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ENVIRONMENTAL EVALUATION FROM CRADLE TO GRAVE WITH CAD-INTEGRATED LCA TOOLS

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ABSTRACT: *Robust product environmental evaluation has to consider the whole lifecycle, called "cradle to grave" analysis. This activity gives wide benefits if carried out in the early design phases. CAD-SLCA integrated systems are innovative eco-design tools usable during product design feature definition in order to support SLCA (Simplified Life Cycle Assessment) method application. The present work describes how the CAD-SLCA approach can be put in practice by considering the assessment of the complete product lifecycle and by using a new software tool which integrates data from different design supporting systems. Particular focus has been placed on the use phase and end of life treatment. An example shows the approach results.*
KEYWORDS: *SLCA, Ecodesign, CAD, Environment*

INTRODUCTION

Human sensibility and market strategies are promoting more and more the environmental aspect that explains why eco-design is becoming an important and useful topic in engineering design. Life Cycle Assessment (LCA) is an environmental accounting and management approach which considers all aspects of resource use and environmental releases associated with an industrial system "from cradle to grave". Specifically it is a method to assess the environmental impact of a product during its lifecycle, from the extraction of raw materials to the production and distribution of energy through the use, reuse, recycling and final disposal of a product. LCA as it is conceived, is a tool for relative comparison and not for absolute evaluation, thereby it can be used as decision makers to compare all major environmental impacts in the choice of alternative courses of action [1]. The core phase of an LCA analysis is the Life Cycle Inventory compilation that regards the identification of all input and output flows concurring in the product lifecycle. This phase is both time and resource consuming and for this reason complete LCA can be carried out mainly to assess the environmental impact of an existing product, where manufacturing, use and dismantling can be estimated with accuracy.

Simplified Life Cycle Assessment (SLCA) approaches were developed to improve LCA usability in the early design stages. They adopt dedicated tools to estimate the environmental impacts of product alternatives and to predict environmental costs or burdens for manufacturers [2]. A large number of simplified LCA methods has been developed to overcome this drawback and make it possible to perform and be used more easily. Many of these methods have been developed for a specific group of products and are not well documented. In the engineering design phase it is not easy to perform an environmental consideration for the complete life cycle when not all product data is available and fixed. Therefore, it is important to evaluate simplified methods and to study what type of information they require and what kind of results they can produce. New emerging Computer Aided Design (CAD) tools are trying to support the integration of SLCA methods within the traditional flow of product design activities. Their scope is to provide a concurrent analysis of product design solutions from a functional and environmental point of view. Such technologies can be called CAD-SLCA. Different solution are available in the market developed by the major CAD software house, however, even if the approach can be considered valid, it still requires wide improvements from a performance point of view.

In this work a method to conduct environmental analyses in the design phase, by CAD interface, is presented and discussed. The proposed approach has been developed looking at mechanical product design field. A simplified LCA not only has to be simple and easy to use but it also has to come up with reliable results. Through the analysis of priorities the best compromise between the CAD-based information and the LCA analysis accuracy has been evaluated. Thus it has been possible to define a CAD-SLCA tool able to propose meaningful results without weigh product design time. In order to demonstrate validity and advantages of this approach a significant case study has been analysed.

BACKGROUND

In this paper the attention is focused on the Life Cycle Assessment Simplification method (SLCA) and Computer-Aided LCA. Eco-design tools help the designer evaluate environmental aspects during the product design phase. A lot of research and tools *regarding the eco-design topics have been developed since environmental interest in the product engineering has become so widespread. The literature review of these approaches shows that many existing tools fail because they do not focus on design, but they aim at strategic management or retrospective analysis of existing products instead [3].*

The research developed in the eco-design context is based on different techniques and characterized by different levels of difficulty related to their implementation [4]. These approaches vary from simple checklists and guidelines as presented in Wimmer et al. and Stevels' works [5,6], to complex methodologies, which require the designer to have a high level of personal knowledge in order to apply them correctly.

Currently, many proposed approaches represent an "ecological" extension of traditional and well known design methods. This is the case of the different environmental versions of the Quality Function Deployment (QFD) [7], such as the quality function deployment for the environment proposed by Masui et al. [8] and the green QFD proposed by Zhang et al. [9]. An extension of the functional analysis method, which takes product life-cycle aspects during the design stages into consideration, was presented by Prudhomme et al. [10]. The use of these tools and methods unfortunately shows a lack of coordination in the design activities, as a consequence these obstacles putting the indications provided by eco-design tools into practice. An important crucial defect is that it is not often evident how to perform the comparative evaluation of the environmental impact of alternative eco-design solutions. CAD-integrated LCA tools can be useful and integrated within the day-by-day design activity, and they can help designers evaluate environmental impact of a product under investigation and compare the different solutions.

