Method for Setting Environmental Targets in Product Development

Incorporating Use-Phase Impact by Subsystem

Daniel Collado-Ruiz and Hesamedin Ostad-Ahmad-Ghorabi

Introduction

Sustainability is becoming a more and more influential aspect of design (Baumann et al. 2002; Poole and Simon 1997), and researchers around the world have defined different approaches to deal with this challenge. The consideration of the product's environmental impact has been given profound attention in what has been called, among other titles, ecodesign (Waage 2007; Howarth and Hadfield 2006; Karlsson and Luttropp 2006; McAloone 2003; Coulter et al. 1995). Literature on ecodesign has mostly set its focus on the processes and tasks that designers need to follow to deliver more sustainable products. Much less attention has been given to the task of actually defining the targets for this process, that is, defining the product design specification (PDS) (Pugh 1991).

Specifying this process (i.e., setting the targets in the PDS) is complex, however. The design process requires the consideration and processing of complex and uncertain information (Chiu 2002; Purcell and Gero 1998; Visser 1995; Wood and Agogino 1996) in a limited time frame and with limited resources. Sustainability increases the scope of the considerations by focusing on the consequences of actions, and on the complexity of the real world (Robèrt et al. 2002). Environmental assessments (Nielsen and Wenzel 2002; Erzner and Wimmer 2002; Goedkoop and Spriensma 2001) confront the user with much information to process (Ernzer et al. 2001; Millet et al. 2007). This amount of information can be overwhelming and limit the application of ecodesign strategies.

Such targets tend to be defined not only for the whole product, but for subsystems as well, for example, consumption of the hard drive inside a computer (Ullman 1997; Pahl and Beitz 1996). For that, it is important to address the following questions:

What subsystems are most relevant to address? Normally, only some of these subsystems will be responsible for the greatest part of the environmental impact. Being capable of addressing only

Address correspondence to: Hesamedin Ostad-Ahmad-Ghorabi, *Email*: hesamedin@ostad.at *Web*: www.ostad.at

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these will enable a greater efficiency in use of time and resources.

How well is the subsystem performing? Targets need to be precise and feasible. Relative targets (normally expressed in percentages) tend to be easier to set. Benchmarking is generally a good strategy.

In the case of environmental impacts associated with materials or logistics, the aforementioned questions are relatively simple to answer. However, in the case of use-phase related impacts, it is often ignored. Even in the case of consumption (e.g., electricity consumption), the environmental impacts are often aggregated for the whole product, making the practitioner ignorant to the origins of those consumptions. In other cases, entire physical elements (e.g., batteries or even engines) are ignored because of not being manufactured or not depending on the company carrying out the LCA. For this, it is critical to have a robust method to allocate the environmental impacts of external elements and consumption to the different parts that are indeed in the scope of the LCA.

This article presents an approach to set environmental targets in product development projects, by analyzing and visualizing use-phase related impacts. In particular, the approach focuses on allocating those impacts to the different parts of the product that are being analyzed. For targets to be relevant both to the market and to the product at hand, the concept of LCA-scaling (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010a) is used. To show the applicability of the proposed approach, a case study is developed in depth, with special emphasis on allocation of the use phase and on target-setting.

State of the Art

Life cycle assessment (LCA) is one of the most widespread tools for environmental assessment of products (Jeswiet and Hauschild 2005; Germani et al. 2004; Nielsen and Wenzel 2002; Ernzer et al. 2001). However, its interpretation is sometimes difficult, partly because of its comparative nature, that is, the need to have a benchmark or reference to compare to. Otherwise, the absolute value gives no information about the improvement potential. In target-setting for design, this can be a major drawback, since it cannot be easily judged whether a product has a high or low environmental impact unless there is a clear benchmark (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010a; Collado-Ruiz 2007).

An environmental expert can help out by giving estimations of such a benchmark. These estimations entail a degree of subjectivity and their variability is not assessable objectively. Additionally, Millet and colleagues (2007) argue that designers, unlike experts, are not normally capable of this endeavor. To deliver this expert-generated information to designers, the authors have developed the concept of *LCA-Comparison Product families*, in short *LCP-families* (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010a). Instead of comparing the environmental impacts of the analyzed products with another particular product, a range of admissible environmental impact values for the given product is obtained (e.g., the range including 95% of competing products, above or below their average). For that, product families are formed by taking the functional unit (FU) of the products as a basis for grouping (coherently to (ISO 2006)). Products in the same family, but with different values for the FU (e.g., television sets of different sizes), are scaled to the value of the product that is being compared (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010a). Since FUs are not phrased and stated in a uniform way, the authors also proposed the use of standardized elements called functional icons or *fuons* (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010b).

