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TOWARDS INTEGRATING LCA INTO CAD

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ABSTRACT

Engineering design is done in CAD systems. Environmental assessment is done by using LCA software. Both worlds have strong relationships – especially when Ecodesign is to be implemented – but they are not necessarily connected. The project presented in this paper wants to link both worlds and show how the reduction of the environmental impact can be considered during engineering design processes. CAD systems include much information about different parameters of the product life cycle, from which Life Cycle Assessment (LCA) can benefit. This paper describes an approach by which LCA could be integrated into CAD systems to provide an easy to apply environmental evaluation in early design stages.

Keywords: Life Cycle Assessment (LCA), Ecodesign, CAD, Visualization, LCA-family

1 INTRODUCTION

Contacts with industry and experiences with industrial projects indicate that the concept of sustainable product development, may it be stated as green product development, Ecodesign, integration of Life Cycle Thinking, environmentally sound product development or else, is more and more getting into the focus of companies. A lot of methods, tools and approaches have been developed to introduce the concepts above into industry such as [1], [2], [3], [4] or [5].

In [6] a dilemma for the use of tools and methods for environmental knowledge acquisition in companies during the fuzzy front end of innovation was discussed: although these tools were regarded as being important to gain new ideas, the survey conducted showed that they were not used for their intended purpose. A similar dilemma and analogy can be observed when it comes to the implementation of tools and methods for sustainable product development in early design stages: Many companies might know about the potentials of such integration, but the realization is too difficult. Conducting Life Cycle Assessments (LCAs), environmental analysis or establishing environmental profiles may confront the engineering designers with a huge amount of data, facts and a considerable rise in workload. [7] proposes an Ecodesign tool that presents the designer with a set of Ecodesign strategies from an expert system and aids in the management of the improvement proposals, including a an effort to export information to LCA software. [8] also developed a CAD-integrated assistant that delivers Ecodesign advice, but in both cases the link with LCA is external, and direct feedback about the consequences of the changes is not intended. Additionally, in the initial stages of design much data may be still fuzzy and subject to changes during conceptualization. How can the benefits of such efforts be seen and understood in design processes? Similar as discussed in [9] for customer goods, paying attention to the visualization of the environmental performance of design concepts to the engineering designer constitutes an effective approach.

As stated in [10] where the multimodality of 21st century literacy is discussed and where for example visualization abilities are described to be used for communication of beyond what language is able to do, visualization of environmental performances in an accurate way in early design stages may be able to access to environmental knowledge, beyond data, facts and numbers.

This paper will discuss the first milestones achieved by the authors' research activities. A preparatory study was conducted together with an international crane developer which shows how the introduction and integration of the visualization of environmental performance into the design department of the cooperating company was initiated. The ideas of this approach as well as the derived requirements for an effective implementation and the path for future CAD integration are discussed.

2 REQUIREMENTS FOR INTEGRATING LIFE CYCLE ASSESSMENT INTO CAD SYSTEMS

Analyzing the environmental performance of a product, e.g. by conducting a LCA according to ISO 14040, is a time consuming and complex task. Any intended implementation of environmental evaluation into early design stages should not lead to an increased workload. For a feasible integration, the complexity of handling and using environmental data has to be reduced.

One approach to do so follows from the fact that not necessarily a new full LCA is required for a new product. When redesigning a product, information about the previous model of the product can be available. If no considerable functionality changes have been developed, that information can be directly compared to a new LCA of the product. However, most products will add new features in the newer model, or simply constitute a new independent product that has a new functionality.

Previous products will therefore need to be considered, but the selection and the approach taken will have to fulfill the following requirements:

- Scalability: LCA results should be scalable; this can be achieved by providing a systematic parametric description of the life cycles of the product.
- Pragmatism: Carrying out an LCA is a complex process, and improvements that incur in greater workload will most probably be set aside. Therefore, any implementation must be carried out in a way to be useful for the practitioner.

In case a new independent product is developed, may it be part of a product family or not, rule-of-thumb extrapolation tends to be used as the most rigorous tool to assess the environmental impact. In [11] the term LCA-family was introduced as a set of products whose LCA shares a common behavior, and can therefore be compared in some practical way. The definition of LCA-families has, among fulfilling the scalability requirement defined above by containing a parametric model, one important trait: it allows comparing LCA results to judge whether a new product has a high or low environmental impact. This is achieved by defining a reference value for comparison of the environmental impacts. The reference value itself can be extrapolated from previous LCA data.