LCA methodology represents an assessment and comparison tool generally used for existing products. Many researchers have proposed to use and apply it as eco-design method [11]. In recent years, many efforts have focused on the development of SLCA methods. The main goal of SLCA is to reduce the complexity of several of the tasks involved, while maintaining the main features and soundness of a complete LCA. Such simplified methods can be employed in the early design stages of a product development, when the data available is incomplete and lacking in details. Perhaps it should be underlined that a complete LCA can only be correctly used for completely defined products and services. It means that products and services and their components, materials and processes are precisely defined before the assessment. Among all the different simplification methods proposed, most of them are related in some way to the reduction of the amount of data required to perform the analysis. This data reduction is usually achieved by excluding some life cycle stages in the assessment as reported by Hochschorner et al. and Hur et al [12, 13]. Despite the soundness of the their application in the design process as a tool of comparison for different design solutions is still a matter of debate.

A complementary approach, aimed to reduce the complexity and to automate the compilation of the life cycle inventory required to perform LCA, is represented by the integration of LCA tools with product life cycle management (PLM) systems [14-18]. A PLM system is an Information Technology (IT) platform, which aims to store and manage technical and administrative data related to the life cycle of the goods produced or services provided [19,20]. Technically, a PLM system is based on a central database, enabling integration of data produced by the different IT systems used by the different departments within the enterprise. Some examples of IT systems are: computer-aided design, manufacturing and engineering systems (CAD, CAM, CAE), material requirement planning, advanced production, manufacturing execution, enterprise resource planning systems (MRP, APS, MES, ERP), supply chain management and customer relationship management systems (SCM, CRM). In the market some CAD-LCA integrated approaches are already available. They makes it possible to evaluate the product being designed from an environmental impact point of view. Therefore it is possible to compare different design solutions concerning the material and the transformation process selection. This integrated approach seems to be functional but inaccurate and incomplete in some aspects. The main above mentioned tools have been developed by the major CAD software house like SolidWorks with the "Sustainability" module or Autodesk with the "Eco Materials Adviser" tool. In our previous work [21] a comparative analysis and critical evaluation of SolidWorks Sustainability tool has been done, this research shows the validity of the method but highlight the lack in results accuracy due to the simplifications of the method employed. The Autodesk Ecodesign tool is intended to give designers an immediate analysis of the ecological impact of a product, key eco indicators allow the designer to explore the impact of changes in material choice or design of the product. This tool offers a really advanced and complete approach for the material selection and evaluation, but it does not consider the manufacturing process and the product use phase. This is a simplification, in fact much of the environmental impact is attributed to the manufacturing and use phases.

PROPOSED APPROACH

The proposed approach aims to develop a SLCA tool which can be used in the product design stage, in particular the approach is focused on the industrial mechanical products. The main goals of this approach are: the acceptable accuracy of LCA indicator values, the user friendliness and, finally, the rapid visualization of LCA results at early design stages.

SYSTEM ARCHITECTURE

Figure 1 shows the system framework of the proposed CAD-SLCA integrated tool. The arrows connecting the different modules represent the flow data exchange which can be managed and modified by a dedicated user interface which allows interaction with CAD and LCA systems. Product geometrical and non-geometrical data can be retrieved from the CAD structure and the connected PLM database.

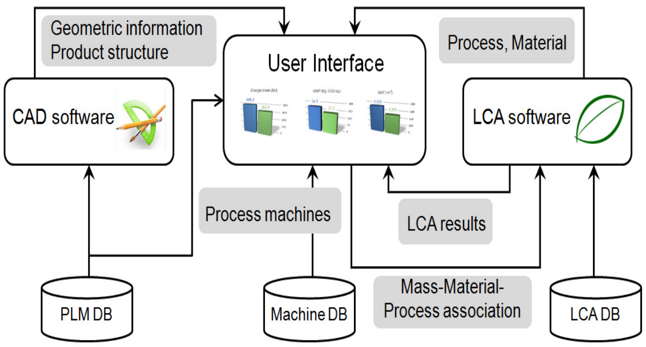

Figure 1. Proposed CAD-SLCA integration approach framework

The geometrical CAD model implicitly contains different data about the component, referred to its shape and dimensions. These values are useful to determine the production process characteristics. The data can be extracted from the CAD software by analysing the model data structure by the use of a specific tool based on the Application Protocol Interface of CAD system. In this case the application has been developed in Microsoft .NET. The user has to select the manufacturing processes, component materials, other processes involved in the use phase and, finally, the end of life treatment for the component. All information can be chosen from the LCA database, where processes are divided into sub-categories according to the different product life cycle phases (raw material extraction, manufacturing process, utilization, end of life).