A new product being developed can then be positioned in its reference range, relative to its LCP-family members. Four areas of environmental performance can then be identified:

- Red area: worse than the maximum range. The new product is performing environmentally worse than 95% of the products in the LCP-family.
- Orange area: above average and below the maximum range. The product is within the range of 95% of similar products but has great improvement potential.
- Yellow-green area: under average and above minimum range. The product is better than average but still has potential for improvement.
- Green area: below minimum range. The new product is performing environmentally better than 95% of its competitors.

Looking at the product's position in these areas, one can decide how aggressive to be in setting the targets for the redesign at the product level. To consider the subsystems, though, it is necessary to go one step deeper and analyze its different parts and components (Ullman 1997; Pahl and Beitz 1996). One should be able to point out which parts should be redesigned and which ones can be kept the same, or similar, to the previous model.

With regard to environmental impacts, subdivision can pose somewhat a challenge. Until the product is sold, most of the impacts occur directly per part, but from the assembly onwards some of the processes that happen during the life cycle may occur in an aggregated manner. This happens very commonly during the use phase, for example, the fuel consumption of a car.

The literature does not currently agree on how to perform the per-part allocation of such impacts. For some environmental aspects, allocating them to parts is a simple task, since they tend to be measured per kilogram of material. This is the case with materials, manufacturing processes, and end-of-life processes. Allocation of transportation is not that common, but weight allocation can be done in a simple manner. Transportation allocation is usually a function of the mass and the distance, so for a given distance the guiding parameter is still the weight.

The use phase, however, can pose more problems. In some cases, energy consumption can be attributed to different parts of the product, for example, where a lamp's consumption is attributed to the light bulb and cable losses (Unger and Gough 2007; Collado-Ruiz 2007), or where fuel consumption is attributed to parts of a car and the transported load (Du et al. 2009; Koffler and Rohde-Brandenburger 2010; Puri et al. 2009; Ribeiro et al. 2008). In some other cases this task is by far more complicated, like in the case of cleaning processes. Per part allocation is bound to be difficult by nature, since many environmental impacts occur in an aggregated manner. In most cases found in the literature, aggregated results are considered *good enough*, and per part allocation is ignored.

In product design, it is not rare to allocate other traits to different components (Akao 2004; Miles 1972; Mudge 1989). Some efforts exist to environmentally assess components and functions (Agbejule et al. 2004; Oberender and Birkhofer 2003; Sakao et al. 2006; Collado-Ruiz 2007), although designers are still not used to such sort of allocation.

Methodological Approach

The goal of this article is to develop a process to specify targets to the environmental impact for product development projects. Such targets will be referred to as environmental targets herein. The process will be stepwise and systematic to make it robust and easy to apply. Environmental targets must specify the product in the same way as other targets do in the project, and must guide the team in the correct direction to reduce their product's environmental impact.

For that, it is important to understand what constitutes a good and useful target. Following the SMART criteria (Doran 1981) is widely considered to be best practice when it comes to defining these targets. For that reason, the research process will be structured in a way as to meet each one of the concepts that each letter stands for: *specific*, *measurable*, *attainable*, *relevant* and *time-bound*.

As a first step, interactions with the environment are listed out of the database of LCA studies of the authors and all those publications with an LCA or LCA case study published in Science Citation Index (SCI) journals during the years 2008 and 2009. The categorization was also checked by going through the use-phase-analysis matrix checklists (Oberender and Birkhofer 2003) to ensure that all potential use-phase stages had been considered. The categories are:

- energy consumption, analogous for electric or fuel (Koffler and Rohde-Brandenburger 2010; Du et al. 2009; Echevenguá Teixeira et al. 2010; Puri et al. 2009; Ribeiro et al. 2008; Unger and Gough 2007; Thabrew et al. 2008; Kofoworola and Gheewala 2008; Chiu et al. 2008; Büsser and Jungbluth 2009; Landfield and Karra 2000):
    - active consumption to perform the function, for example, lifting weight or illuminating
    - active consumption to perform additional functions, such as moving elements or controlling components
    - losses due to imperfections of the system (They generally constitute a percentage of the previous.)

