

Estimating environmental behavior without performing a Life Cycle Assessment

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Abstract

Many authors have agreed on the interest of considering environmental concerns in the early stages of product development. However, most ecodesign tools are based on life cycle assessment principles and require a model to give information about the product's environmental performance. This modeling can have negative effects on team performance and on the potential for innovation, not to mention on the project's duration. Additionally, the model requires information that is not available in the early design stages. This paper analyzes the potential of inferring conclusions about the life cycle stages with the highest impact, out of similar products. Out of a database of previous products, environmental profile estimations are carried out, that is the assessments of the contribution of each life cycle stage to the total impact and the variability of measure. It is then possible to discard – or ensure consideration of – life cycle stages. Furthermore, the level of the conclusions is assessed on a five-point scale. The proposed approach is applied to four case studies with different levels of abstraction and the relevance of the conclusions is assessed. The article resolves the potential of estimating the distribution of the environmental impacts along the life cycle.

Keywords: Ecoinnovation, Life cycle assessment, Estimations, Ecodesign, Early design stages, Industrial ecology, Product development

Introduction

Sustainability has positioned itself in the spotlight of public consciousness, and industry is responding by positioning environmental performance as an important parameter to consider during a product's development. As a result, many new products claim to have a lower environmental impact. Environmental performance during design receives different names, like ecodesign or design for sustainability (Waage, 2007; Coulter et al., 1995), and most authors agree on the importance of assessing and improving the product's performance as early as possible in the design process (Carillo-Hermosilla et al., 2010; McAlloone, 2003).

Most approaches and methods share a common trait of starting the process with some sort of environmental assessment. A popular method for this is Life Cycle Assessment (LCA). It seems obvious that designers who are not experienced in assessing the environmental impacts of their products, will require some guidance in this process. For this assessment, a model of the product is necessary, even though the product has yet not been designed. Solutions to this are to select a previous product, some benchmark market product, or to carry out estimations of how the product will be designed. This creates a barrier to LCA implementation in the design process, in addition to already existing barriers such as complexity, time-consumption, uncertainty of results and need for information (Millet et al., 2007; Sousa and Wallace, 2006; Jönbrink et al., 2000). Additionally, Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010c) showed that exposure to a model – and most particularly a complex LCA model – can provoke the effect known as fixation (Liikanen and Perttula, 2010; Purcell and Gero, 1996), hindering designers' creativity and thus innovation.

For all those reasons, LCA is known to be of little application during the early design stages. By the time it is possible to perform any LCA it is generally too late to make big changes on the product (or they are too expensive). The higher the potential for improvement, the lower the amount of information about the product is available, and therefore the lower the quality of the assessment (Lindahl, 2005). Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010a) presented the common relationship between environmental behaviors of similar products. That relationship was studied for the product's environmental impact as a whole (one impact category and the whole life cycle). If such relationships also exist for different life cycle stages, then tentative LCA conclusions could be extracted from previous cases. If their variability can be assessed, information might be even more useful than having a complete LCA of a previous product. The current article seeks to analyze the possibilities and potential of inferring an approximate environmental profile of a product. How approximate these estimations are is also a matter that will be assessed. The purpose of this paper is to define the relevant life cycle stages in the early design stages, exclusively using information about previous products and avoiding fixation effects.

Environmental assessment in the early stages

A widespread approach to assessing environmental impacts of products is LCA (Jeswiet and Hauschild, 2005; Nielsen and Wenzel, 2002; Ernzer et al., 2001). It consists of a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle (ISO, 2006).

Conclusions derived out of LCAs are mainly based on comparison (ISO, 2006): comparing life cycle stages, parts of the product, product alternatives or the product with other products as per comparative LCA. In cases where a single product is assessed it is difficult to judge whether its impact is high or low. The International Organization of Standardization (ISO) guideline 14044 (ISO, 2006) points out the need to specify the functional unit (FU), defined as the quantified performance of a product system for use as a reference unit. Environmental comparison of products becomes possible when products are functionally similar. Although popular, many detractors of LCA have pointed out its flaws when it comes to efficient application in the design process (Millet et al., 2007; Sousa and Wallace, 2006; Jönbrink et al., 2000), namely:

- Performing an LCA is a time-consuming and complex task, requiring special training and much information about the product.
- Much of the information is not available in the initial stages of product development. Later in the process, more information is available but options for product changes are limited.
- Models used in LCA are different than models used during design processes. This makes the integration of LCA into product development difficult.
- Results have a high degree of uncertainty.

Even in cases where alternatives besides LCA are defended (Erzner and Wimmer, 2002; Brezet and Van Hemel, 1997), the core of the methodology still includes, in some way, LCA principles (Ostad-Ahmad-Ghorabi et al., 2006; Goedkoop et al., 2004; Horne et al., 2009).

Because the early stages have the highest potential for product improvements, many authors have aimed to perform an environmental assessment at this point (Sousa et al., 2008; Ostad-Ahmad-Ghorabi et al., 2008; Sousa and Wallace, 2006; Ostad-Ahmad-Ghorabi et al., 2006; Luttrupp and Lagerstedt, 2006). However, they all include some sort of environmental assessment, more or less abridged. At this point in the process, little information is available for product assessment. This combination of phenomena is sometimes referred as the design paradox (Lindahl, 2005). In addition, it is shown that processing too much environmental information in the early stages hinders creativity of solution ideas and provokes fixation (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010c). A possible strategy to handle environmental

information in the early stages – where there is no specific product yet – is to draw conclusions from similar products. To indicate and group products that are similar, the concept of families has been proposed in literature, understood as a set of different products that have a common set of traits. A product family would be a family that has common functions, parts or properties. This selection can be partly systematized adopting a functional perspective (Alizon et al., 2007; Dahmus et al., 2001), or one of mass customization (Thevenot and Simpson, 2007; Jiao and Tseng., 1999). Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010a) adopt an environmental approach in the LCA-Comparison Product Families (LCP families) to set targets for environmental impact values.

