9	1	LCD Screen	Glass	5.6
10	5	Screws (DB)	Steel	0.6
11	1	Battery Housing	Plastic (ABS)	14.6
12	1	Buzzer	Piezoelectric	1.3
13	1	Diode	Steel/Copper	0.05
14	2	Capacitors	Steel/Copper	0.3
15	2	LEDs	Glass/Steel Wire	0.2
16	1	Integrated Circuit	PWB	3.3
17	2	Wires for batteries	Copper/Rubber	0.3
18	2	Wires for buzzer	Copper/Rubber	0.4
19	1	PRC (8 wires)	Copper/Rubber	0.7
20	1	Switch Board	PWB	3.8

Table 3. Bill of materials for semi-mechanical clock

Part #	Quant.	Description	Material	Wt. (g)
1	1	Bell	Cast Iron	63.4
2	1	Ring Screw	Iron	4.7
3	2	Dials	Plastic (ABS)	1.3
4	1	Bell Holder	Iron	9.1
5	1	Nut	Steel	0.6
6	1	Washer	Steel	0.5
7	1	Battery (C)	Zinc/graphite	74.2
8	1	Battery Cover	Plastic (ABS)	4.2
9	1	Back Plate	Plastic (ABS)	50.9
10	3	Screws (Cover)	Steel	2.5
11	1	Motor Brace	Steel	3.8
12	2	Screws (Motor)	Steel	0.9
13	5	Gears	Plastic	1.1
14	2	Screws (box)	Steel	0.5
15	1	Back of box	Plastic (ABS)	3.9
16	1	Rotatable Shaft	Plastic (POM)	0.1
17	1	Bushing	Brass	0.2
18	1	Motor Housing	Steel	10.9
19	1	Piece (motor)	Steel	0.2
20	1	Plast. piece (motor)	Plastic (POM)	1.3
21	1	CAM (motor)	Plastic (ABS)	0.1
22	1	Winding (motor)	Steel/Copper	7.2
23	1	Capacitor (motor)	Steel/Copper	0.5
24	1	Wire (motor)	Copper/Rubber	0.3
25	1	Gear Housing	Plastic (ABS)	1.1
26	1	Rotatable Shaft	Plastic (POM)	0.2
27	1	Magnetic Gear	Plastic (POM)	0.4
28	3	Gears	Plastic (POM)	0.6
29	1	Inductor	Copper w/ ABS	4.5
30	1	ECB	PWB	1.3
31	2	Capacitors	Steel/Copper	0.2
32	1	Front of Box	Plastic (ABS)	5.0
33	2	Wires (gear box)	Copper/Rubber	0.5
34	2	Plate (gear box)	Steel	1.5
35	1	Hammer	Iron	2.9
36	1	Screw	Steel	0.2
37	2	Wire	Copper/Rubber	0.5
38	1	Face Cover	Glass	59.6
39	3	Clock Hands	Steel	0.3
40	1	Number Ring	Plastic (ABS)	16.7
41	1	Inner Casing	Plastic (ABS)	45.8
42	1	Outer Casing	Plastic (ABS)	59.7

Working with these benchmark products, the function-component matrix was first developed, and environmental impacts were then allocated to functions. In the order of importance from customer requirements, eight sub-functions were identified, i.e., activate alarm, keep correct time, store energy, set time, set alarm, display time, support internal components (inner housing), and house all components (cover). Components listed in the BOM were assigned percentages based on the sub-functions to which they contribute. For example, the environmental impact of the back plate cover of the mechanical clock was allocated in the following fashion: 70% to outer casing, 10% to setting alarm, 10% to setting time, and 10% to storing energy (Table 4 has a complete listing of the component-function allocation percentages). In general, these percentages are obtained by surveying designers and customers, and therefore have some subjectivity associated with them.

All three benchmark alarm clocks were analyzed to obtain the function-impact matrix. Figure 2 illustrates the results from the function-impact matrix. It shows the contribution of the eight sub-functions of the function-impact matrix for the three clocks. For the electric alarm clock and semi-mechanical clock, it was found that the primary sub-function, activate alarm, is the largest contributor. For the mechanical clock it was found that some of the secondary sub-functions, i.e., cover and inner housing, dominate the environmental impacts, while the primary function, "activate alarm" has a relatively small environmental impact.