Table 1 Difficulty levels used to assess the allocation rules-of-thumb

Difficulty	*Description*
Low	Always the same parameters are used, and impacts are always allocated to the same parts (e.g., losses attributed to a gearbox).
Mid	Parameters are not always the same, but some alternatives exist, (e.g. surface or volume for cleaning). Parts to consider might be coupled with the parameter selection.
High	Complex physical phenomenon (e.g., combustion or light irradiance) specific to the product. It might not always be possible to allocate.

- use of consumables due to main use (Muñoz et al. 2009), such as batteries, printing cartridges, or filters
- use of elements due to degradation, such as losses, cleaning, or anodization (Echevenguá Teixeira et al. 2010; Gasol et al. 2008)
- exchange of spare parts (Kofoworola and Gheewala 2008; Landfield and Karra 2000)
- consumption (of energy and materials) during maintenance (Thabrew et al. 2008; Kofoworola and Gheewala 2008; Gasol et al. 2008; Chiu et al. 2008; Landfield and Karra 2000)
- assembly, setup, promotion, and disassembly of the product (Tharumarajah and Koltun 2007; Svensson and Eklund 2007)

In most of these cases, an allocation rule-of-thumb can be found, but with high variation in level of difficulty. The scale presented in table 1 was used to assess them. The assessments are presented in table 2.

In order to avoid potential double counting or confusion, it is proposed to first list all the environmental inputs and outputs, as well as all the subsystems. This concludes in the stepwise methodology presented in figure 1.

The first allocation to be carried out is that of spare parts and consumables. A multiplying factor of how many times they get exchanged is applied to their total impact.

Energetic requirements are subsequently assessed in order of level of difficulty. A reasonable starting point is to analyze the losses first as a percentage of the total consumption, and to attribute them to those elements generating those losses, such as cables, pipes, and so on. Allocation rules for this are generally related to some physical unit like length.

The next consumption to be addressed is that generated by physical properties (i.e. weight) of the product, comprising:

- transportation of the component (e.g. parts of a car while the car is being used).
- relative movement (e.g. positioning for control or movement of elements on a crane).

These values can be calculated as a percentage of the total (using proxy variables such as weight) or as the total amount

Table 2 Allocation criteria for different impacts

Use-phase impact categorization	*Common allocation criteria*	*Difficulty*
Energy consumption: Active consumption to perform the function	Can be calculated out of physical phenomena.	High
Energy consumption: Active consumption to perform additional functions	Can be calculated out or properties of the product (at least approximately).	Mid
Energy consumption: Losses due to imperfections of the system	Percentage of the active consumption at some point of the system.	Low
Use of consumables due to main use	These elements are part of the system, and the impact of replacements should be attributed directly to them.	Low
Use of elements due to degradation	This tends to be presented as an aggregated impact. Some will depend on the shape, materials, or other properties of the component. They should be assessed individually.	Mid
Exchange of spare parts	Each part should be allocated the environmental impact of all the expected exchanges. This would also include those parts that are exchanged only in a percentage of the cases (e.g. a part that is changed in 20% of the sold products would be accounted 1.2 times).	Low
Consumption (of energy and materials) during maintenance	It should be allocated to the part that needs the maintenance, although sometimes it could be attributed to other elements of the design that make it more difficult to do the maintenance.	Mid
Assembly, setup, promotion and disassembly of the product	Most times there is a physical parameter that dominates the allocation process, but they tend to be complicated (assembly or disassembly time, part importance etc.) However, weight or volume can generally be used as a good approximation of these variables, if data is not available.	Mid

of energy required to carry out those movements or tasks. Whichever way this is calculated, this avoids the difficult task of allocating the energy of the main function to the generating component.

Finally, it is possible to allocate other aggregated processes, like degradation, cleaning, maintenance, and so on. They tend to be difficult to allocate, and three strategies to deal with them are:

- Allocate them according to a physical unit that approximates their effect, for example, allocating cleaning processes depending on the cleanable surface.
- Allocate them according to some simplified variable, such as weight or volume, or even equally to all parts. This considerably simplifies the process, although the errors can many times be minor (ISO, 2006).
- Assign them to the whole group. No visibility of the contribution per part is achieved, although sometimes this can be the only option.