Through LCP families it is possible to compare a product's LCA result with that of its competitors and say whether it is performing equally, better or worse than a particular range, e.g. than 95% of the products in the market. For that, functional units must be established systematically and uniformly. This can be done through functional icons (fuons) as presented by Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b). In efforts to systematize the selection of products that fall under the same family – be it product family or LCP family – often times the result depends on the expertise of the person carrying out the selection. For conclusions to be generalizable, it is important to consider all of the aforementioned approaches.

Methodological approach

Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010c) point out the relevance of delivering so-called soft information to designers. This sort of information is understood as allowing designers to focus on the relevant aspects from the environmental point of view, without exposing them to models of the product that could be problematic, for example provoking fixation. This is a challenge, as all environmental results come from such models, often highly complex ones.

A common sort of soft information used at the early stages is the selection of a series of hotspots that need to be studied. One such hotspot – and one of the most widely used – is the selection of the most relevant stages of the product's life cycle regarding its contribution to the overall environmental impact. This paper attempts to find out whether it is possible to exclusively define relevant life cycle stages out of past information from previous products' environmental performance. This would allow such an assessment to be performed in the early design stages. A tentative answer would be affirmative: an expert on environmental assessment would easily discard some stages and prioritize others. The subsequent question is whether this process can be automated, and which parameters that automation could be based on. The answer could potentially be defined as a set of statements that can be made about a particular life cycle stage for a statistically representative group:

- The stage is very relevant, and must be considered.
- The stage is of at least middle importance, and it could even be critical. It should be monitored.
- The stage is of at most middle importance, but it could also be irrelevant.
- It cannot be disregarded, but it will never be a key stage in the life cycle.
- The stage is not relevant, and can be disregarded.
- The stage could be important or not: no conclusions can be drawn.

The hypotheses that spawn from this argumentation are the following:

1. When analyzing samples of several products, it is possible to infer the behavior of some life cycle stages for the whole product family. This requires the possibility of:
 - (a) Assessing the average performance.
 - (b) Assessing the uncertainty or variability of that performance.
2. The robustness and extensiveness of this assessment depends on the level of detail, making it possible to have some assessments when little information is available, and better assessments if the product is more constrained.

This paper studies those hypotheses for two sets of products: chairs and hard drives. Any type of office chair and any sort of hard drive that were available were included, so the product family would be defined as loosely as possible. The effect of detailing technological traits of the product is studied in the second case. Additionally, applicability of the conclusions on more abstract levels (when defining only the general functionality of a product) is assessed, first with an extension of the hard drives into a more general digital storage devices, and with products described by the container fuon (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010b). Considering very diverse criteria, conclusions should be inferable to any product family, independent of the way in which the user selects the products.

The procedure for each analysis is:

1. Select a set of products for which environmental information is available.
2. Calculate for each product the environmental impact at each stage. For the purpose of this paper, the following stages are used: raw material extraction, manufacturing, distribution, use and end-of-life.
3. Calculate averages (μ) and standard deviations (σ) of the contribution of each life cycle stage to the total environmental impact. Additionally, calculate the ranges that are expected to include the majority of products.
4. Assess the relevance of each life cycle stage according to the previous model.

- Assess the level of information and reliability of the model. In case it is not sufficient, the set of products should be subdivided for better resolution.

Each stage will be assessed on its average contribution (in percent) to the product's life cycle impact. Nevertheless, an average can be misleading when drawing conclusions from a sample. The standard deviation gives an indication of how spread out the values are. If the value spread is high, it means that the set of products can perform in many different ways for that stage (it could be the most contributing or the least). For the purpose of this paper, an assessment of $\mu \pm 3 \cdot \sigma$ was used, including over 95% if the distribution is normal, and at least 89% if it is not (Dekking et al., 2005). In some case, $\mu + \sigma$ was higher than 100% or $\mu - \sigma$ was lower than 0% (or both). This phenomenon, here called saturation, was taken into account by always selecting a maximum of 100% and a minimum of 0%. For obvious reasons, this range includes the totality of products in the sample. An exception was made for the end-of-life stage, as due to allocation issues, positive impact on the environment from material recovery was considered. Table 1 shows the possible conclusions that can be drawn from this information.

Table 1. Different conclusions that can be extracted from analyzing different products, and their value in drawing conclusions

Description	Stars	Graph	Limits
The stage is always considered to be relevant	★		$EIS > 0.8 \times EITotal$
The stage is always considered to be irrelevant	★		$EIS < 0.2 \times EITotal$
The stage is sometimes relevant, or of medium importance	✧		$EIS > 0.4 \times EITotal$
The stage is sometimes irrelevant, or of medium importance	✧		$EIS < 0.6 \times EITotal$
The stage has different levels of relevance, but no extremes. The range is, however, too big to conclude			Unsaturated wide range
The stage could have any sort of relevance (could be very relevant or very irrelevant)			Could be 0% or 100%

Notes: EIS =Environmental. impact of the stage; $EITotal$ = Total environmental impact

The full model was rated by giving an amount from zero to five stars, based on table 1. One, half or no stars were given to each life cycle stage. A higher sum of stars represents a model that allows one to draw conclusions closer to those of a full LCA regarding which life cycle stages to focus on. The case studies and figures 1 to 8 show examples of how this star-rating

represents the capability of each model to assist in decisions-making on which stages to consider or disregard in generating ideas and concepts for the new product.

Product-specific case studies

The first set of case studies was carried out for office chairs and hard drives.

