Tool for the Environmental Assessment of Cranes Based on Parameterization

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Abstract

Information constitutes one of the main barriers for applying LCA, due to complexity and need for great amounts of it. However, most of the parameters that determine the data are defined early in the product development process. Knuckle-boom-cranes constitute a complex product, which poses a particularly pressing need for simplification. This paper models the LCA inventory information out of design parameters. The paper also presents a tool implementing this.

To develop the parametric model, a three step approach is followed. In the first step, knuckle-boom crane designers of an international manufacturer are asked to point out key design parameters. An LCA is then conducted for a representative crane of the same manufacturer. Interdependencies between design parameters and inventories are analyzed. Design parameters influencing the LCA results are defined as primary parameters. Parameters through which it is possible to calculate the LCA inventory are defined as secondary parameters. The relation between primary and secondary parameters is analyzed. Indicators are developed for comparison, and the validity of this parametric model is checked by analyzing six more cranes, different in size and performance.

Keywords: *Simplified LCA, Product modeling, Engineering Design, Ecodesign, Result visualization, Environmental performance indicator, Cranes*

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Background, aim and scope

With the rise of sustainability as a strategic aspect, environmental concerns are becoming a key issue in design (Hunkeler and Vanakari, 2000). Reducing the overall footprint of a product on the environment has gained popularity with names such as ecodesign, design for environment or design for sustainability among others (Coulter et al, 1995).

Environmental information is generally presumed to be necessary, to make sure that designers will focus on the most influencing aspects. Therefore, most ecodesign methodologies begin the process with such an assessment. Life Cycle Assessment (LCA) is one of the most widespread methods for this type of assessments (Jeswiet and Hauschild, 2005; Ernzer et al, 2001), and even in cases where it is not fully applied, its principles are generally considered (Ernzer and Birkhofer, 2003; Erzner and Wimmer, 2002).

Some barriers still withhold it from being common practice in industry (Millet et al, 2007), mainly data requirements and difficulty. This is substantiated by industrial feedback: LCA generally requires too much data which would be unknown or fuzzy, and is constantly subject to changes during early design stages.

LCA methodology is also generally time-consuming. This has motivated different efforts in the direction of simplifying or accelerating the process. ISO (2006) points out a percentage of representativity under which materials or processes can be disregarded. The use of databases, such as those provided by Ecoinvent (Frichknecht et al, 2007), shortens the time needed to get to a preliminary result. Other efforts have been carried out in order to ease information reuse, steps in the analysis or information collection. Wimmer and Züst (2003) present rules to select whether a component can be left unanalyzed. Ostad Ahmad Ghorabi et al (2008) parameterizes the product to extrapolate results for similar products. Sousa and Wallace (2006) and Sousa et al (2008) aim at creating groups, for which a neural network can be trained to give LCA results.

Some tools aim at integrating databases with quick assessments tools, in order to facilitate the process for the end user. Goedkoop and Spriensma (2001) develop an assessment method, that is complemented with a list of standard materials and processes and their assessment through that method. The tool Greenfly Online (Horne et al, 2009) provides a platform for these assessments, focusing on the intuitiveness of the process.

Since the early stages have the greatest potential for improvement, many authors have concentrated in bringing the environmental assessment to this point (Ostad Ahmad Ghorabi et al, 2006; Bhamra et al, 1999). One of the main problematic that they have faced is the lack of information about the product before the product is developed, presented by Lindahl (2005) as the design paradox. Luttropp and Lagerstedt (2006) present ten rules to be applied in those early stages, as a way of dealing with this paradox.

One approach is to limit the amount of parameters that are tracked. That is the philosophy behind approaches like such of Singhal et al (2004), in which Key Environmental Performance Indicators (KEPI) are defined for a particular product group, and used as a guidance on the environmental friendliness of the product. These KEPI can can cut the costs and time to produce an LCA assessment in 90% or more (Pennington et al, 2007).

Most of the presented tools or approaches deal with environmental assessment in a generic way, aiming at developing a tool that will be valid for any sort of environmental assessment. However, through commonalities between similar products, new designs have the chance of reusing design information from previous models. Most products that are brought to the market are not designed from scratch, but actually constitute redesigns and improvements of previous products. For that matter, this paper will analyze one specific type of product, to come up with a specific tool to give information to designers out of the information that they handle in the early stages of their redesigns.