If, for example, the environmental impacts of a chair are known, and a lamp is added up for users to read when they are sitting on it, the total impact is expected to be higher than that of a chair, and the increase will probably be as high as the impact of a lamp. By deriving the appropriate LCA-family, in this case it might be a family with accurate information on chairs and lamps as family members, a reference value for the expected environmental impact of the new product “chair with lamp” can be calculated. The reference value of a family always constitutes the best case scenario of an environmental design concept realization. A new concept can then be compared with the reference value to judge whether it is doing better than the reference value or not.

To be able to form an appropriate LCA-family, as follows from its definition, its members have to share certain properties. Table 1 lists different types of LCA-family members.

Table 1. Types of products

Similar	The products share the same traits (normally functional, described in the product’s functional unit), but might differ in quantities, e.g. light bulbs with different power
Equivalent	At least one trait is the same and at least one trait is different. Chairs with and without lamp would be an example of equivalent products. Much can be inferred from one another, although there are missing parts that will have to be patched.
Different	There are no common traits. There is no potential for comparison and as long as one of them is the new product, they will never be included in the same LCA-family.

Similar or equivalent product types fulfill the requirement for scalability (like in the example with the chairs and the lamps, provided enough data is available), whereas different product types are not scalable.

When starting to develop a new product, its LCA-family members first will be composed of some similar products; for the chair with lamp example that would be some similar chairs and some similar lamps. Considering the different traits of the product, a reference value is derived from this LCA-family, to be further compared with the LCA result of the product in question. For a next concept of a chair with lamp, the previous chair with lamp will constitute the LCA-family and the similar "only chairs" and similar "only lamps" will then be removed from the family. The environmental performance of the second concept will then be compared with the first concept. The LCA-family is a growing, dynamic family which always contains the best suitable family members for environmental comparison as illustrated in Figure 1.

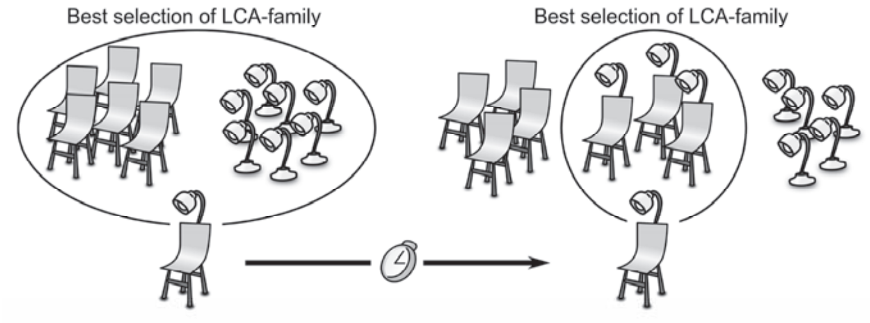

Figure 1. Evolution of LCA-families

To be able to implement environmental evaluations effectively into early design stages, results must be shown in some sort of visual interface, as discussed in [12]. This way, users will interactively be able to track the product's environmental impact due to design changes. Through the research activities of the authors, visualization in CAD software is intended. Other methods have proven to be widely accepted when integrated into these sorts of systems. One of the most common examples would be Finite Element Analysis (FEA) which are part of some CAD software already and help to visualize calculations and provide information for product concept improvements by using an easily interpretable color scheme that is associated with higher or lower stresses. In the case of environmental impact evaluation, it would be convenient to use such sort of schemes.

With the approach presented, only information about the relative performance of the product (better or worse than average) is presented. Nevertheless, both, the FEA in CAD and the intended LCA module in CAD will be able to provide results from a more accurate model for further design decisions, optimizations and improvements.

In the following, the first steps taken in a series of research activities to achieve a CAD implementation are discussed. In this first step, the requirements and structure of a needed database, a possible interface and its usability have been investigated through a preparatory project.

3 PREPARATORY STUDY - INDEPENDENT DEVELOPMENT OF AN LCA-FAMILY

Within the scope of a conducted project with an international crane developer, engineers in design of the company were involved in the development of a first draft of a tool with a corresponding input interface for environmental evaluation of product concepts in early design stages. This tool was realized in Excel. Several products of the same product family of the company were investigated. The task was to conclude from the environmental performance of one family member to the environmental impact of the others. To have an idea of the environmental impact of the cranes, a LCA based on ISO 14044 was conducted for the most common crane.