Case study 1: Office chairs

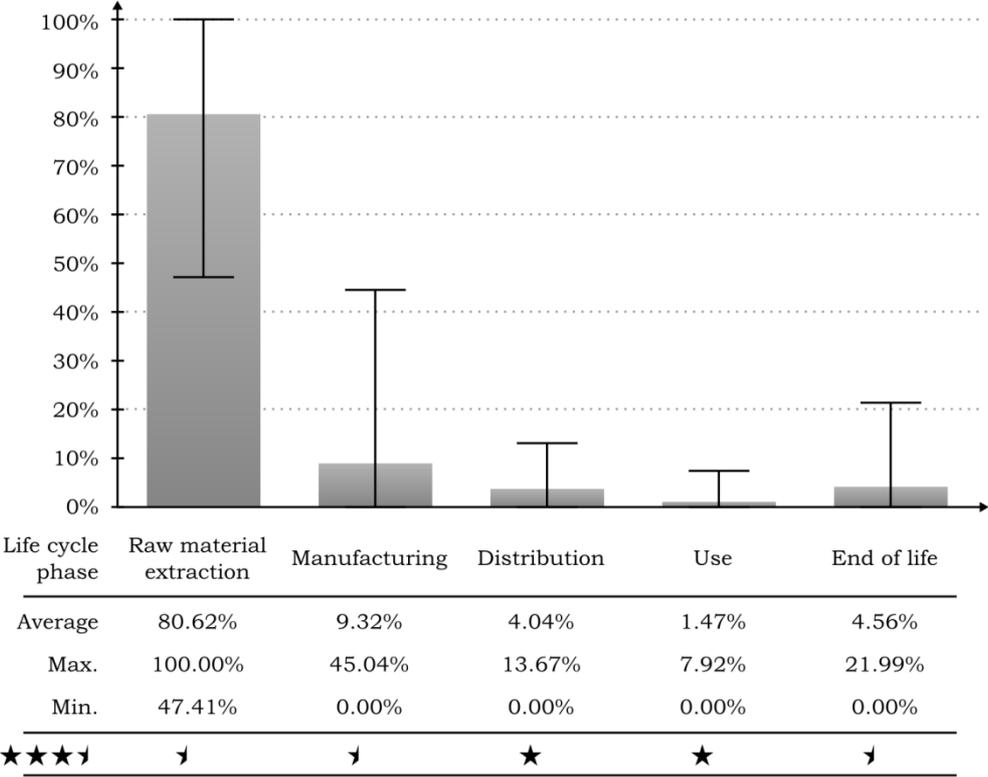
Following the five-star procedure, 31 different office chairs were analyzed in step 1 of this case study. Publically available data such as Environmental Product Declarations (EPD) or product data sheets were consulted. The models of the product's life cycle were developed from here; or when specific data were available for all stages, the environmental impact per life cycle stage was retrieved. Among these products, office chairs from companies Steelcase, HÅG (both with publically available EPDs) and Formway (Babarenda Gamage et al., 2008) were analyzed. The list of products was completed by using available industry data of different companies from previous projects conducted at the Vienna University of Technology. A life cycle model was established and environmental impacts were calculated. For example, in the case of the HÅG chairs, the EPD gave information about the material composition, recycled content of each material, energy consumption (per type) for the chair's manufacture, as well as waste and emissions disaggregated per life cycle stage. These were introduced into the software SimaPro to perform a unit process LCA. Where more information was not specified, it was taken from database processes, e.g. from Ecoinvent. Assessment results were benchmarked with those in the EPD to ensure that the model was representative. If allocation differences existed, the model was adjusted after this check.

For the environmental assessment in step 2, the Environmental Design of Industrial Products (EDIP) method (Wenzel et al., 1997) was used, and in particular the impact category indicator for Global Warming Potential (GWP) was considered for further analysis. This indicator was selected because it is relatively extensive in the environmental aspects it considers, and yet it provides a single indicator that is commonly understood. Of course, designers may need to use other impact categories, or more of them. Company policy, knowledge from the environmental department, or even the designers own training may drive them to explore beyond GWP. In a fairly high number of impact categories – seven out of the ten studied by Nansai et al. (2008) – the results tend to be highly correlated, and thus not profoundly different to those presented in this paper. In the other cases, designers may be faced with conflicting results, both of them informative, if for example the key impacts are toxicity in the end-of-life stage and GWP in the manufacturing and use phases.

In any case, this gathering of information concludes in a list of all the environmental impacts for each stage and for every chair. Because the contribution of each stage to the total impact is assessed, these percentages were calculated.

In step 3 the averages (μ) of each stage, as well as the standard deviation (σ) were calculated. The limits of the range between $\mu - 3 \cdot \sigma$ and $\mu + 3 \cdot \sigma$ were calculated, and when saturation appeared, these values were substituted by 0% or 100%.

Figure 1: Estimation of environmental impacts for a group of chairs (N=31)



In step 4, results are plotted in figure 1 and analyzed. The model provides reliable conclusions for the distribution and use stages. Their contribution to environmental impact will be low (not more than 20%). For manufacturing and end-of-life, conclusions are not as reliable: values will generally be low, but they could reach up to 45% and 22% respectively. The raw materials extraction stage has a high impact, although its percentage can vary widely: most products will be over 47%, but no more can be specified. Focus should therefore be on improvement in the materials, but should also consider the manufacturing and end-of-life processes.

Conclusions comprise two statements that are robust, and three that present high variability. According to step 5, that adds to a total of three and a-half stars (with N=31 products). The model is of mid-high quality, which for most projects is good enough to be used in the early stages.

Case study 2: Storage drives

For the case study of digital storage drives, a total number of 32 products were analyzed. The products comprise a set of nine magnetic hard discs with different capacities, different Secure

Digital (SD) Cards (in total eight pieces including SD, SDHC, SDHC and SDXC), six Solid State Drives (SSD) with different capacities and nine different USB flash disc drives. To assess the products environmentally, product models were built and life cycle data were collected. Thorough literature research was conducted and inventory data were derived from publications in the field of electronic products. Data sheets and publicly available data from manufacturers were also considered and taken for product modeling. Material composition of hard discs was derived from disassembly studies (Sunil Mohite, 2005). Life cycle data of Printed Circuit Boards (PCB) were modeled by merging data from Kunnari et al. (2009), Kramer (2006), Nagel (2003), and the EcoInvent database (Frichknecht et al., 2007). Distribution scenarios have been modeled by considering major manufacturer countries and consulting LCA studies (e.g. Liu et al., 2010; Duan et al., 2009; Kunnari et al., 2009). Additionally, data about manufacturing processes were obtained by consulting an expert in the Institute of Solid State Physics at Vienna University of Technology who holds a patent on a similar product. The use stage was modeled by consulting an expert in the Institute of Solid State Electronics at Vienna University of Technology who is responsible for archiving digital data and maintaining IT systems in the Institute. The end-of-life scenarios were modeled considering recycling and landfill processes (Duan et al., 2009; Kunnari et al., 2009; Sunil Mohite, 2005). GWP contribution, percentages and statistical data were calculated analogously to the previous case. Results are plotted in figure 2. In this case, manufacturing, distribution and end-of-life will generally be almost irrelevant. No conclusions can be drawn from the raw materials extraction and the use stages: some products might be use-intensive and others material intensive. Both life-cycle stages should be targeted, even though one of them will probably have a low impact. For more information, additional subdivision of the product-set is necessary.

