Design for Sustainability through a Life Cycle Assessment Conceptual Framework Integrated within Product Lifecycle Management

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A Thesis Presented

by

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DEDICATION

I would like to dedicate this thesis to my parents, Weikang Zou and Xiaoqing Wang. As an international student, studying abroad is large expense to my family. But they have constantly supported me throughout the past three years. Without their encouragement, I would not have been able to finish this work. I would also dedicate this to my friends that have helped me.

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ABSTRACT

Design for Sustainability through a Life Cycle Assessment Conceptual Framework Integrated within Product Lifecycle Management

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The need to include sustainable design principles during product realization poses several challenges in need of research. The demand for greener products has increased while competition has shortened product realization processes. Product Lifecycle Management (PLM) provides solutions in accelerating the development process and time to market by managing the information through a full life cycle of a product line. Life Cycle Assessment (LCA) provides a way to predict the environmental impacts that should be expected over the complete life cycle of a given product, but LCA methods are not well suited to efficient comparison of product alternatives during early design stages. Customers and other stakeholders demand products that not only comply with regulations and minimize environmental impacts, but also minimize costs and maximize certain performance objectives of a product. Thus, an approach is needed to unify validation of new products compliance with holistic consideration of environmental impacts along with other objectives over a complete life cycle for the selection of the optimal design concept in an efficient manner.

This research addresses these matters by proposing the approach of integrating LCA software with a PLM system. A conceptual LCA framework- LCAatPLM (Life Cycle Assessment of assembly tree in PLM) is proposed that allows environmental assessment of assembly tree directly extracted from PLM. Firstly, relevant existing solutions are reviewed and several challenges are identified that prevent integration. By decomposing the structure of both PLM and LCA, a common foundation is identified for the integration. Then, a design methodology is developed to show the use of LCAatPLM within PLM environment. A charcoal grill design case study is detailed to show how evaluations can be made based on achievement of strategic goals, along with verification of compliance and the visibility of LCA and other results. Our findings show that design executions through LCA integrated with PLM reveal environmental criterion at early stages. It can be considered with other design criteria to identify and select optimal alternatives. This research transforms LCA as an evaluation tool used after a design is already completed to one that can guide designs earlier within the PLM environment.

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CHAPTER 1

INTRODUCTION

With the increasing pressure of environmental regulations, such as RoHS, REACH, WEEE, the selection of design and manufacturing processes which comply with these regulations and also have much lower environmental impacts has become increasingly complicated. Many companies realize that in order to stay competitive in today's market, it is crucial to introduce environmental thinking during the design of a product. Nowadays, as more and more people care about the environment, customers tend to prefer greener products. More sustainable products will not only build a good reputation of a company's brand, but also increase their market share. Including environmental thinking and complying with regulations seems inevitable for every company that wants to survive in their market.

1.1 Research Motivation

The motivation of this research is based on the need for companies to develop greener products in shorter term and to prevent the regulatory violations and late change. Today manufacturers and retailers are facing a regulatory avalanche in the field of environmental legislation on a worldwide scale. They are exposed to a continuously growing variety and therefore complexity of legal requirements for placing their products on more than just the domestic market [1].

On one hand, companies have to meet these ever growing environmental regulations so that they can at least enter the market. On the other hand, another central objective for them is fulfill customer needs, which are increasingly directed toward the social and environmental performance of a product [2].

The results of industrial surveys identified CAD geometric models as data reference, Computer-Aided Design (CAD), Product Lifecycle Management (PLM) and Product Data Management (PDM) systems as the most used tools during the design phase [3]. Product Lifecycle Management (PLM) is an integrated approach that combines methods, models and IT tools for managing product information, engineering process and applications for the entire lifecycle of a product. Many authors agree that PLM is the key concept for the establishment of eco-design processes [4] [5] [6] [7]. The opportunity to influence a product's environmental impacts is prevalent in the design phase. Connecting PLM and sustainability might provide useful insights to a sustainable new product development approach [8].