This paper presents for the first time an LCA-based tool for cranes that faces those problems. The data was collected during several studies for an international crane manufacturer. Seven different crane models were considered for its development. The crane typology considered is knuckle-boom cranes. A generic model was generated to parameterize the LCA process out of parameters that are known during the initial definition of the product. A total of thirteen parameters suffice to establish the environmental profile of any new crane of this type (Ostad-Ahmad-Ghorabi, 2010). The time reduction attained makes it possible to include LCA in these early stages, since the workload is considerably reduced in comparison to a conventional LCA and the information is readily available. The robustness of the results is studied in this paper.

Additionally, three generic performance indicators are also presented, to make the results more visual and easy to interpret. The indicators are based on previous products, so that the user can compare the performance of the new crane to previous ones. The whole package was integrated in a computer tool to be used by the industrial partner.

Materials and methods

The purpose of the paper is to come up with a way of assisting in the environmental assessment of design decisions, without the need of a final product. In particular, knuckle-boom cranes of an international crane manufacturer are selected as object of the study. There are three elements to be developed:

1. Development of a parametric model to describe the LCA results out of a reduced set of parameters that are known in the early design stages.
2. Calculation of indicators to assess the environmental and technical performance of the crane, so that cranes of different sizes are comparable.
3. Implementation of the previous concept in a software tool.

Once all three are developed, six more knuckle-boom cranes from the same manufacturer are assessed, both out of primary parameters, and completely. The variations between both cases are assessed and discussed.

To set up the parametric model, following three steps were taken:

- *Step 1:* Analysis of the design process and derivation of key design parameters for cranes.
- *Step 2:* Conduction of a full LCA of a crane, to understand the inventories of this crane and other cranes of the same typology.
- *Step 3:* Determination of the interdependencies of design parameters and inventory data.

In step 1, designers were asked to provide insight and data of how a crane is designed and developed. They were inquired about the most important design parameters that are defined in the very early conceptual design stages. These parameters are defined as primary parameters.

In step 2, a representative crane type from the company was selected for environmental evaluation. A full LCA was conducted, and the necessary input/output data were collected consulting the manufacturing company, suppliers and customer. To model the life cycle of the crane, the key design parameters were pointed out.

To be able to assess the crane, following information of the life cycle has to be known:

- Raw materials stage: weight of the materials used.
- Manufacture stage: manufacturing processes and their quantities.
- Distribution stage: packaging used, transport modes.
- Use stage: energy use of the crane to fulfill its performance.
- End of life stage: end of life treatment scenarios.

In step 3, all the interdependencies of parameters were studied. Most input/output data – and through it inventory data – can be linked to a more reduced set of parameters, through which they can be calculated by different models or databases. Firstly, all input/output data are listed to group those that are the same. Then, the relations between all the remaining parameters are compared pairwise. For each group of relations, a common a parameter is selected. Such parameters are defined as secondary parameters, and the data in the LCA inventory can be described through them. Those not directly linked with other input/output data constitute a secondary parameter of their own. An example of this could be the amount of fuel used during the lifetime (aggregated from the crane's operation, transportation and transportation of its body), which can be linked to the CO_2 or NO_x emissions in the inventory.

The relation between these secondary parameters and the primary parameters was studied. As was specified in Step 1, primary parameters are not defined by the LCA information but rather out of what information is available in the early stages. Secondary parameters, to the contrary, are derived directly out of information needed for LCA. The links between the two can be derived from:

- Guidelines such as the dimensioning of the body for crane mounting, where the required dimension follows from body-building instruction (Volvo, 1993) in which the lifting moment is the only input parameter.

- Physical interdependencies such as the different efficiency factors in order to calculate the necessary power needed for the hydraulic pump.

- Statistical data such as the scrap in each of the manufacturing sites.

For those secondary parameters that were not represented in – or possible to be calculated from – the current primary parameters, new primary parameters were added to the list. These parameters were assessed by the designers from Step 1 to ensure that they would also be available in early design stages.

Results

The most important primary parameter of the crane is the maximum lifting moment, which is specified by the customer at the beginning of the project. The second key performance parameter is the crane's weight, which is optimized (i.e. minimized) by the manufacturer. For a given power supply, any additional dead-weight of the crane will reduce the effective load it can lift. Being mainly made of steel, differences in material composition come from advanced use of alloys. From the preliminary definition of the design parameters, Product Design Specifications (PDS) are successively developed and all attributes of the crane are documented.