The model has a rating of three stars, which is considered to be mid-quality. This also points out the need for further refining the product group. Figure 3 shows the new graphs for static hard drives and portable hard drives. Static hard drives are more dependent on the technology used (figure 3a). Portable drives have a very homogeneous behavior (five-star model, see figure 3b). Subdividing further, magnetic hard drives (with N=9) also provide a five-star model, whereas solid state drives (with N=6) still have a high variability (three-star model, figure 4). The model cannot get any better without specifying models and brands. This points out the importance of this type of assessment, as consulting one particular LCA of a benchmark product – sometimes recommended in literature – could point towards only one of the two relevant life cycle stages.

Figure 2: Estimation of environmental impacts for a group of hard drives (N=32)

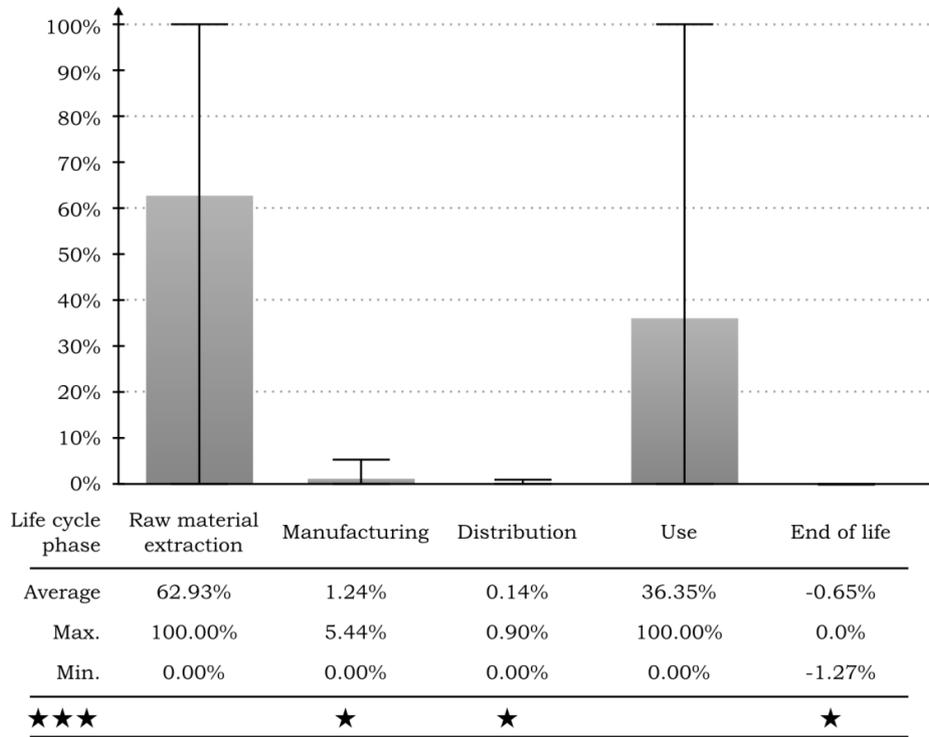


Figure 3: Estimation of environmental impacts for a group of static hard drives (N=15) and a group of portable hard drives (N=17)

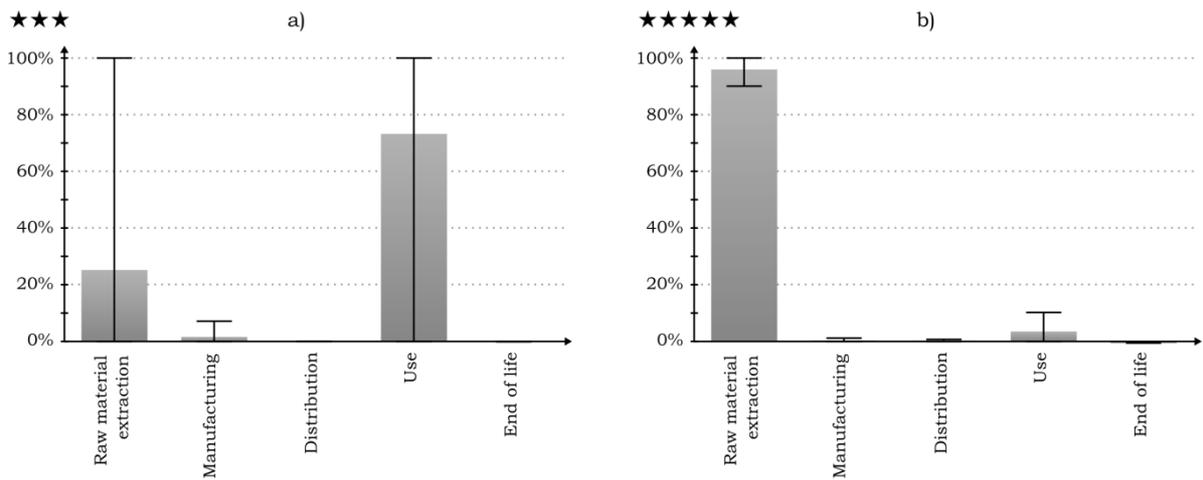
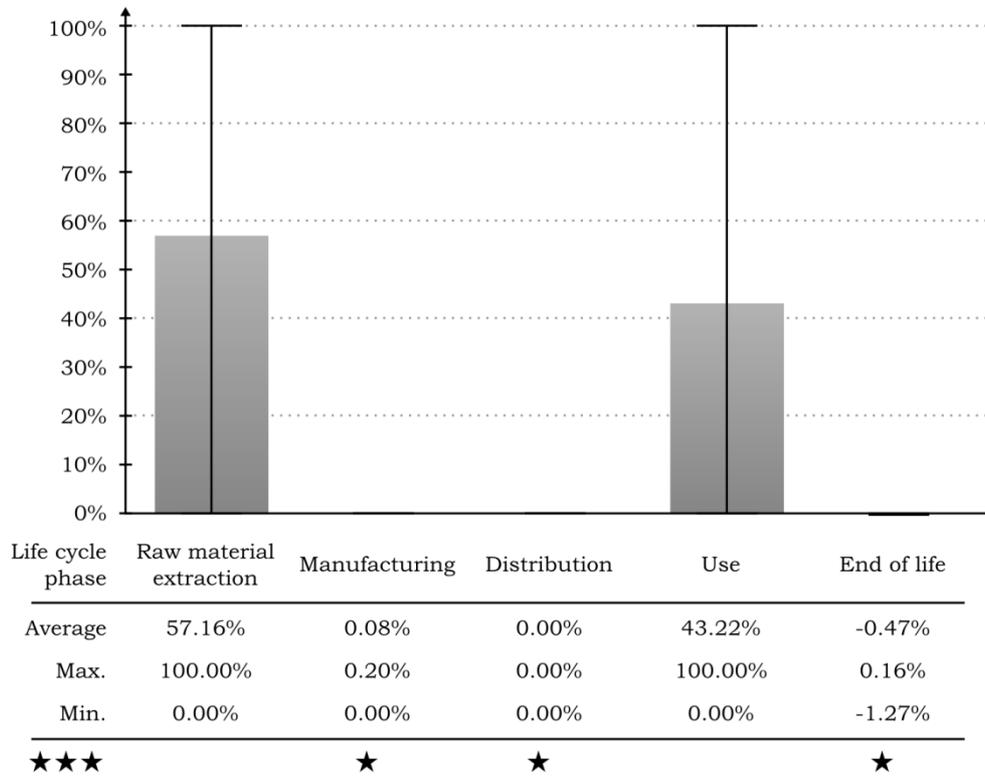