It can be seen that although moving from mechanical to semi-mechanical to electronic design does bring convenience to customers (i.e. no need to wind up the clock by hand and easy time reading), the "new" concepts do not bring environmental advantages. The lack of environmental benefits for the electronic clock is seemingly explained by the fact that the production of PWBs is a very polluting process. One may argue that if the first time an electronic alarm clock was proposed, a function-impact matrix had been developed, the concept may not have been selected for further development if environmental performance was an important factor for consideration. As has been stated, perhaps the most important potential application of the function-impact matrix is for concept selection during early design. With the support of LCA data, decisions made in terms of environmental performance are now placed on a rigorous, objective footing, as opposed to be largely based on intuition and experience.

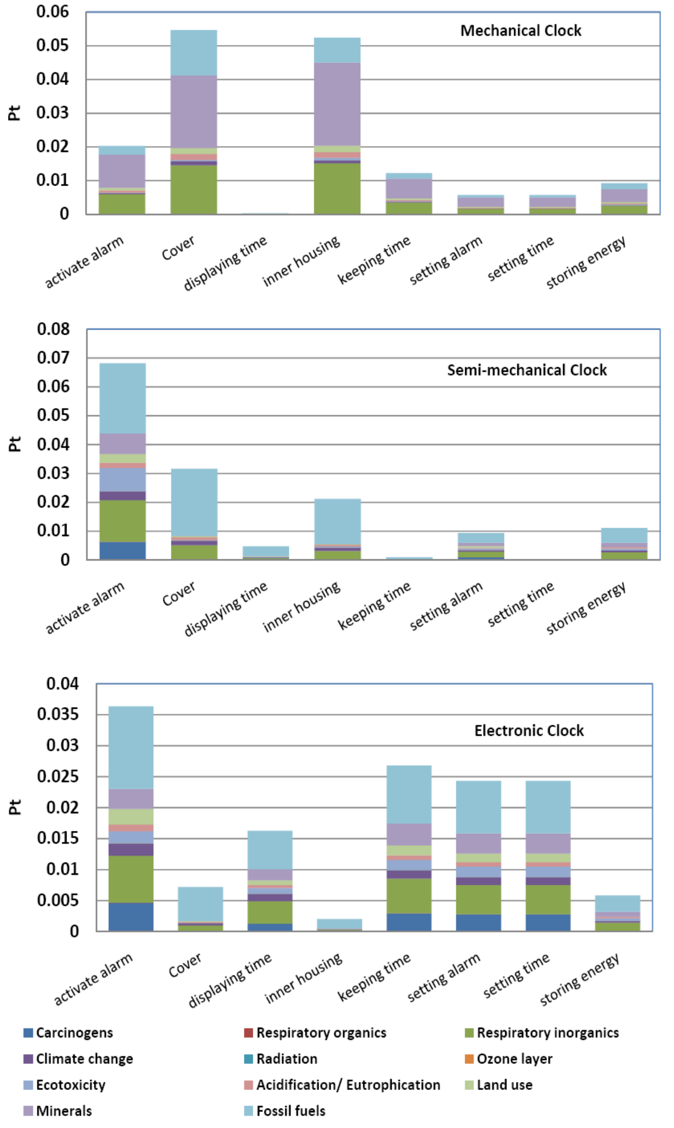

Figure 2. Environmental impacts associated with eight sub-functions for the three clocks.

An analysis of the results presented in Figure 3 results in a ranking of three clocks with regard to how each of the eight sub-functions is achieved. For example, for the primary function "activate alarm" the mechanical clock has the lowest environmental impact while the semi-mechanical has the highest. For “inner housing,” the mechanical clock has the highest impact while the electronic one has the lowest. This suggests that one can develop a “hybrid” design by combining the best approach (from an environmental perspective) to achieve each function. For example, to re-design the alarm clock for reduced environmental impacts, one possible combination is to use the mechanical clock as the baseline design since it has the lowest environmental impacts associated with the primary function “activate alarm”. Secondary functions such as “cover” and “inner housing,” for which the mechanical clock has significant environmental impacts, can be achieved by adapting concepts from the electric clock. Given these observations, a new design was developed by undertaking the following changes to the original mechanical clock design:

- Replaced brass outer/inner housing with ABS on all possible components;
- Replaced brass/steel gears with polyoxy-methylene plastics;
- Replaced brass screws with nylon screws;
- Replaced brass bell & hammer with cast iron.