Manufacturing of the cranes follows a common pattern through the different manufacturing sites, distributed among European countries. Components are passed from one site to the other for painting, pre-assembly or final assembly. At this point it is possible to list the set of primary parameters presented in Table 1.

Table 1 Primary and secondary parameters used for the crane model

Life cycle	Primary	Provided by	Secondary
General	Maximum lifting moment	Crane manufacturer	Weight of body, fuel consumption of truck for carrying body, fuel consumption for the operation of the crane
Raw materials	Total weight of crane	Crane manufacturer	Fuel consumption of truck for carrying crane
	Estimated weight distribution of each component	Crane manufacturer	Total weight of crane, end of life treatment, occurring scraps, treatment of scrap during manufacture, fuel consumption of truck for carrying crane, assessment of used materials
Manufacture	Manufacturing site	Crane manufacturer	Scrap, transportation distance, consumption of electricity, natural gas, diesel and water; manufacturing processes
Distribution	Weight of packaging	Crane manufacturer	Total weight of the crane including packaging, distribution processes
Use	Type of pump, flow rate	Pump supplier	Volumetric losses in the pump, fuel consumption for the operation of the crane
	Operating pressure of the pump	Pump supplier	Volumetric efficiency factor, total efficiency factor
	Swept volume of engine	Data-sheets of truck engine, crane operator	Pressure in cylinder of truck engine, specific fuel consumption
	Specific fuel consumption	Data-sheets of truck engine	Fuel consumption of truck engine during crane operation
	Gear transmission ratio and amount of gear stages	Crane customers	Revolution per minute of truck engine, power losses due to gear transmission, power needed from the truck engine, specific fuel consumption
	Operating time of the crane over its lifetime	Crane operator	Fuel consumption of the crane over its lifetime
	Volume of oil tank	Crane manufacturer	Necessary amount of hydraulic oil over the lifetime of the crane, assessment of maintenance
End of life	Location of end of life treatment	Crane operators	Electricity mix for end of life treatment, related environmental impacts

When developing the LCA in step 2, some scenarios need to be decided. In other cases, the input/output data will depend on external factors, e.g. the installation of a variable or fixed displacement hydraulic pump. Although the manufacturer recommends the use of variable displacement pumps – it increases energy efficiency – the final decision depends on the customer and on economic considerations.

The secondary parameters are obtained from the LCA model. The calculations followed internally by the LCA are recorded for the crane, since they are the link between the secondary parameters and the inventory. The relations between primary and secondary parameters are also shown in Table 1, as well as their origin. Most information comes from the crane manufacturer in the early stages, although some new primary parameters were added, which need to be provided by the suppliers and the crane operators.

Table 2 shows the nature of the links between each primary and secondary parameter. Additional per-part weight distribution needs to be estimated by the designers as primary parameter, although this proved not to be a problem during the testing of the tool. Process and material information can be later retrieved as secondary parameter by input/output balances from the manufacturing sites.

Table 2 Relations between primary and secondary parameters. Sources of information represented by P: Physical calculations; S: Measurements and statistical processing; G: Guidelines and other documentation

Secondary parameter	Source	Primary parameter depended
Weight of body	G	Maximum lifting moment
Fuel consumption of truck for carrying body	S P	Maximum lifting moment
Fuel consumption for the operation of the crane	P	Maximum lifting moment, total weight of crane, type of pump, flow rate
Fuel consumption of truck for carrying crane	S P	Maximum lifting moment, total weight of crane, type of pump, flow rate
Total weight of crane	S	Estimated weight distribution of each component
End of life treatment	S G	Estimated weight distribution of each component
Occurring scraps	S	Estimated weight distribution of each component
Treatment of scrap during manufacture	S	Estimated weight distribution of each component
Assessment of used materials	G	Estimated weight distribution of each component
Scrap	S	Manufacturing site
Transportation distance between sites	S	Manufacturing site
Consumption of electricity, natural gas, diesel, water	S	Manufacturing site
Manufacturing processes	S	Manufacturing site
Total weight of the crane including packaging	P G	Weight of packaging
Distribution processes	S	Weight of packaging
Volumetric losses in the pump	G P	Type of pump, flow rate
Volumetric efficiency factor	P	Type of pump, flow rate
Total efficiency factor	P	Type of pump, flow rate
Pressure in cylinder of truck engine	G P	Swept volume of engine
Specific fuel consumption	G P	Swept volume of engine, gear transmission ratio and amount of gear stages
Fuel consumption of truck engine during crane operation	G P	Specific fuel consumption
Adjusted revolution per minute of truck engine during crane operation	D	Gear transmission ratio
Power losses due to gear transmission	G P	Amount of gear stages
Power needed from truck engine	P	Gear transmission ratio and amount of gears
Fuel consumption of the crane over its lifetime	S P	Operating time of the crane over its lifetime
Necessary amount of hydraulic oil over the lifetime of the crane	P	Volume of oil tank
Assessment of maintenance	G	Volume of oil tank
Electricity mix for end of life treatment	S	Location of end of life treatment
End of life related environmental impacts	G	Location of end of life treatment