Figure 4: Estimation of environmental impacts for a group of static hard drives based on solid-state technology (N=6)



Complex case studies

In order to gain insight into the potential of this approach, it is important to apply the same methodology to broader groups of products. Common functionality will be taken as the guiding parameter for grouping them. Therefore, the hard drive case study will be expanded to any sort of digital storage device, and a second case study of container products (defined by the funon named container from Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b)) will also be assessed.

Case study 3: Digital storage devices

15 additional storage media were added to the original 32 hard drives including CDs (in total seven pieces including CDRoms, DVDs, Blue Ray discs and rewritable CDs), seven different RAMs and a floppy disc. Information was mostly gathered from publications and from the same experts consulted for the hard drives. Data for the modeling of RAMs were found in Liu et al. (2010); Kunnari et al. (2009) and in data sheets from the manufacturers.

Figure 5: Estimation of environmental impacts for a group of digital storage devices (N=47)

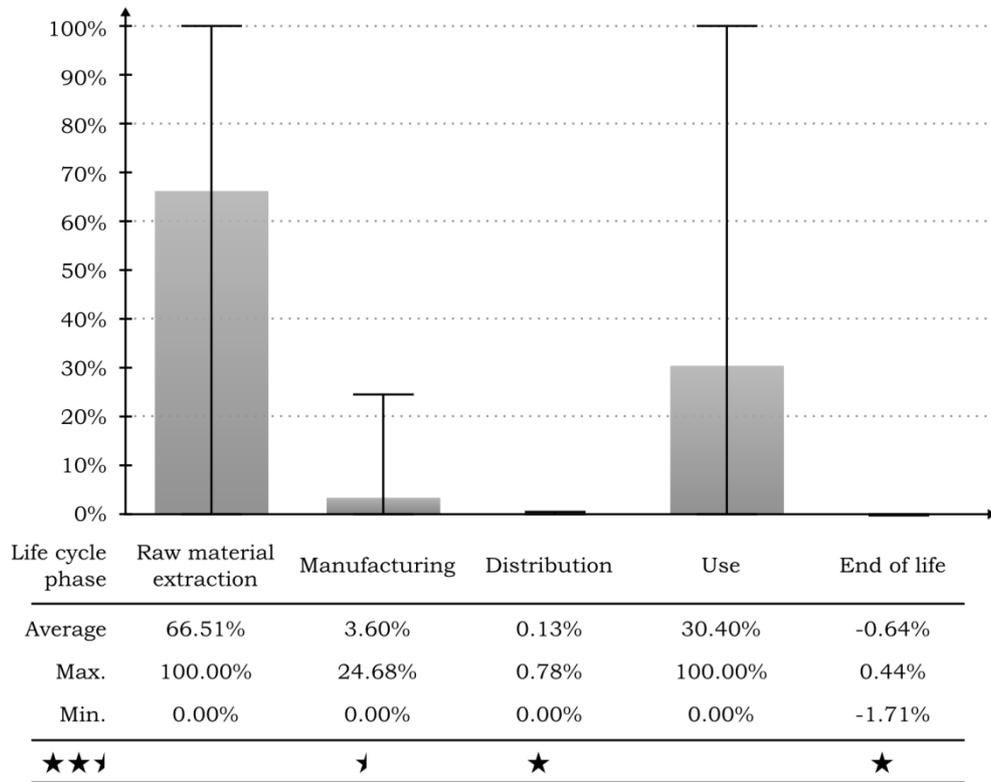


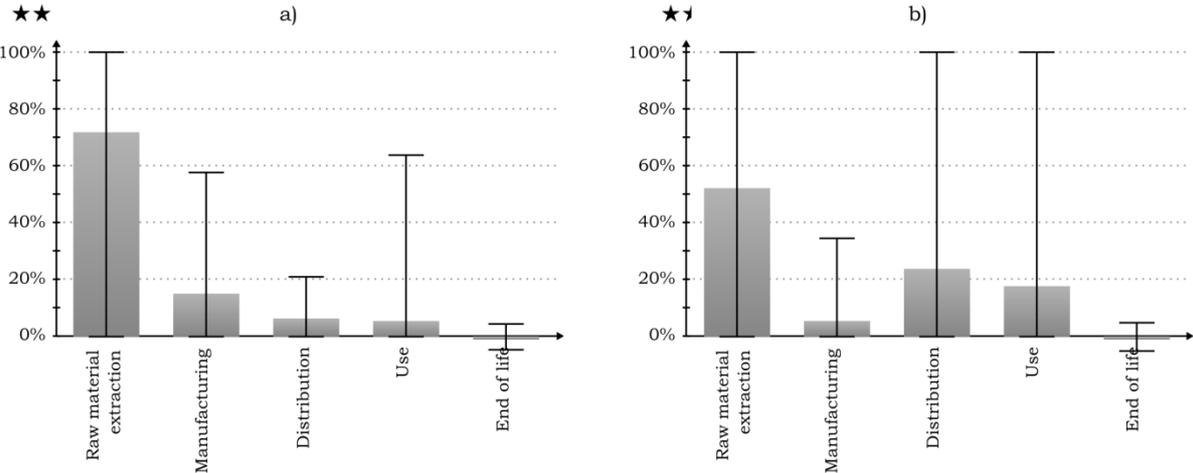
Figure 5 shows the distribution of the environmental impacts for this group. The figure's relative distribution is very similar to the distribution in figure 2. The conclusions established for hard drives can apply generally to most digital storage devices: low impact on the distribution and end-of-life stages, manufacturing impacts that could reach up to 25%, and the highest impacts appearing either on the raw materials extraction or use stages. Their impacts will not necessarily be high, but they could reach very high values. The model's rating is two-and-a-half stars, i.e. low-mid quality. If no further selection can be done, both raw materials extraction and use stages should be optimized.

Case study 4: Container Fuon