The user interface allows the connection with the machine database. It contains all data (energy consumption, utilization range, manufacturing process type, etc) of the different machines available in the company. According to the selected manufacturing process, a list of machines is shown and the system proposes the most suitable by using decisional rules related to the specific geometrical product data. An important feature of the proposed approach is the possibility to modify the manufacturing processes selected from LCA database with the selected machine information (e.g. energy consumption). Therefore real process data can be computed. All the information from CAD and LCA software can be merged by the user and a "mass-material-process" link is created and sent back to LCA software to calculate the environmental impact of the product. For each component, designers can select more than one process for each phase in order to recreate the complete life cycle. The Results are automatically presented in the user interface as data and graphs, allowing a rapid comparison between different solutions to be made.

APPROACH IMPLEMENTATION

The proposed approach covers the whole product life cycle from the raw material extraction to the end of life treatment, through the manufacturing and use phase. In the following parts, the approach divided in its principal life cycle phases is explained, divided by the principal life cycle phases: Manufacturing, Transport, Use and End of life (EOL).

Manufacturing Phase

The manufacturing phase includes the material selection and the production processes used to transform the starting stock material in the finished product. A research for this topic has been carried out in [21], where the commercial available CAD-SLCA integrated tools have been evaluated. The considerations arisen from this comparison led to propose a better approach for the environmental analysis of the manufacturing phase. The manufacturing process distinguishes different types of mechanical components according to the manufacturing processes which they undergo. The main product components used in mechanics can be classified in three families, according to the manufacturing process: moulded components; machined components, and sheet metal components. These types of families and the related manufacturing parameters have been analyzed in order to reach the right compromise between LCA result accuracy and easy as well as rapid product data retrieval. Through the analysis of different manufacturing process characteristics, a list of parameters has been determined for each family. The main parameters related to the moulded family part are: material type, amount of scrap, percentage of recyclable scrap and the type of machine used. In the case of machined family part the parameters to be considered are: material type, starting stock material, the main machining processes, amount of scrap and the type of machines used. Finally, the parameters for sheet metal family part are: type of material, the starting *dimension of sheet metal, amount of scrap, the type of machines used and the quantity of scrap which can be recycled. The proposed approach for the manufacturing phase allows the entire production cycle to be considered, by taking into account all the processes employed and the real machine data used for the specific case, selected by the user from the machine database. This database contains all the data for the input and output flow of the machines available in the considered enterprise.*

Transport Phase

The product is generally featured by different components, each of them can be manufactured in the same factory where the product is assembled or can be made outside by a different company. Whilst in the first case there are no transportation for the components, in the case that they are manufactured by another company, each component can have one or more transport types with a specific distance. The proposed approach takes into account the transport phase and it gives the possibility to select and assign one or more transport type for each component by the Transport tab in the Component form.

Use Phase

In the LCA analysis the use phase represents an important aspect and sometimes it is the most relevant contribution to the environmental impact of a product. This phase includes both the use of the finished product and the use of each single component. The quantities and the processes included in this phase regard all that can be attributed to the use of the product. The proposed approach for the use phase is based on the selection of different usage processes for the product and of its single component. It is possible to select from the LCA software database and assign all the processes concerning the use phase to the product or to each component. Another important and relevant aspect of the Use phase is the degradation of the components and their subsequent substitution or maintenance. It is essential that this issue is considered in the LCA analysis because the component replacement and repair have a relevant contribution to the environmental impact, in fact a component replacement corresponds to the consideration and computation of two or more of them. Thanks to this tool are possible to analyze the complete product lifecycle, Manufacturing, Use and End of Life phases can be evaluated. The user can select and assign a usage process for the product. This selection can be multiple, so different processes for the Use phase can be selected, for example electrical power consumption, other consumption material like lubrification oil, water, compressed air and others. Usage processes can also be assigned to component level, each component can have multiple and different processes. The choices for the components are shown in a summary table, and the user can also modify these selections. The last table shows the life time period for each component of the product (LfpC), and automatically calculate the number of component (NC) used during the product life time period (LfpP).