To make the targets *measurable*, particular scales or variables must be defined. Different impact category indicators can be used, depending on contextual or strategic factors. However, it is very rare for people involved in design–or in its management–to know how much environmental impact is acceptable. Even if the values for a previous model of the product are known, setting *relevant* yet *attainable* environmental targets is still a complicated task. Benchmark information can be useful at this point, to decide to place the product in a particular range, for example, among the best 5%. LCP-families (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010a) provide a set of ranges that assist in setting the relevant environmental targets per part. By using environmental impact category indicators through LCP-families, it is ensured that the targets are *measurable*, *attainable* and *relevant*.

It is possible to judge both absolutely (in units of environmental impact) and relatively (in percentage) the reduction needed to position the product among its competing market. If

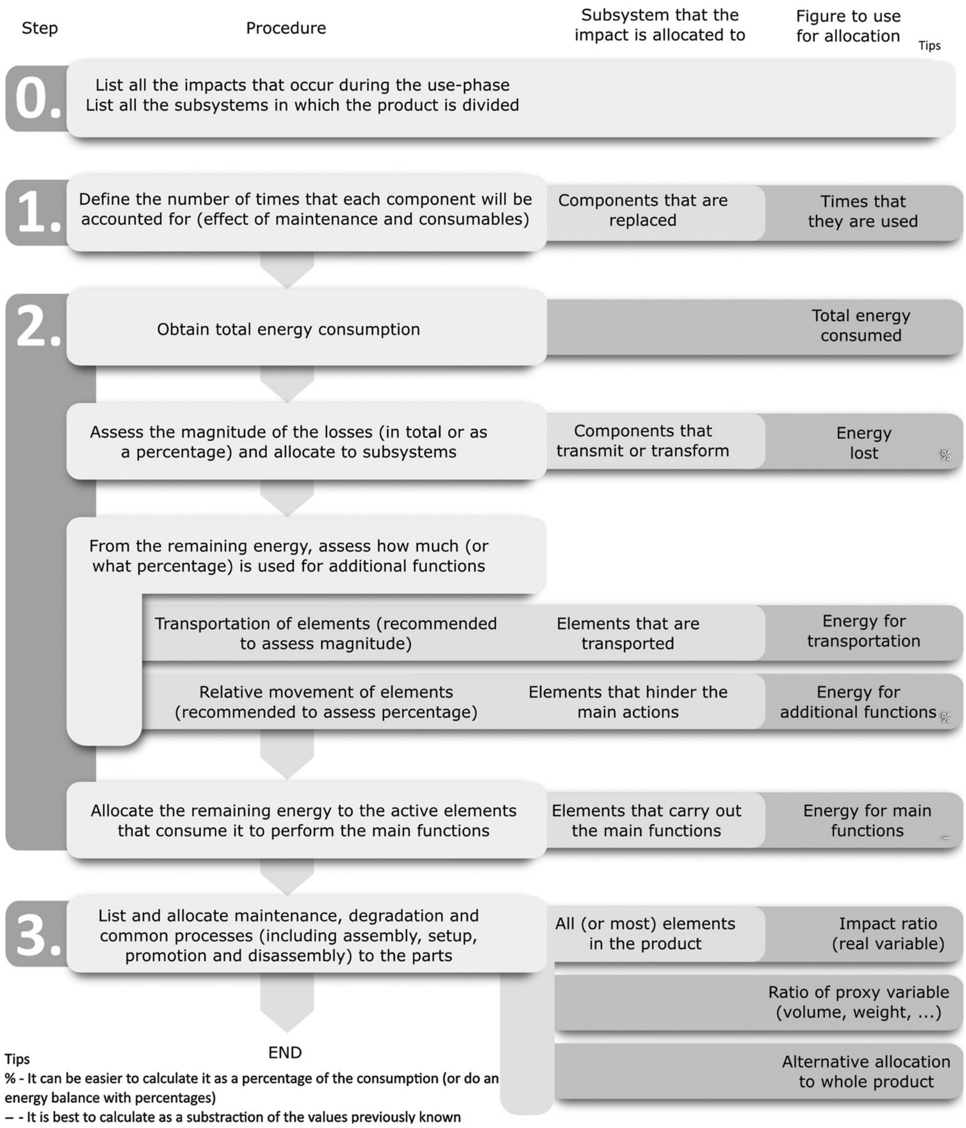

Figure 1 Methodology for use-phase process allocation.

the target is to reach an impact better than 95% of competing products, it would be possible to define target reductions for each part in an intuitive way. If the environmental impact of each part is represented visually, such as in a Pareto graph, the reference ranges can be used as background to give this perspective required for target setting. An example of this is shown in the case study.