To reach a higher level of abstraction, the fuon physical container is also analyzed. This fuon describes products that partly or totally enclose other physical elements, protecting them or isolating them from the external environment (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010b). However, many products that respond to such a description have an additional functionality regarding the transportation of other goods. For those products, Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) developed another fuon called logistics-intensive products. This fuon is defined as an element with the intention to allow transportation (once or more), protecting and allowing the necessary stacking or manipulation. Both fuons will be analyzed together in this case study.

The expectations are that a first preliminary assessment of the environmental profile estimation will be possible for such an abstract concept. Successive refinement and detailing of the product should then lead to higher rated conclusions (with more stars). On a first assessment, only products that are classified as containers are considered, i.e. excluding those classified as logistics-intensive. The sample (N=19) includes a filling-bottle for home-use, paper and plastic bags, trash cans and cardboard boxes of different sizes (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010b). Figure 6a shows that the end-of-life stage will not have a considerable environmental impact in any case, and manufacturing and distribution commonly have mid-low values, although they could reach considerable figures. Raw material extraction and use stages could reach very high or very low values. Further refinement is recommended (low quality two-star model, one for end-of-life and two halves for distribution and manufacturing).

Figure 6: Estimation of environmental impacts for container and logistics-intensive products a.) N=19 for container products only, b.) N=33 for container and logistics-intensive products

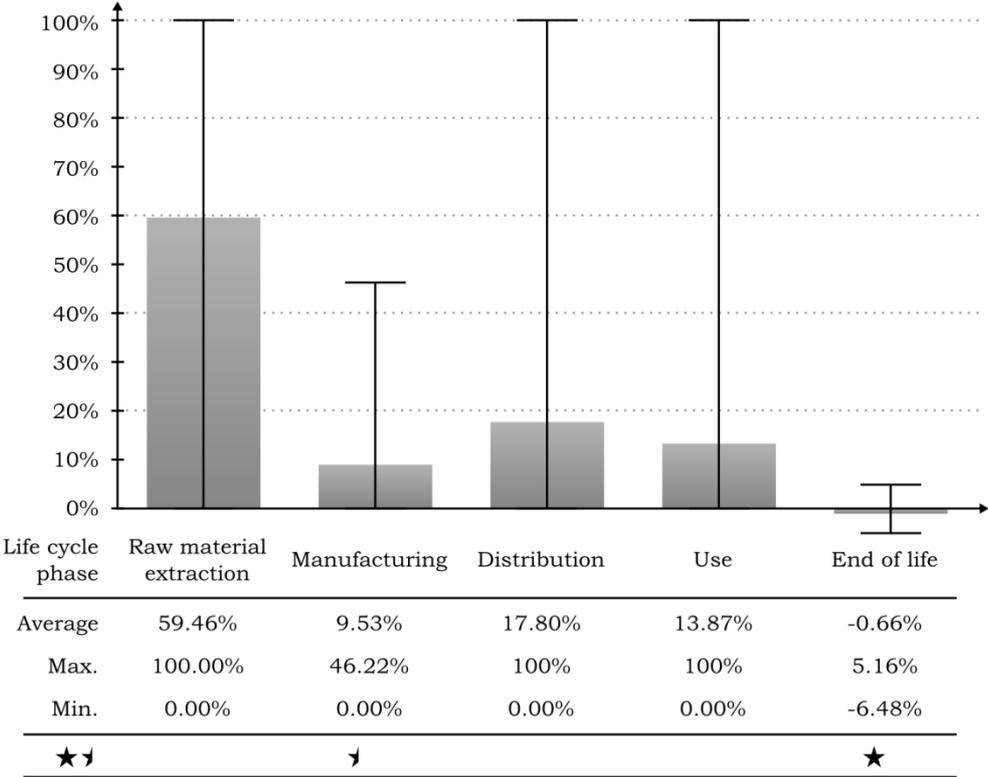


The manufacturing and use stages follow an interesting pattern. They are relatively similar in their maximums (58% and 63%), although the star rating grants half a star to the manufacturing stage (below 60%) and no star to the use stage. Similarly, the distribution stage, with a maximum of 22%, is close to receiving one star. The graph shown in figure 6a should allow designers to consider both manufacturing and use stages as of similar importance.