Comparative indicators – to assess the crane in comparison to others – need to be relative, since ISO (2006) only allows for comparison of identical functional units. Since each crane is different in size and mechanical performance, indicators in Equation 1 can be used (Ostad-Ahmad-Ghorabi, 2010; Ostad-Ahmad-Ghorabi and Collado-Ruiz, 2009) for each crane i, being the product's weight expressed in kg, the maximum lifting moment in mt (meter-tons) and the environmental impact in MJ, measured by the Cumulative Energy Demand (CED) method. The same process could be followed with any other impact category, or even a combination of them. CED was selected because it gives an aggregated value that is found convenient for decisions during the design process.

$$
\begin{aligned}
&I_1^i = \textit{Maximum Lifting Moment} \,/\, \textit{Weight}_{\textit{Crane or part}} && \text{Unit: mt / kg} \\
&I_2^i = \textit{Weight}_{\textit{Crane or part}} \,/\, \textit{Total Environmental Impact} && \text{Unit: kg / MJ} \\
&I_3^i = I_1^i \times I_2^i && \\
&I_3^i = \textit{Maximum Lifting Moment} \,/\, \textit{Total Environmental Impact} && \text{Unit: mt / MJ}
\end{aligned}
\qquad (1)
$$

I_1^i represents the per-kilogram efficiency, and it constitutes an important value for dimensioning. I_2^i is the amount of material present per unit of environmental impact. I_3^i constitutes a measurement of the product's eco-efficiency. When a group of cranes are available, these values can be normalized for a simpler interpretation, through the ratio between each I_i and I_{max}, being I_{max} the maximum value in the database for each I efficiency. Equation 2 presents these normalized values.

$$
\begin{aligned}
I_1^{'I} &= I_1^i / I_1^{max} \\
I_2^{'I} &= I_2^i / I_2^{max} \\
I_3^{'I} &= I_3^i / I_3^{max}
\end{aligned}
\qquad (2)
$$

The dimensionless range]0;1[indicates that the new product is performing worse than the best case up to now. For the case of $I_i^{'} = 1$ the new concept is as good as the best case. $I_i^{'} > 1$ constitutes an improvement. To visualize and categorize $I_i^{'}$, ranges and a simple color coding was developed in accordance with the crane manufacturer:

- A red indicator is given to values less than 0.6. That means that the current efficiency is lower than a 60% of the best case, which is insufficient. This indicates that the design 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. Efficiency is lower than 90% of the best case, which leaves still much room for improvement.

- A green indicator is given to values greater than 0.9. At least 90% of the efficiency of the best model is reached. In case of being over 1.0, the new product is better than the best product in the database, i.e. it constitutes an environmental improvement.

The parametric model, including the indicators, was implemented in a computer tool. Designers input the primary parameters as in Figure 1, and the tool shows an assessment of the crane's environmental impact as-is. Then designers can modify weight, material or process properties, to further detail the model of the crane. Figure 2 shows the tool's output screen. Additionally, the computer assesses the relative efficiency indicators (*I_1, I_2 and I_3*) through their value and color code.