The conducted LCA was then taken as a basis to derive a parametric description of the life cycle phases of the product, a pre-requisite for scalability fulfillment. A representative parametric description was possible, since the cranes turned out to be, from an LCA point of view, from the type "similar" as defined in Table 1. The investigated products shared the same (or very similar) LCA traits.

Furthermore, the parametric description used as a basis to develop the input interface of the tool, helped to reduce the amount of data to be dealt with in early design stages significantly. This fulfills the "pragmatism" requirement stated above. The parametric description affords some 16 parameters, including information from all life cycle stages, for the product crane to be defined to conclude to environmental impacts of cranes from the same family. In other words, any similar crane to be developed can be environmentally evaluated by the 16 parameters derived.

To be able to access all environmental data by this set of parameters, a database was developed and the derived parameters were linked to the environmental data in the database. Accordingly, the input interface only asks for these 16 parameters which cover all life cycles. Some of these parameters could even be dropped in case an implementation in CAD is achieved since they can be derived from a CAD system automatically. An example here fore would be the specification of the weight of a part or component or the amount of pieces of a part, where, by specifying the material, the weight of a part is known or in a assembly drawing, the amount of pieces of a part are known. Figure 2 sketches the described approach and compares it to normal LCA processes (those defined by ISO 14044 or derived). The normal process takes many sources of information to develop a complex model and inventory, that will then be assessed by means of a computer to deliver LCA results. The proposed approach is to use embed those environmental sources and the information included in LCA systems to reduce the time required, and to take as little time from the user as possible.

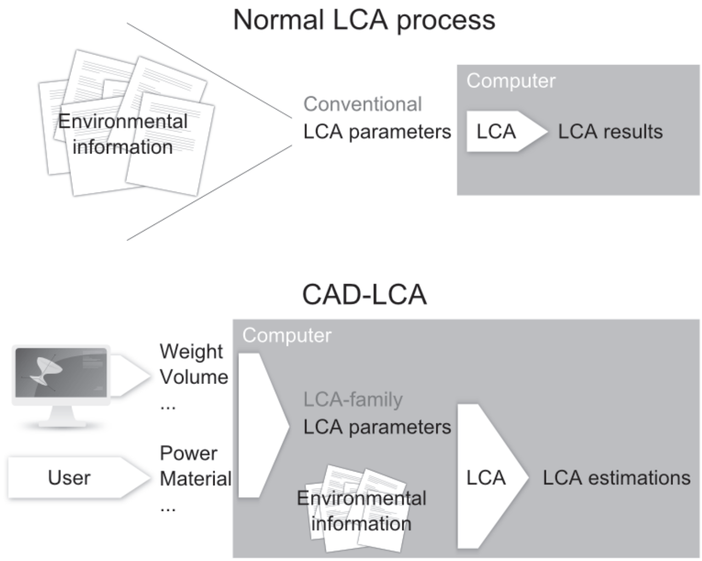

Figure 2. Scheme for implementation of environmental information in a CAD system

To be able to judge from an environmental point of view whether the current concept, hence design of a part is performing better or worse than previous realizations, different indicators for the crane types of the family were developed.
For each of the crane types the weight of its parts in kg and the total environmental impact expressed in t-CO_2-equ was calculated and put into the database. The impact category was selected for different reasons including understand ability and correlation in many situations will other impact categories [13]. Taking the maximum lifting momentum expressed in mt into account as well, following indicators were derived and used for comparison:

$$I_1 = \frac{Weight_{Crane/part}}{Maximum\ lifting\ momentum} \tag{1}$$

$$I_2 = \frac{Total\ environmental\ impact}{Weight_{Crane/part}} \tag{2}$$

$$I_3 = \frac{Total\ environmental\ impact}{Maximum\ lifting\ momentum} \quad (3)$$

While I_1 describes the technical characteristics of a part, hence the crane, and constitutes an important value for dimensioning, I_2 and I_3 are valuable indicators for the characterization of the environmental performance of the respective part. These indicators are calculated for each part and for each crane type. For comparison, the indicators of a part under investigation are compared with the minimum value of this indicator available in the database for the different crane types. The minimum value constitutes the best case scenario.

The ratio I' of the investigated indicator value I and the minimum indicator value I_{min}:

$$I'_x = \frac{I_{xmin}}{I_x} \quad (4)$$

gives a dimensionless value which is able to express the percentage of approximation of I to I_{min}. $I' > 1.0$ indicates an environmental improvement.