By scaling the size of components based on the relative strength of each material, a new bill of materials was developed for the re-design. A preliminary LCA was then conducted on this new design. Figure 3 compares the life cycle environmental impacts of the new design with the three benchmark clocks. It can be seen that up to a seven-fold reduction in the environmental scores is achieved for the impact categories considered, i.e., ecosystem damage, human health effects, and resource depletion.

4 SUMMARY AND CONCLUSIONS

In this paper, a novel eco-design methodology has been proposed to support concept design. Central to this methodology is the Function-Impact Matrix, a new tool that uses information from Function-Component matrix to distribute the life cycle environmental impacts across the functions performed by the product. This new tool is critical since concept design is generally function focused, and almost all new designs are actually novel combinations of existing functions/concepts of existing products of similar or different types.

The use of the function-impact matrix has been demonstrated through the redesign of an alarm clock to achieve reduced environmental impact. Three clock types were benchmarked: a mechanical clock, a battery-powered semi-mechanical clock, and an electrical clock. Using the mechanical clock as the baseline design, an improved design was proposed that replaced brass with ABS and other plastics for cover and inner housing. An LCA of the redesign reveals that as much as a seven-fold reduction in environmental impact, when compared with the three benchmark clocks, can be achieved. An interesting fact observed in this case study is that the analysis reveals functions that contribute significantly to the overall environmental impact; thus, suggesting areas for additional improvement.

As is evident, the proposed method is different from traditional design, where focus is usually on the structure that delivers a certain function. Our method analyzes how different products achieve desired sub-functions, and calculates environmental impacts for each function. This allows new designs to be established with dramatically smaller environmental impacts.

It should be noted that there are uncertainties associated with any LCA result. Moreover, assigning a percentage to the role of each component based on its contribution to every sub-function is somewhat subjective and also has uncertainty. These uncertainty issues need to be addressed in future work. Moreover, much work remains to integrate our methodology with standard design tools and processes.

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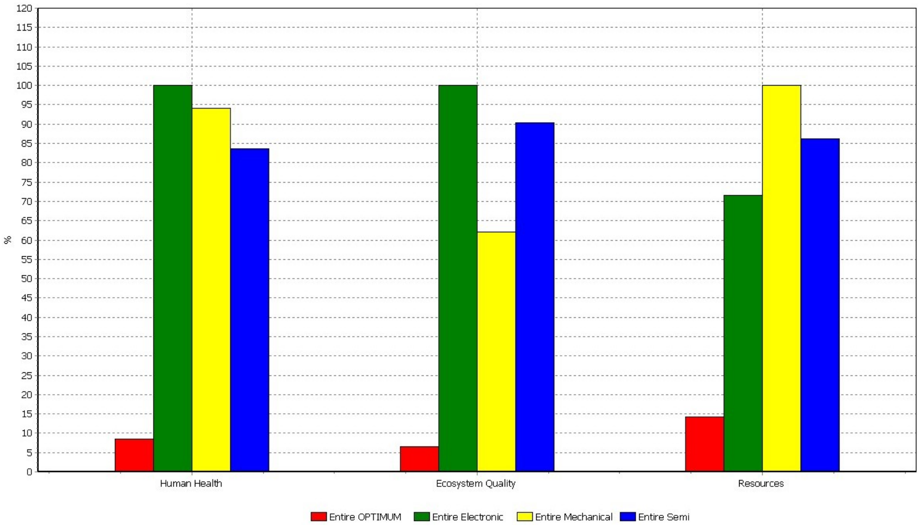

Figure 3. Comparison of Life cycle environmental impacts: optimal design vs. benchmarks.

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Table 4. Percentage contribution to eight sub-functions for all mechanical clock components.

Function **Component**	Activating Alarm	Keeping Time	Storing Energy	Setting Alarm	Setting Time	Displaying Time	Supporting Internal Components	Housing Components
Bell	100							
Fancy Screws								100
Face Cover								100
Top Casing								100
Side Casing								100
Bottom Casing								100
Back Plate	10			10	10			70
Screws (mech)							100	
Gears		100						
Hammer	100							
Knobs				50	50			
Clock Hands						100		
Gears w/ rods		100						
Gear		100						
Spring/Washers		100						
Face Plate							100	
4 rod inner housing							100	
Inner Housing Plate							100	
Face Plate Housing							100	
Winders			100					
Small Coil			100					
Large Coil			100					
Small Gear w/rod			100					
Large Gear w/rod			100					
Wheel w/ Spring		100						