As for the environmental impacts, Life Cycle Assessment (LCA) is the most commonly assumed method for assessing the environmental impact of a product or service through all its life cycle stages. However, Figure 1.1 demonstrates the paradox of eco-design: between knowledge of the product, potential environmental improvement and design solutions [9]. The impacts of a product upon the environment is determined at the design phase, and often in the very early design phase. As the knowledge of the product increases from conceptual stage to detailed design to manufacturing, the opportunity for environmental improvement is reduced. Also, the design spaces are relatively large in the beginning of product development when ideas and conceptual solutions are quite open. Supporters of integrating environmental aspects into product development as early as possible, not handled independently gave several literatures [10] [11]. However, LCA requires detailed product design information, which makes it unsuitable for use in the early design stages [12] [13] [14]. As a result, a full LCA will be unfeasible for the study of alternatives that substantially differ from the originally assessed product [15]. By the time the products are mature and enough LCA-relevant data are available for a comprehensive environmental evaluation, much of the design space is locked-in.

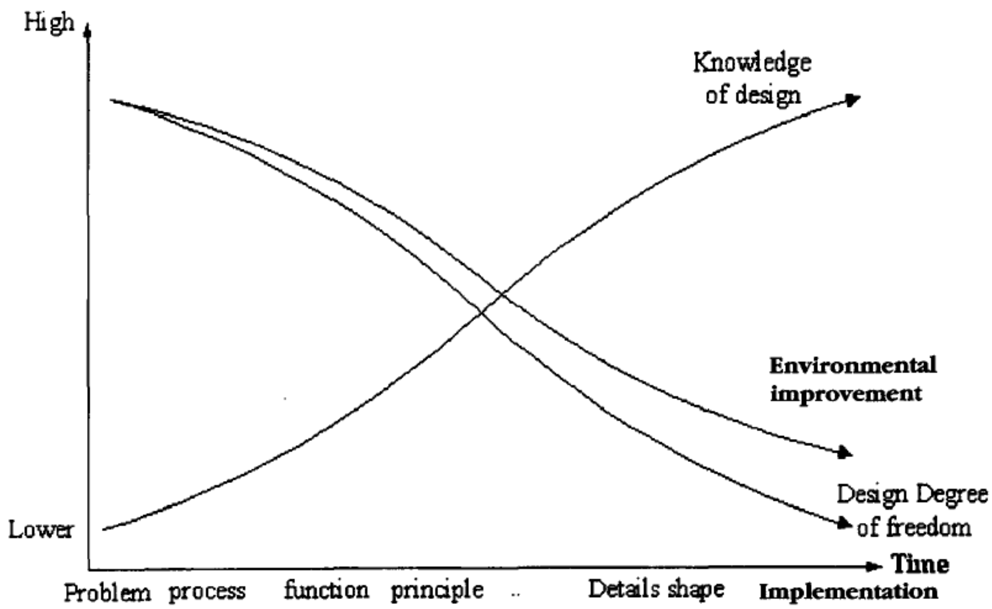


Figure 1.1 The paradox of eco-design

Also, a comprehensive LCA is very costly and time consuming and sometimes not affordable for small business [16]. And it requires specific high-level expertise for interpretation [9]. A survey of designers conducted indicts designers are typically overburdened with product functionality and cost reduction objectives [17]. Lagerstedt [18], also claims that designers do not want too much information, as provided by most LCA analysis.

In summary, LCA is not a design tool but an evaluation tool that seems not to be used during the design process. This research tries to mitigate these limitations of LCA during design process through the idea that uses PLM as the establishment of eco-design process while uses LCA to evaluate the environmental impacts. Since a LCA study can be performed based on Bill of Material (BOM) and Bill of Process (BOP) provided by PLM, this leads to a potentiality for integration. We hope that, while PLM helps accelerate the design process by managing the information of a product over its entire life cycle, LCA is performed at early design stage based on the same information so that environmental impacts can be considered along with other priorities. In the end, sustainable design methodologies and frameworks were developed by our research group [19] [20] [21] [22], which guide and direct this thesis work.