The results of the environmental evaluation were visualized by providing an environmental profile for the product. Further, to visualize the approximation of I to I_{min} a simple colour coding was proposed:

- A red indicator would be given to values lesser than 0.6; that means that the best case performance is covered in a maximum of 60%, which is not sufficient. This is an indication that the concept/design of the part or component has lead to a considerably worse environmental performance than what could be best possible.
- A yellow indicator is given to value ranges between 0.6 and 0.9. That means that the best case performance is met in a maximum of 90%. The best case scenario is still not reached, but it constitutes a moderate approximation.
- A green indicator is given to values greater than 0.9; that means that the best case performance is covered in at least 90% or, in case the indicator is greater than 1.0, it is better than the available best case value. Should the latter case occur, an environmental improvement has been achieved. The new part should be the best case reference for future investigations

The idea of visualizing the environmental performance by colour coding the indictor results was appreciated by the engineers of the cooperating company.

However, the Excel draft is not the final goal of the research activities. Rather, the results achieved in this first step highlighted possible obstacles when aiming at a CAD implementation. It also showed the positive aspects of the followed approach and showed its currently existing limits.

It needs to be mentioned that a realization in Excel, although appreciated by the crane developers, constitutes an additional tool/software which needs to be used and applied in product development separately. This fact may be a burden to some engineering designers, as they see themselves confronted with additional tools and methods to be implemented in design. This is why an easy to apply implementation in a CAD environment seems to be a reasonable approach to facilitate environmental evaluation in early design stages.

4 TOWARDS INTEGRATION INTO CAD

In order to take the step into established CAD systems, there are two main topics to be addressed: the information between the CAD system and the LCA environment, and how systematic the process is in general.

4.1 Information that is handled

When modeling a product, designers tend to describe it with a series of parameters. Some of them, as seen, will be derived from the CAD, e.g. the volume of a part or component. Nevertheless, there is always a set of them that describe more broadly the performance of the product, e.g. energy efficiency. These parameters can be called *primary*. Their environmental impact only comes clear as they are linked to other inventory parameters that are to be called *secondary*. In reality the *secondary* parameters are linked to the *primary*. In the example, a motor's energy efficiency will depend on the design of the components, and therefore on its final weight and shape. . Figure 3 illustrates the idea of the different sorts of parameters.

Figure 3. Primary and secondary parameters.

Secondary parameters are feasible to be modeled, and LCA results will very likely be a conclusion of them, since they constitute the parameters that describe the Life Cycle Inventory. Nevertheless, understanding of the *primary* parameters – maximum lifting momentum in the crane example – will give greater insight onto the scalability of the product.
CAD systems often divide their files in product parts and product assemblies. Assuming this division, and a known 3D CAD model, the process to complete a product to get an estimation of its environmental impact, prior to any reference, would be the following:

1. Definition of each part:

- Material
- Where it comes from
- How it is processed
- Power consumption if applicable
- Maintenance needed
- Disassembly (y/n) and processes during end-of-life

2. Definition of the assembly:

- *Primary* parameters to be studied
- Where it comes from
- Power consumption and any other resource demand not attributable to any part in particular (losses)
- What end-of-life treatment do parts receive when they are not disassembled

With this additional information – and the possibility to adapt the answers to the specifics of the company, i.e. by defining materials and sources from the company instead of generics – it is possible to complete the product's life cycle inventory, and thus carry out an LCA that, in global, is very close to a normal LCA, with the interface as the only difference. The module should allow quick adaptation to variations in the parameters, since some variations in the part's shape could affect the processes through which it goes.
On the other hand, the database handled (to calculate a reference value to compare with) will consist of a set of products with their parameters – both *primary* and *secondary* – and the associated environmental impact. LCA methodology is used as the link to calculate the environmental impact from the inventory data, i.e. the secondary parameters.
The most important limits which have to be overcome for a CAD implementation is the static nature of the database. As stated in this paper, LCA-families have a dynamic nature; family members come and leave, depending on the problem investigated. This implies a continuous change in the database. Currently a considerable effort is needed to include new and/or updated data. The most important restriction so far is the following: should the environmental performance of a certain product or its respective components be better than the best case value defined in the database, this investigated performance should constitute the new best case value. In other words, the database should provide a dynamic growing and recalculate best case indicators I' whenever needed and provide them for further evaluations automatically. This aim needs advanced database programming and is not realized in Excel.