Figure 1. Screenshot of the input parameters in the implemented tool

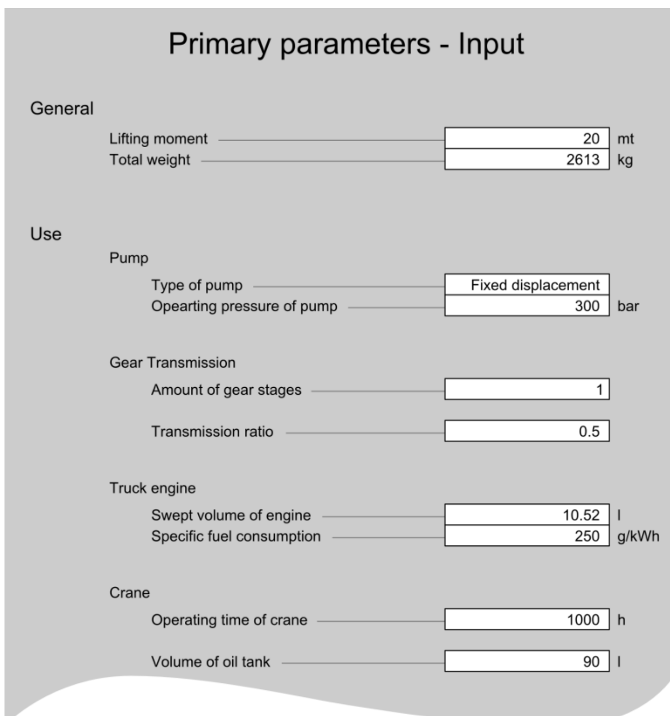
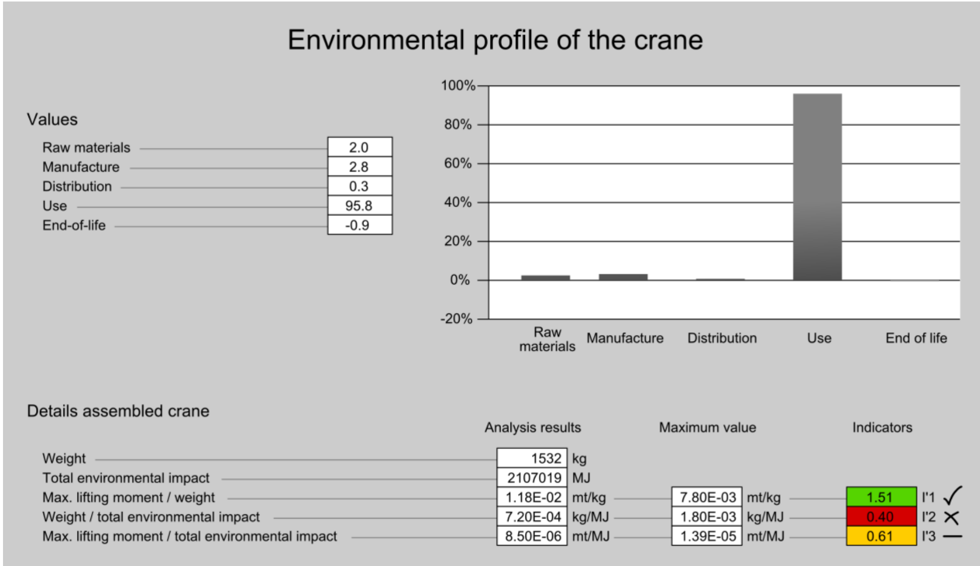


Figure 2. Screenshot of the output: the environmental profile and the results for the final crane



To study the robustness of the parameters listed in Table 1 for knuckle-boom cranes, six more cranes from the same typology – varying in size and performance – were analyzed. Data were collected for all these cranes and the interdependencies of primary and secondary parameters were checked to be valid for all six cranes. The environmental impact was assessed both through the model directly, and through the newly gathered inventory, i.e. with additional secondary parameters. Table 3 shows these results. It can be seen that there is no more than a 4% deviation (indicated as E.I.Dev. on the Table) between the proposed model and the complete LCA in the worst case scenario.