1.2 Research Scope and Purpose

The goal of this research is to design of product with a holistic consideration of environmental impacts along with other objectives over a complete life cycle through the integration of LCA into PLM, and try to mitigate the limitations of LCA that is not suitable to be used during the design process.

This is done by firstly identifying several challenges that prevent LCA from integrating within the design process. Also, current solutions on integration of LCA with PLM/CAD is reviewed. The conclusion shows that different representations of product model between LCA and PLM are used. PLM uses product structure to represent the product model, while LCA uses process model to form the full product lifecycle and does not care product structure. To this end, LCAatPLM (Life Cycle

Assessment of assembly tree in PLM) is proposed. It is a conceptual LCA framework that maintains the representation of product structure usually used by designers during design in the form of an assembly tree in PLM. An environmental assessment that is based on the same structural items could easily transform and reuse existing product presentation directly from PLM system. Through this, an integration system is formed with PLM serves as the foundation and LCAatPLM is integrated into PLM like other design supporting tools (Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), etc.).

Secondly, a design methodology based on the integration system is proposed. It illustrates a way on how to take environmental impacts into consideration at early design stage using the integration. Designers work out different alternatives of the product and store relevant information in the PLM system. Then, based on that information, environmental evaluations of these potential alternatives are acquired using LCAatPLM. Different categories of environmental impacts are transformed into a dimensionless number through normalization, characterization and weighting with the aim of simplifying the results to designers. Then, these environmental results are stored along with other design attributes in a common place in PLM. A final decision making process is performed based on the preferences of the decision makers.

A case study of redesigning a charcoal grill is performed to illustrate the proposed concept and methodology. Firstly, we look at LCA information of an existing baseline design acquired from literature, and use that information to methodically identify the ideal new design concept of the product. As the BOM is developed in PLM, we examine potential parallel processing capabilities of: evaluation of the design in relation to the goals anticipated for the selected design strategy, verification of any compliance issues, comparison of the design concept to other candidates, and the visibility of the LCA results with those of other objectives to indicate throughout a design process the design intent of why a selected concept is the most sustainable design.

In sum, the objective of this research is to prescribe a way how LCA can be best integrated with PLM and propose a design methodology that shows how to introduce environmental criteria into design process as early as possible. It is important to understand that LCAatPLM still cannot reach the accuracy of a complete LCA model of a product. It is especially for designers to reveal environmental results and understand the environmental impacts of a design decision at earliest design stage. It transforms LCA from an evaluation tool used after a design is already completed to one that can guide designs earlier within the PLM environment.

1.3 Thesis Outline

The remainder of this thesis is organized as follows. Chapter 2 reviews background and prior work related to sustainable design, PLM, LCA and decision-making. Then, an overview of the existing solutions on the integration of LCA with PLM is presented in Chapter 3, State of the Art. This includes current interfaced approaches and integration approaches of connecting LCA with PLM or CAD. Besides integrating LCA into PLM, some concepts of integrating environmental impacts into PLM are presented. In Chapter 4, several main challenges of integrating LCA into PLM are identified based on the literature review. In Chapter 5, a new LCA framework is proposed to address the challenges identified. After introducing the LCA framework, a design methodology using the proposed system is introduced in Chapter 6. A case study of redesigning a charcoal grill is implemented to validate the proposed system and methodology in Chapter 7. Chapter 8 concludes with a summary of benefits and limitations of this work and recommendations for future work.

CHAPTER 2

BACKGROUND

This chapter first summarizes previous research in sustainable design done in the Center for e-Design. Prior works include NASDOP (Normative decision Analysis method for the Sustainability-based Design of Products) and integration of sematic framework with PLM. Then, background about PLM, LCA and other relevant knowledge are presented.

2.1 Previous Work

With the increasing demand of greener products while developing time has decreased, LCA methods are not well suited to efficient comparison of product alternatives during early design. Products that not only comply with regulations and have lower environmental impacts but also minimize costs and maximize other performance objectives are expected by customers and stakeholders. To this end, previous published works in the research group introduce approaches to address these issues.