It is important to define the improvement as a project with strict deadlines, that is, with time constraints. Each target should be defined as to whether it will be included in the next design, or in further models. In that sense, the environmental targets should be included in the PDS, so their deadline concurs with the deadline of the product development project. By including it in the PDS, the *timeliness* of the goal should be ensured.

Considering the information required for the proposed approach, engineers involved in the product development process should be able to carry it out with readily available information or competent estimations. This fact was contrasted successfully with several professional engineers.

Case Study

To clarify the applicability of the method, a case study of a knuckle boom crane was developed. The product studied is depicted in figure 2. LCA inventory data and results were available for a product family of five cranes (from Ostad-Ahmad-Ghorabi 2010). These cranes had been analyzed in the scope of a project done between the Vienna University of Technology and an international crane manufacturer. A new LCA was performed for a new middle-size crane model based on those inventories.

Cranes are designed considering a finite life fatigue strength. The admissible load cycles are therefore an essential parameter to be considered when a crane is operated. Depending on the load spectrum driven, more or less load cycles can be operated, determining the effective operation hours of the crane. Data

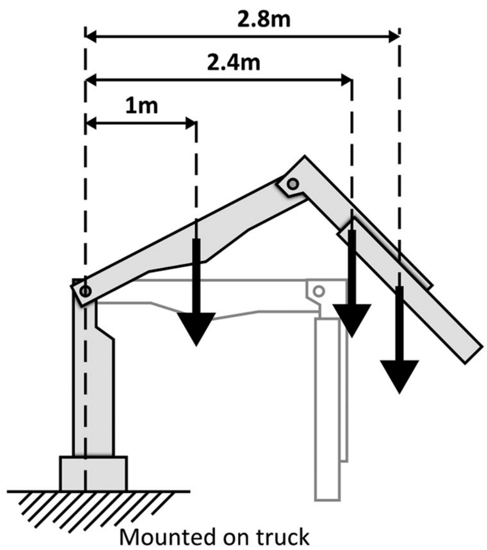

Figure 2 Scheme of the truck-mounted crane, the different parts, and how moment allocation has been performed. m = meters.

for average-use scenarios of cranes were provided by the crane manufacturer. They consider different operation modes for the crane, such as lifting containers, lifting bulk material, or lifting standard pallets with goods, and an average load spectrum. Further, average load cycles per hours, average operation time of the crane per day, and average working days per year have been investigated together with the crane manufacturer by consulting customers from different industries. Considering all data, the functional unit for the new crane is determined to be 8,000 hours of operation with an average of 4 meter tonnes (mt) of lifting moment. The average data, operation hours, and load spectrum equals 10 years lifetime for the new crane.

Similar to the cranes analyzed in work by Ostad-Ahmad-Ghorabi (2010), the new crane consists of components that are manufactured in-house through globally distributed manufacturing sites, and parts that are provided by external suppliers. Both are completely assembled before the crane is delivered to a customer. However, there are also some components which have to be installed by the customer before the crane can be operated. The motor or the hydraulic pump are the most important components to be named in this regard.

From the manufacturer's point of view, only components installed in-house can be optimized, as the crane manufacturer has no direct influence on parts that are installed by the customer. Therefore, only parts manufactured and installed in-house were those considered in the case study.

Step 0 in figure 1 asks for the listing of all impacts during the use-phase. Main use-phase impacts of the crane follow from:

- maintenance
- fuel consumption of truck engine for the operation of the crane
- fuel consumption of truck for carrying mounting body and dead weight of crane

The product is subdivided into its in-house manufactured parts. The motor, pump, and gearbox are also considered. Other parts (minor parts) are considered aggregated as one entity.

Step 1 in figure 1 assesses the number of times each part is replaced along the life cycle. Hoses are replaced every five years and filters are changed annually. Considering 10 years lifetime, the environmental impact of the hoses must be multiplied by a factor of two, and that of the filters by a factor of 10. This impact will be included in the category *Other parts*.