Depending on the life time period of product and components, different number of units for each part are computed in the environmental analysis, this allows the maintenance and replacement phases to be considered. Currently present commercial CAD-LCA integrated tools available in the market just allow the power consumption to be considered. By the use of these tools, the environmental impact for the Use phase is extremely simplified and it does not represent the real product scenario, therefore the evaluation error can be significant.

End of life Phase

Product End of life (EOL) phase refers to the end of the function period of the product, when its use is no more useful or possible and its functions are no longer carried out. Depending on the EOL treatment, not only changes the environmental impact of EOL phase changes, but also the impact attributed to the others lifecycle component phases. In Gehin et al. work [22] the EOL reflection to the lifecycle environmental impact is studied and calculated. For example, if the component i is recycled in a closed-loop system (it is assumed that the recycled material is used to manufacture the same type of components) or remanufactured, or reused, then for each usage cycle between 2 and the number of usage cycle (ui) and for the percentage of recovered product, the material stage impact is set to zero. If the component i is remanufactured, or reused, then for each usage cycle between 2 and ui and for the percentage of recovered product, the manufacturing impact is set to zero. The environmental impact attributed to each lifecycle phase can be calculated depending on the EOL choices, in the mentioned research paper [22] the complete treatment is described and explained.

The proposed approach provides to select the EOL treatment for each component (Figure 2), the user can choose it and input the relative information to be computed in the LCA analysis. Different scenarios can be considered in the EOL phase: Reuse, Recycling, Remanufacturing, Other treatment (Disposal, Incineration, Landfill, etc...). In the Reuse case, the reuse times can be specified for the calculation of the environmental impact, a component can be reused more times during the product lifetime period, after that the component cannot be used anymore and recycle, remanufacturing or other treatment can be selected. For the Recycle case, the user can select "Closed loop" or "Generic recycle" as recycle types, in the first case the material is reused for the same component production, in the other case the material is used for other applications. The Remanufacturing treatment can be selected and considered in the analysis specifying the environmental impact of the remanufacturing phase, expressed in percentage of the manufacturing impact. A component can be remanufactured for specified times, the main reason is the material degradation, after that it can be recycled to produce new material or may undergo other treatments such as Incineration, Landfill and others. The last choice which can be selected is "Other treatment", in the following tab an EOL process can be selected from the LCA database. Some processes which can be found in this option are Incineration, Landfill, Municipal waste, etc..., despite the user interface these processes can be selected and removed by specific buttons.