An approach was developed to methodically account for LCA along with uncertainty and product costs over the same life cycle. The method introduced the mathematical rigor of a normative approach to select an optimal design concept by the holistic consideration of multiple objectives [19].

Another approach presents an ontological framework designed to represent both the objectives that pertain to sustainable design and the applicable sustainability standards and regulations. This integrated approach not only can ease the adoption of the standards and regulations during a design process but can also influence a design toward sustainability considerations. The results show that both the standards and criteria may be considered at early design stages. Furthermore, it can be used to capture, reveal, and propagate the design intent transparently to all design participants [20].

A Bill of Material (BOM)-based approach was introduced to select the most suitable materials for multi-criteria decision making of the optimal product design. Surrogate models are constructed which consist the environmental objectives with other traditional design objectives. Then novel feasible approximation approach are used to identify optimal concepts in the design space beyond the original data set of the known design alternatives. This method can streamline LCA estimation for material selection of major components in a new BOM at the early design stages [21].

Finally, a semantic framework developed in our e-Design center is integrated with a commercial PLM system. This integration approach is a semantic extraction process that executes the interface from PLM to a framework compatible with the semantic web, while maintaining the PLM's BOM. Design execution within a semantic framework facilitates dynamic linking of product information throughout the design process. It also preserves and propagates the BOM related information from PLM in all design stages [22].

In summary, these previous work within the research group have covered LCA, PLM, knowledge management, multi-criteria decision making, material selection, etc. This research, based on these previous works, took advances toward further benefits by deployment of some of these concepts or methodologies above.

2.2 Product Lifecycle Management (PLM)

As designers notice a growing volume of files generated by CAD system, engineers realize there is a need to keep track of them in one place. In the late 1980s, Product Data Management System (PDM) has emerged. PDM is usually considered to be a subset of PLM. A PDM allow designers to standardize items, to store and control document files, to maintain BOM's, to control item, BOM and document revision levels, and immediately to see relationships between parts and assemblies. This functionality allows them to quickly access standard items, BOM structures, and files for reuse and derivation, while reducing the risk of using incorrect design versions and increasing the reuse of existing product information [23].

PLM evolved from the PDM approach. While PDM focuses on management of product data within product design, PLM has a management focusing on data, processes and applications for the whole life cycle of a product. PLM is an integrated approach including not only items, documents and BOM, but also analysis results, specifications, engineering requirements, manufacturing processes, product performance information, suppliers and so forth. PLM is also a system. A modern PLM system has capabilities of design workflow, program management, and project control and speed up operations. The web-based system can not only address only one company but it also enables global collaborations between manufacturers, suppliers and customers. PLM is a collaborative backbone allowing people of different fields to work together effectively [24].