Energy consumption is allocated in *step 2*. First, the fuel consumption of the truck engine for the operation of the crane is calculated. The source of energy is a diesel motor connected to a hydraulic pump through a gearbox, as shown in figure 3. To calculate the fuel consumption of the truck motor for the operation of the crane through its lifetime, a typical truck engine was considered for which data sheets were publicly available (Gruppe 2008). The crane manufacturer provided technical specifications and the data sheets for the fixed displacement hydraulic pump which is usually installed for this crane size (Rexroth Bosch Group 2012). Since no specifications were available for the gearbox, a simplified gearbox model with a transmission ratio of 1:2 was considered. Considering a 3% loss in the gearbox and considering all efficiency factors (volumetric efficiency factor and hydraulic mechanical efficiency factor of the pump) and the specific fuel consumption of the motor, a total of 40,124 liters of fuel are consumed through the 8,000 operation hours of the crane.

Allocation of the fuel consumption was then distributed between the motor, the gearbox, and the hydraulic pump. Losses were attributed first as a percentage of the total consumption since these estimates are considered of low difficulty by experts (see Table 1). Efficiency factors of diesel engines are around 40% (Tschöke and Heinze 2001). Gear losses are given as around 2%–4% per reduction stage, depending on the gears used (Haberhauer and Bodenstein 2005). Figure 3 therefore shows 60% loss for the diesel engine and an average of 3% loss for the gearbox. For the pump, the percentage was not known and an estimation from operation data was taken.

The total remaining energy for moving the crane results in 22.5%, which is effectively available for lifting the load and the parts of the crane. This does not include consumption due to transportation, which was accounted for independently based on weight.

Relative movements (i.e. lifting the arm of the crane) were allocated based on moment (out of the part's weight and average distance to crane column, as shown in figure 2). An average of 4 mt was considered for the load. However, fuel cannot be directly attributed to the load, but rather to the active elements (i.e. cylinders). The material composition is approximately the same for the different sized cylinders; bigger cylinders have to be allocated more energy, since their dead weight is bigger. Weight allocation is selected and it is assumed that bigger scaled cylinders also consume linearly more.

Step 3 in figure 1 addresses aggregated processes. Oil changes are required for maintenance of the cylinders. For the same reasons as above, weight can be used as a proxy variable to

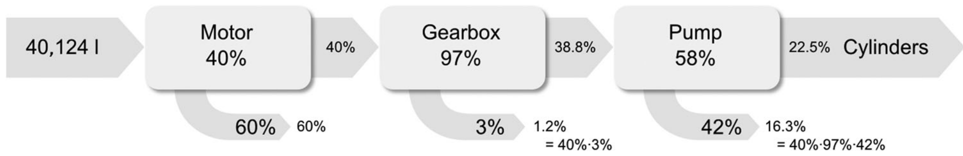

Figure 3 Scheme of the losses and consumption in different components outside of the crane. l = liters.

divide the impacts among all three cylinders. Another use-phase impact to allocate is the body needed to mount the crane on a truck. The purpose of this part is to hold the crane. Once again weight allocation was used.

Once allocation was done, and to have an objective assessment of the magnitude of these values, reference ranges were developed. The functional unit had been defined as operation time and a lifting moment (8,000 hours and 4 mt). These two parameters are candidates for scaling. Since operation time is the same for all cranes, the only potential parameter is the *lifting moment*. With data from five cranes available (N=5), an assessable linear regression model can be set up (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010a).

The characteristics for dependent variable *environmental impact* and independent variable *lifting moment* are:

$$R^2 = 0.958 \rightarrow Linear$$

$$p = 0.004 < 0.05 \rightarrow \textit{Significant relation}$$

$$Residuals : p = 0.986 \rightarrow \textit{Normal distribution}$$

To assess the environmental impact, cumulative energy demand (CED) was used. This parameter was considered representative enough for the crane manufacturer's interest, and comprehensive enough to give an overview of the general environmental impact of the product. However, for the methodology's purpose, other impact categories could equally be used, additionally or alternatively. The linear regression model can be described by:

$$\textit{averaged environmental impact} = 804.72 + 358.92 \cdot \textit{lifting moment} \quad (1)$$

For a *lifting moment* of 4 mt, the *averaged environmental impact* is equal to 2,240 gigajoules (GJ). To obtain the reference range, the standard deviation of the environmental impact of the products within the family (Collado-Ruiz and Ostad-Ahmad-Ghorabi 2010a) must also be calculated, which follows as $\sigma = 163$ GJ. The reference range needed for the comparison of the new crane with its LCP-family is determined by *assessed impact* $\pm 2\sigma$, with the numerical values for the higher and lower limits of the reference range of $L_H = 2{,}567$ GJ and $L_L = 1{,}914$ GJ respectively.