Figure 6b shows a second assessment for products described by both the container and logistics fuon (N=33), including freight containers, multi use bottles, envelopes, food cans, drinking cans and a pizza box. The end-of-life stage is once again irrelevant, and the manufacturing stage will generally be of low relevance (sometimes reaching up to 35%). For all the other stages no conclusions can be drawn, so further detailing will most probably be needed (one-and-a-half star rating, low to very low quality).

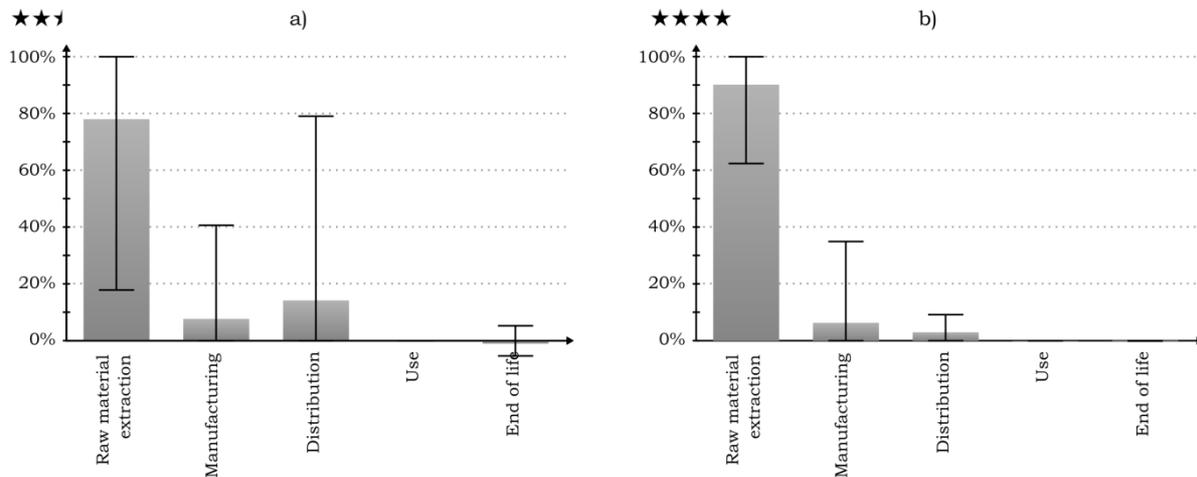
An additional study was performed with all products described by the fuon container, regardless of whether they were also described by the fuon logistics (N=52). Figure 7 shows a slight decrease in the quality of the assessment, still rating one-and-a-half stars like the case of logistics fuon.

Figure 7: Estimation of environmental impacts for all container and logistics-intensive products (N=52)



A final study was performed for disposable (single-use) containers. This filter was applied both on the total 52 products (Figure 8a) and to the 33 logistic-intensive products (Figure 8b), expecting greater homogeneity in the second group. The first case (N=28) provided a two-and-a-half star model. The end-of-life and use stages will have a low impact. Manufacturing will generally be of low impact, although it could be up to 41%. No conclusions can be derived about raw material extraction and distribution. The quality of the conclusions for single-use logistics-intensive products (Figure 8b, N=8) is considerably higher: distribution, use and end-of-life stages can be discarded, manufacturing will generally be of low importance (reaching at most up to 35%) and raw material extraction will be the most impacting stage (62% in its weakest scenario). These conclusions constitute a four-star model.

Figure 8: Estimation of environmental impacts for disposable products: a) N=28 out of 52 products, b.)N=8 out of 33 logistics-intensive products



Comparing figure 8 with figures 6 and 7 shows that, as constraints increase, the model can become more and more detailed, and conclusions receive higher ratings.

Conclusions and outlook

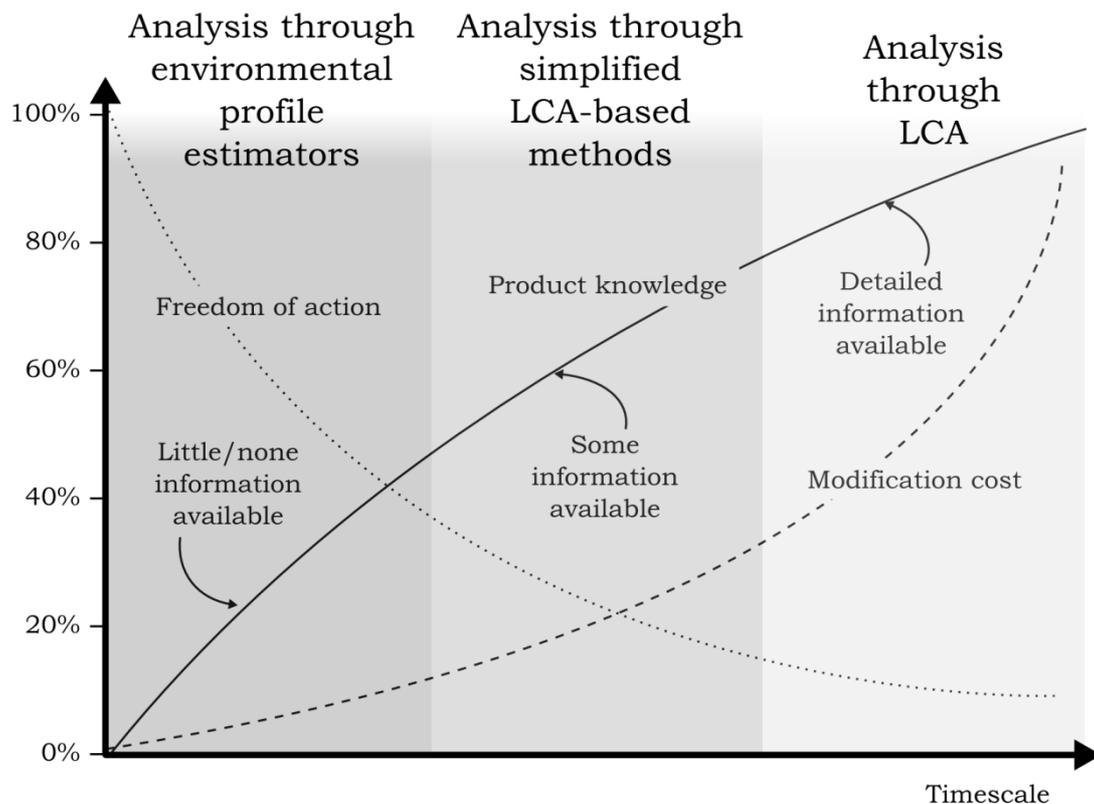
The experiments substantiated the hypothesis that some extent of common environmental behavior can be inferred from product groups. Different levels of detail in the description were assessed, and the type of product and the main functionality already seems to allow some level of conclusions. Empowering designers to extract environmental information during the early design stages is therefore possible.