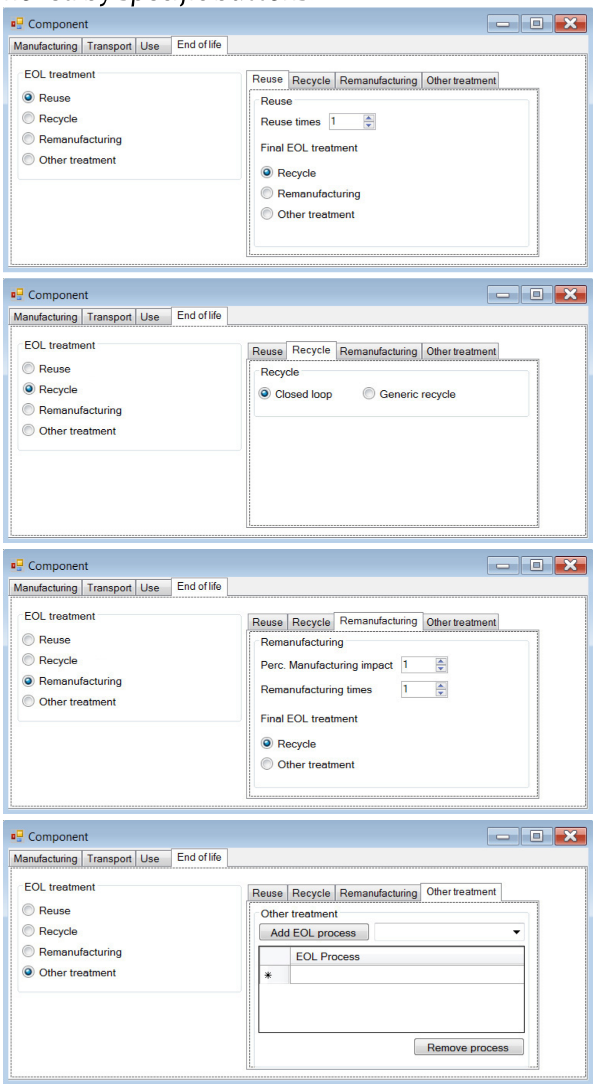

Figure 2 – Screenshot for the Component End of life phase

An EOL treatment can also be assigned to the product, in this case the same treatment is automatically computed in the analysis for all the components which characterizes it. Alternatively it is possible to specify the EOL treatment for the components which have a different EOL process compared to the product. In the next paragraph both the Use and EOL phase are illustrated and explained through a significant test case.

APPROACH VALIDATION AND DISCUSSION

The proposed approach has been validated and discussed through a case study. In this paragraph the LCA analysis is described and the choices made are illustrated and motivated. A simple comparison of different EOL treatments has been evaluated to demonstrate the opportunities offered by this approach.

EXPERIMENTAL CASE STUDY

The test case is a washing machine, analyzed from an environmental point of view. The LCA analysis has been conducted for the complete lifecycle, but only the Use and End of Life phase are examined and explained.

The overall LCA results have been obtained by analyzing the product lifecycle phases: manufacturing, use and End of life. The work focuses on the product Use phase and End of Life strategies.

Use phase

The lifetime period considered for a washing machine is 6 years; the data considered in the analysis are: energy, water and detergent consumption and component maintenance. In the Use phase not only have to be considered the consumptions, but also the product maintenance has to be evaluated. During the product lifetime, as for other products, it may happen that some of its components must be replaced as a result of their failure or breakage. In this case in the LCA analysis, the replaced components have to be computed. In the proposed approach it is possible to specify the lifetime of each component and through the product lifetime, the number of replaced components is automatically calculated. The processes selected for the product use phase are: Water (103.500 lt), Electricity (1866 kW), Washing detergent (186 kg), this data has been taken from a washing machine technical report (Use phase data of a washing machine, ENEA). The components which have to be replaced considering both their lifetime and the product lifetime are: hydraulic pump, electrical resistance, door seal, elastic belt, pressure valve, drain pipe group.

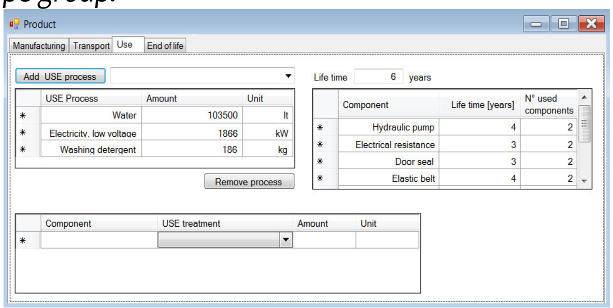

Figure 3 – Screenshot for the Product Use phase End of life phase

For the End of life phase the EOL treatment for each component has been considered. According to the proposed method, the EOL tab included in the component form (Figure 2) has been compiled with the corresponding data. In this paragraph the EOL treatments for each component are not shown. In Table 1 a summary overview of the EOL treatment for the components is shown.

Table 1 – Summary EOL treatment overview

Components	EOL	Components	EOL
Aluminum	Recycled	Steel and	Recycled
Plastics	Recycled	Electronic	Disposal
Rubber	Recycled	Concrete	Disposal

From the table it is possible to see that most of the components of the washing machine are recycled at the end of life, only some of them are disposed due to their impossibility to be recycled. A component has been taken as example to show the choices concerning the EOL treatment, the selected part is the command dashboard. The manufacturing material of this component is Polypropylene (PP), at the end of the washing machine lifetime this part is still functional but it cannot be reused because a new model will be produced. As a consequence this consideration the material can be recycled to produce other components from the same company (closed loop) or may be sold by those who recycle the material for the production of other goods. In this case the material is recycled not in a closed loop, but generic recycle has been selected.

RESULTS DISCUSSION

The LCA analysis for a complex product, like the washing machine, provides to assign for each component all the information about its lifecycle. As discussed above, this information is: the manufacturing material and process cycle, the eventual transportation from the manufacturing site to the assembly site, the specification about the use phase and the EOL treatment. After this data selection, the LCA analysis results can be visualized by the user through the "LCA results" tab (Figure 4). In the result tab each single lifecycle phase can be selected and the corresponding LCA results can be shown in form of tables and graphs. In the figure below the total LCA results are shown. Manufacturing, use and end of life contributions can be visualized.