The environmental impact of the new crane resulted in 2,348 GJ, which is above the *averaged impact* and below L_H. This means that the product is performing slightly worse than average, but still within the range of 95% of the products within its family.

For each part, use-phase allocated impacts were aggregated with materials, processing, distribution, and end-of-life impacts (which could easily be allocated by weight or something else similar), to plot the graph shown in figure 4.

Figure 4 singles out the motor as the biggest single contributor to environmental impact, given the high amount of energy loss. For the owner of a fleet of crane trucks, it would be environmentally sound to prioritize a change in the trucks' power supply rather than in the types of cranes that are installed. If more efficient motor technologies are used (e.g., electric motors), the percentage of power allocated to the motor would be less (there would be less losses), and percentage-wise more would be attributed to the cylinders and other active parts.

It is important to point out the effect of weight in general of the whole arm (consisting of the extension cylinder, the outer boom ram, the lifting cylinder, the outer boom, the extension boom, and the main boom). Most parts on the left side of figure 4–except for the motor–are part of this system. Having to constantly lift their own weight, they are the main reason for the crane requiring the high amounts of energy that it does. Weight reduction is therefore the most sound strategy when it comes to the crane itself.

Also, cylinders have an important role, not only because of their weight, but also because of the active power consumed to activate them. This relative importance was previously unknown to the engineers in the crane manufacturing company. With the help of the approach presented in the article it was possible to visualize this effect.

The presented visualization helps to set targets as to specific values for these reductions. A reduction of the environmental impact of 107 GJ (a 4.6% of the total) would be necessary to position the new crane system below the family's average. To make it better than 95% of the competition (i.e. to bring it into the green area) the reduction should be of 433 GJ (an 18.4% of the total). A combined optimization of the motor and the pump of 31% would position it among the best 5%. It is also possible to define a challenging target of a 23.2% optimization of the cylinders to position the crane above average. To reach a similar result through weight reduction of the rest of the parts in the crane, it can be calculated that around a 30% reduction is needed. These values would constitute the environmental targets that specify the product in the PDS.