4.2 Systematic process for LCA-families

Section 3 presented a specific case study of how an LCA-family is developed. This task can be replicated by a user with environmental knowledge. Nevertheless, users of CAD tools are not bound to have such knowledge, nor to be willing or capable to analyze that sort of data. Therefore, the environmental information must be embedded in the software. Furthermore, algorithms must be included to:

- Calculate the LCA values from the CAD file
- Develop the LCA-family for a given database and product
- Assess the performance of the product by comparing with the previous

In the preparatory study, some of the 16 parameters were derived directly from CAD information. Therefore, the calculation of the environmental impact of a product should take as much of this information as possible. The additional information – presented in the previous section – should be an input from the user, in some interface that is similar to that of the rest of the CAD interface. For example, FEA modules normally require additional information to be typed in order to carry out the analysis. A very important criterion for the CAD tool will therefore be that this information is easily introduced and modified, by a correct integration of the inputs.

Once modeled the product, the intended algorithm will select those that are more likely to constitute an LCA-family for it, as shown in Figure 4, from among the products in the database. For this, coincidence of the different parameters is sought. An estimator model will be developed by mathematical algorithms to infer how that one of those parameters influences the reference final impact, and the results of the LCA will be compared to those of the reference.

Figure 4. Internal work scheme in the tool

Furthermore, it is necessary to assess the deviation of different results, to be able to assess up to which point the database is consistent, and up to which point a product is over or below average. This estimate measure for the error can be assessed as the difference between estimated and real values for the products in the family. When new products are added, they can contribute:

1. Decreasing the error, by making slight modifications to some parameters, and only slightly changing the environmental impact
2. Increasing the error:

- Because of a considerable environmental improvement, therefore raising the stakes for future products
- Because of a considerable increase in environmental impact, therefore lowering the stakes. This should only occur in cases where there is a justification for the poor environmental performance.

In order to be able to show color-coding in the CAD tool, one last final step has to be taken: the total environmental impact of the reference product must be allocated per part. In cases where parts have a common structure, this will be simple, since a standardization of the naming and terminology will serve this purpose. Otherwise, categories can be considered and this same allocation can be performed group wise instead of individually.

In this case, there is an additional dimension of information that is not present in other methods: time along the life cycle. That way, apart from the information shown in the color code, it will be necessary to show a bar chart with the different environmental impacts along the whole life cycle, see Figure 5.

The fore mentioned conditions (both regarding information and structure) will serve as a base to set the road-map for the development of the tool. The next section will present this road-map, as well as the lines of work that are being taken.

5 OUTLOOK

The preparatory study indicated that a CAD implementation of LCA is a promising approach for environmental evaluation of product concepts in early design stages.
Furthermore, it has shown that a key success factor for bringing LCA to early design stages is the way results of environmental evaluations are visualized. Design processes are complex itself, and conducting LCA is also a complex task. Merging these two processes by adding the right theory will lead to a successful integration of LCA into early product design stages.
Similar to FEA modules integrated in CAD, where some few parameters need to be specified to obtain visualized and understandable results of e.g. stresses, strains or displacements even for non FEA experts, any intended LCA implementation into CAD need to be easy and simple for application. This can be achieved by introducing a parametric description of LCA-families, where the specification of only few primary and secondary parameters by the user help to access all the secondary parameters, hence inventory data, needed to obtain the LCA estimations.
Analog to FEA, where the accuracy of the specified mesh and the solver used influence the accuracy of the results, in case of an integration of LCA into CAD the accuracy of the LCA-family and the specifications of the primary parameters will influence the accuracy of the LCA results estimations.
And similar to FEA, where a color scheme indicates different stress, strain or displacement magnitudes in a part or component, a similar color scheme can be used to visualize the environmental impacts of a part or component, either by showing the absolute impact or, as discussed in this paper, by comparing to a reference value of the LCA-family. Figure 5 illustrates how such visualization might look like.

Figure 5. Proposed visualization of environmental impacts in CAD

By doing so, it will be then possible to analyze products which are not only similar, as it was the case in the preparatory study, but also equivalent.
The authors' research activities will follow the following road map:
Milestone 1: Preparatory study and feasibility study
Milestone 2: Understanding scalability issues. Development of LCA-family theoretical background
Milestone 3: Development of scaling references – primary and secondary parameters
Milestone 4: Visualization of results and programming
Milestone 5: Embedding database and interface into CAD

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