PRELIMINARY EVALUATION OF FEM-LCA INTERACTION

The proposed approach covers the complete product lifecycle, allowing selecting the starting stock material, the manufacturing process, the use phase specification and the end of life treatment. Through this approach is possible to evaluate the environmental impact of the product and compare different design solution obtained with material and manufacturing process change. It is evident that a material change can influence both the manufacturing process and the component geometry according to the new material's mechanical properties. At this aim a FEM analysis can be performed to evaluate and optimize the component shape according with the loads defined in the design specifications. FEM analysis can be adopted as shape optimization tool, indeed some dedicated FEM software provide specific module for this scope. In this work shape optimization test has been conducted for a specific washing machine component. The analysed component is the transmission pulley attached to the steel drum. A material change from aluminium alloy to a special recyclable plastic reinforced with glass long glass fibres involves a change in the geometry of the component according with the different mechanical resistance properties. This optimization has been conducted using the specific shape optimization tool included in a ANSYS. The result of this optimization is a geometric change and mass reduction among the initial design solution, in fact using the special reinforced plastic, with the same applied loads is possible to reduce the section due to the higher mechanical resistance of the plastic material. The aluminium alloy pulley has a weight of approximately 1,2 kg, whereas the plastic solution has a weight around 0,45 kg. This different material and the consequently shape modification causes an environmental impact change, in particular using the special recyclable and fibreglass reinforced plastic the LCA impact results decrease compared to the Aluminium alloy solution (Figure 5).

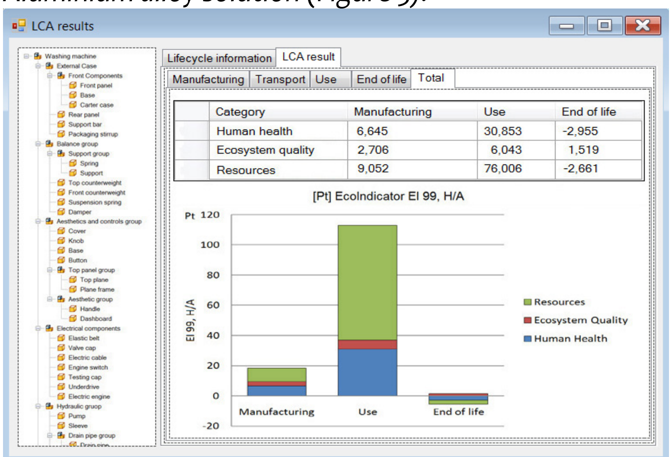

Figure 4 – Screenshot for the Product Total LCA results

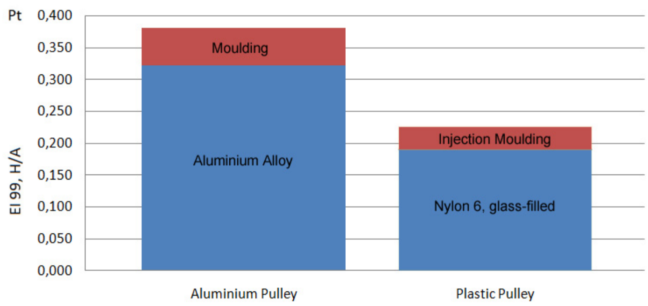

Figure 5 – LCA results comparison between different material solutions

This approach has been performed as a test case in this work, to show the potential and powerful application of FEM analysis in conjunction with LCA and integrated with CAD systems in design process. This test highlights the possibility to deep specify this method to the proposed approach in future.

CONCLUSIONS

The present work describes a new approach and the related preliminary software system useful to support the simplified LCA analysis during the early design phases. The approach is based on data extraction from the traditional design systems databases (ERP, PLM, CAD data structure). Data is properly elaborated and a rapid environmental estimation impact is provided by the user.

This approach seems quite robust in terms of accuracy but it needs several human interventions in order to choose parameters (i.e. the manufacturing processes and related parameters). This represents still a limitation due to the designer effort in terms of time. Furthermore the Uses and EOL phase contribution to the impact should be validated through a wider number of case studies by using different classes of products. On the other hand, the system usability is highly appreciated by the designers due to the integration with tools they generally use.

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