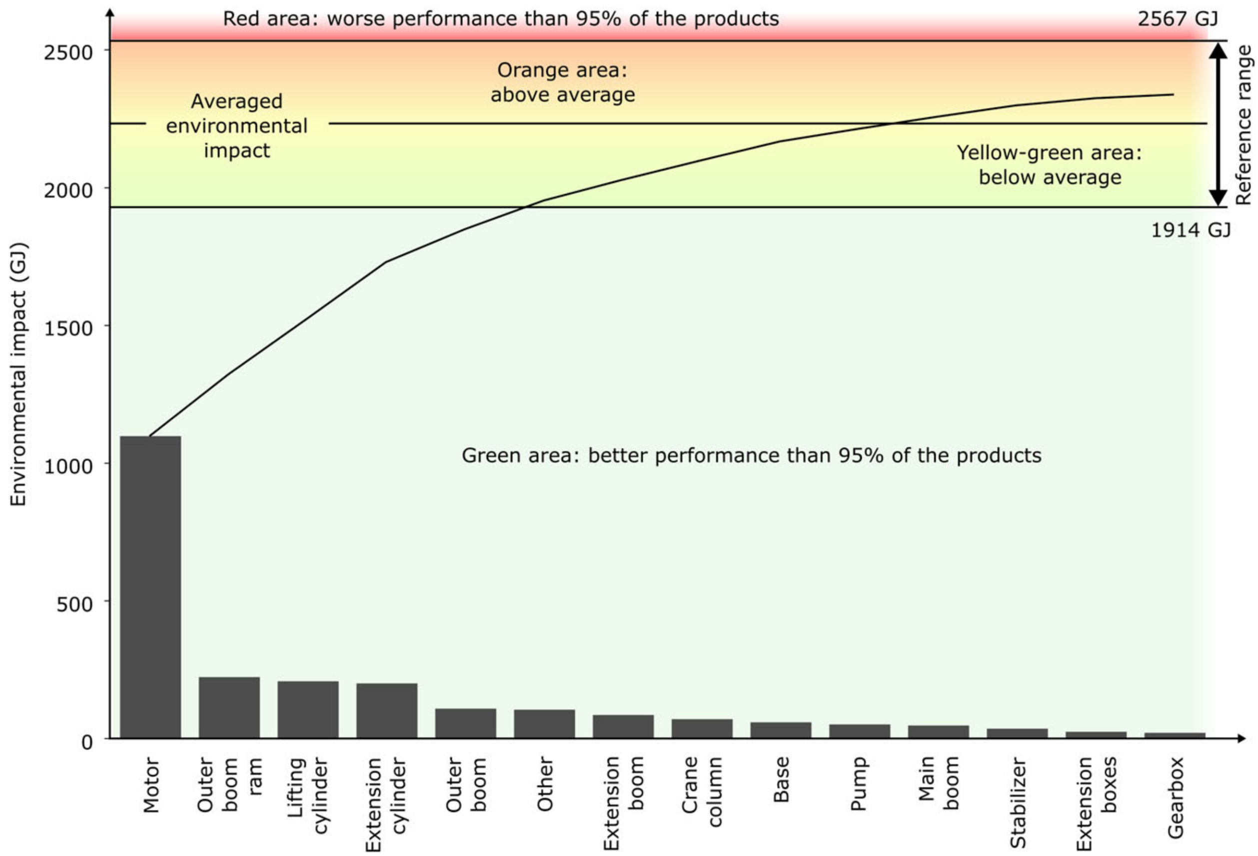

Figure 4 Pareto graph of the new crane including reference ranges (x-axis: crane components; y-axis: environmental impact using cumulative energy demand as indicator). GJ = gigajoules.

Conclusion and Outlook

This article has shown a systematic way to specify environmental targets for redesign projects, by using LCA scaling and use-phase allocation.

The section *Methodological Approach* presented a systematic stepwise procedure to allocate use-phase impacts to different subsystems or components based on physical variables that are generally known by designers. This approach was tested for a knuckle boom crane in the section *Case Study*. The results show the usefulness of having the use-phase impacts attributed to different subsystems and visualizing them. When the use-phase is the dominant impact, this allows the assessment of which parts constitute a higher percentage of the overall impact. Furthermore, using LCA scaling data it is possible to define specific values for improvement.

The case study has focused on installed cranes on a fleet of trucks. However, other points of view could have been modeled, for example, that of a crane manufacturer looking to optimize their cranes independently of the motor, pump and gearbox–which are generally produced by different manufacturers. In that case, the method proposed could be applied to allocate the environmental impacts of these elements to the rest of the parts as well, thus allowing the crane manufacturer to prioritize the optimization of the different parts (mainly cylinder and other arm elements).

This situation is not exclusive to the case at hand. In exchangeable power accumulators (i.e., batteries), the impact is instinctively attributed to the battery, since this is where the energy sits (e.g. Muñoz et al. 2009). However, energy consumption is carried out elsewhere in the product (accumulators are often not even included as part of the product). The impact of these accumulators (and of all of those used along the life cycle) should be attributed the same way that the energy impact is attributed in the product. This proposed allocation would point out the source of consumption as the problem, and not the batteries themselves.

Finally, it is important to specify that not only use-phase processes can be modeled according to the proposed approach, but also such things as general marketing or sales initiatives, aggregate end-of-life treatments, and disassembly processes.

Although many allocation rules have been taken from LCA studies, the methodology is far from common practice in LCA. Much of the information required to allocate is available, especially for designers. Making it available during the decision-making process has the potential to foster innovative ideas for environmental improvement. It thus helps in setting the specific per-part environmental targets that the product needs in order to become more sustainable.

One major limitation of the method, since it refers to the use-phase, is the inherent uncertainty in the data. This method relies strongly on users' experience or knowledge of previous data. One potential further line of research would be to facilitate the data-gathering through databases and feedback systems.

In order for this approach to be implemented extensively, this approach should be integrated with the software and tools currently used by designers or LCA practitioners. Therefore, further research is currently being taken in that direction, to enable this approach to be integrated within computer-aided design (CAD), product data management (PDM), and LCA software.

Additionally, the nature of the estimations has not been thoroughly considered. There are multiple ways of obtaining the information needed to apply the method, and in some cases the method could prioritize availability over reliability. Further research spawning from this article would be to assess in which estimations the risk would be worth implementing in the method.

The authors believe that this new approach has the potential to contribute in considering environmental criteria in redesign projects. Currently, one of the challenges that is commonly faced is the lack of a means to establish an environmental specification, and the proposed approach constitutes a robust step forward in this direction.

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