The proposed approach confronts the different flaws attributed to LCA in design. The only information specified by the designer is the type of product. This fact reduces – in comparison to LCA – time-consumption, need for product information, and need for specific modeling. The fourth flaw pointed out in literature is the high degree of uncertainty. Whilst not eliminating uncertainty, the proposed approach gives information about the robustness of the results. This assessment of the uncertainty is presumably the highest level achievable before knowing the product. The statistic of standard deviation (σ) was used for this purpose. The amount of cases that fall out of ranges defined by this statistic are limited. For the studies, $\mu \pm 3 \cdot \sigma$ was used, although other less (or more) restrictive ranges could be considered. It could be seen in the case studies that estimation was robust enough to draw conclusions.

Of course, the more the group set is specified, the fewer products it will include. Even though the star rating might seem better, a model with fewer products is representative of a smaller portion of the market. In the extreme case, an over-specified set may include one only product: representative of a very small part of the market though it may have a good star rating. Practitioners should be wary of the representativeness of the figures: it is important to inter-

pret the ratings alongside with the sample size. The proposed approach helps designers define important life cycle stages to focus on in order to define specific strategies. Sometimes these strategies constitute complete approaches in themselves, i.e. Design for X strategies. If end-of-life is the most important life cycle stage, for example approaches like Design for Disassembly and Recycling might be preferred. In use-phase dominated products, energy efficiency strategies are most times the appropriate approach to consider. Focusing on the raw materials or manufacturing stages instead highlights strategies like Design for Manufacturing. As happens with many approaches to environmental improvement, there is a risk of proposing ideas that, instead of reducing the overall environmental impact, just shift the burdens from one life cycle stage to another. The current approach cannot specifically deal with this issue, as it is applied prior to the idea generation itself. Once those ideas – and concepts later – are developed, other well established tools can be used to assess their performance, potential burden shifting, and divergence of the new concept with regards to the database information. The visualization of the environmental profile estimations (figures 1 to 8) can also be seen as a way of presenting this complex and fuzzy information, that will provide designers with the possibility of drawing conclusions from the very early stages. In some situations, such as the second case study on storage drives, this visual assessment might be of more relevance than a complete LCA of a previous product. It is important to stress that the results, even if coming from sturdy LCA information, are tentative and preliminary. Even if the ranges become very small, the present method can never substitute for a complete LCA, as the products in the database might consider different parameters for manufacturing, geographical location, use conditions, etc. The results can guide in selecting priorities or key strategies, but should not be used in giving feedback about the actual performance of a product. Assessments of different levels of detail can be carried out at different moments in the product development process. Figure 9, based on the description of Design Paradox from Lindahl (2005) shows this timing, depending on the product information available.

Figure 9: Different moments in the product development process and the environmental assessments that can be done



The assessments carried out in the early stages have proven to give some level of information – albeit sometimes low – even in the case of very high levels of abstraction. In the last case study presented, not even the product type was specified, but rather the function (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010b). This implies that the main functionality of the product was specified, without detailing any of the technical parameters or constraints of the product. Even defining only that the product will be a container of matter, some conclusions can be drawn. The effect of different decisions (e.g. technologies or constraints) can be used as a filter, to get to better quality results.

This paper opens a research line in the area of environmental profile estimations. The concept, the way of assessing sets of products, and the form of visualization constitute a field that can potentially be combined with other existing research. Integration with LCP-families (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010a) and scaling through functional unit parameters might increase the potential of this visualization: further research is needed to analyze whether the scaling proposed in LCP-families can be extrapolated to different life cycle stages, allowing an absolute-figure analysis. Furthermore, benchmarking could be performed at the life cycle level instead of overall level, allowing a finer tuning of the product specification. Up to this point, only the processing of information has been emphasized. This has been carried out by

gathering large amounts of information. However, for this to be practicable, information should be readily available for designers or decision-makers in the early stages. For a company that has LCA information from previous products, this could be implemented in some sort of database. For the broader public, further research should generate a software tool and database to quickly supply the user with environmental profile estimations out of internal data.

In this paper, disaggregation could only be carried out at life cycle stage level, as no other common taxonomy exists. Nevertheless, if such a disaggregation were to be done at inventory level – through the development of a process taxonomy – conclusions could be extracted as to the most contributing processes per life-cycle stage. A similar discussion could apply to different impact categories in which the product can be assessed. Additionally, the authors followed coherent criteria when selecting where each impact is to be considered. Should this not be considered, the star-rating of the results would be lower. The aforementioned taxonomy would ensure that the higher star-rating is possible even with different experts carrying out the LCA analyses. The current research has been carried out up to an analytical level. Many conclusions could spawn directly from understanding the processes and impacts inside the different stages, and from seeing the differences from results when varying different selection parameters (e.g. watertight containers or not, transparent or not,...). Although the theory proposed by Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010a,b) can help in the selection process, the analyses are currently difficult to implement. Further work should be carried out regarding the applicability of different artificial intelligence algorithms to this analysis, so that potential improvements (such as changing a technology, or reconsidering a constraint) are pointed out in an automated manner.

This paper has shown that estimations of the life cycle impacts per stage can be performed without a model of the product, using previously existing information. Environmental profile estimations are a good aid for this, and the uncertainty can be visualized to ensure that conclusions are as apparently robust as the information behind them. This should grant designers the sort of information that is needed in the early stages, when no model of the product is yet existent. At this point uncertainty and potential are high (Lindahl, 2005), and environmental profile estimations provide suitable information in moments where the design paradox impedes proper environmental assessment.

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