Table 3 Comparison of the models out of only primary parameters, and those calculated by adding more specific secondary parameters available later in the design process

Model		Primary only				Detailed secondary				E.I.Dev.
Name	*mt*	E.I. (GJ)	I_1	I_2	I_3	E.I. (GJ)	I_1	I_2	I_3	%
Crane 1	5.4	1195	0.0068	6.6E-7	4.5E-9	1215	0.0068	6.5E-7	4.4E-9	1.67
Crane 2	10.7	1965	0.0064	8.5E-7	5.4E-9	2007	0.0064	8.3E-7	5.3E-9	2.09
Crane 3	16.7	2573	0.0069	9.4E-7	6.5E-9	2637	0.0069	9.2E-7	6.3E-9	2.46
Crane 4	20	2801	0.0078	9.1E-7	7.1E-9	2870	0.0078	8.9E-7	6.9E-9	2.42
Crane 5	31	3862	0.0072	1.1E-6	8.0E-9	3987	0.0072	1.1E-6	7.7E-9	3.13
Crane 6	78	5390	0.0104	1.4E-6	1.4E-8	5614	0.0104	1.3E-6	1.4E-8	3.99

Discussion

The final parametric model reached in Section 3 contains thirteen primary parameters through which the complete LCA inventory is modeled. Table 3 includes the assessment of 6 cranes through the model and through a much larger and detailed set of secondary parameters. Deviation is in all cases under 4%, showing that the model developed for the cranes behaves close enough to a full LCA, with less than a 5% deviation (ISO, 2006).

Changes in the basic working principles of the crane – or radical innovation – could naturally render these results obsolete. Nevertheless, it has been seen that for different crane models from the last years the parametric model is robust enough to fit with ISO standards. Another element of discussion is the suitability of the primary parameters from the user point of view. As was anticipated in section 2, some additional primary parameters were included in the model once the LCA was conducted. Examples of these are operating time, type of pump or truck engine, which are specified by the customer. Information about this needs to be retrieved in order to carry out an assessment. Additionally, per-part weight allocation must be performed by the design team.

The time required for sourcing these additional parameters is the only time burden to conduct an LCA in the early stages. Although this is considerably less than a full LCA, this topic was considered important enough to be discussed with the design team for their assessment. In their eyes, the fact of deciding only on thirteen parameters was seen as a greater time-saving improvement than the additional workload of anticipating this data. In any case, this data was regarded as easy to gather, and normally already available or possible to estimate in the early conceptual stages.

Implementation in a software tool was also positively perceived, most particularly regarding the indicators and their visualization. Color coding was appreciated by the engineers of the industrial partner. The indicators contributed to the decision-making process, by giving feedback on very early design decisions, up to the point of affecting the initial PDS. This very initial assessment sometimes has a variation as the crane is further developed, but in general terms the first assessment is representative of the final crane.

The tool is able to compare with previous data. This requires a particular database to be set in place, having design data, inventory data and indicator values for all cranes. Management of this information should include updating the different values of I_{max} when new cranes are added.

Two main assumptions guided the process, i.e. the similitude between products in the same product family and the availability of common data within the family. The first can be controlled in any case with a coherent definition of such families. The authors have already developed some work in this direction as to suitability of products for comparison and scaling of data (Colladо-Ruiz and Ostad-Ahmad-Ghorabi, 2010a). Due to the second assumption, the model is only applicable to the product family of the industrial partner in particular. Even with the general applicability of the conclusions, the model should be slightly modified from manufacturer to manufacturer. The authors have also carried out some work on the shared parameters between groups of products in broader terms (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010b).

Recommendations and perspectives

The parametric model in this paper acts as an interface between the engineering designer and the LCA process, most specifically during the early design stages. One of the greatest potentials of the tool presented here is the possibility of working with preliminary information, and further detail the model if there are considerable changes. This has been applied to those processes and materials for which the relations are known. Further development of the tool can include statistical estimations of how cranes are normally developed, to avoid introducing some of those parameters, and to make these automatic estimations even more productive.

Although appreciated by the industrial partner, what this paper presents constitutes a tool that is additional to all those already used in the design process. This may be a source of overwork and a burden to its application. For an efficient implementation, the model should be brought into the software environments already used by engineering designers, i.e. CAD systems (Ostad-Ahmad-Ghorabi and Collado-Ruiz, 2009). Analogously to Finite Element Analysis modules, ecodesign modules should be integrated in a usable way in CAD and Product Data Management (PDM), and results visualized in a seamless manner. This would open the possibility of further integration and detailing when the geometry of the model is available, compatible with approaches such as those of Leibrecht (2005) or Roche et al (2001).

This paper presents a sector-specific parameterization that makes environmental assessment at early stages possible. The same philosophy can be replicated in other specific sectors or for other product families. Nevertheless, there is still research to be carried out in order to generalize the conclusions. Models can be adapted to other sectors, and this should be a step in the integration of environmental assessment in the product development process.

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