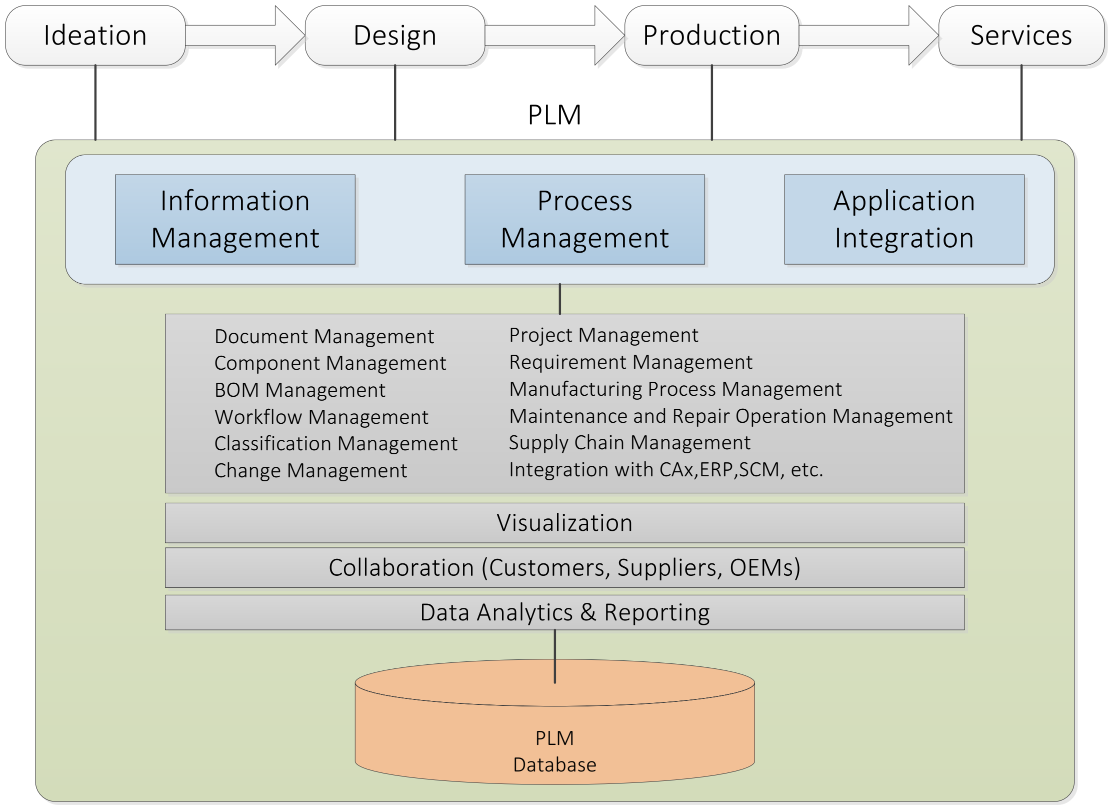


Figure 2.1 PLM architecture

Usually PLM integrates data process meta model managed by a database and a central controlled data vault for the storage of all created proprietary models and documents (e.g. CAD models, documents,), Figure 2.1. PLM method and tools can be clustered into three groups [25]:

- Information management (e.g. methods for identifying, structuring, classifying, modelling, retrieving, sharing, disseminating, visualizing and achieving product, process and project related data)
- Process management (e.g. methods for modelling, structuring, planning, operating and controlling formal processes like engineering release process, review process, change process or notification processes).

- Application integration (e.g. methods for defining and managing interfaces between PLM and different application like CAD, CAM, Computer-Aided Engineering (CAE) and integrated enterprise software such as Enterprise Resource Planning(ERP), Supply Chain Management(SCM)).

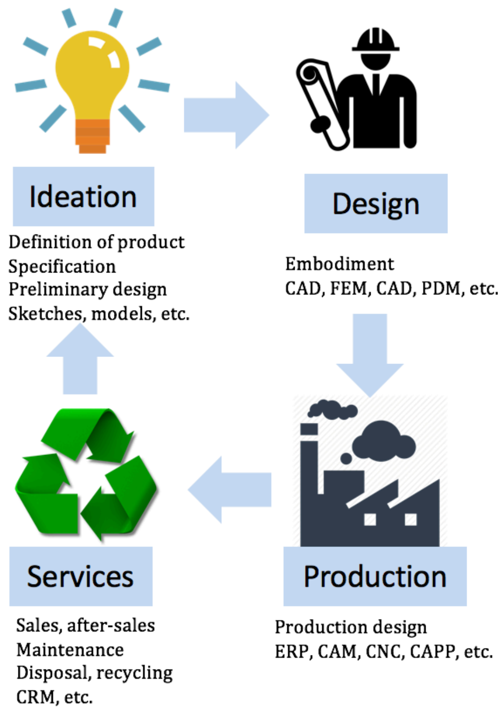


Figure 2.2 Relevant software used in different design action

A strong advantage of PLM is its application integration with data provided with different IT systems used by different departments of enterprise, Figure 2.2. Computer-aided design, manufacturing, and engineering system (CAD, CAM, CAE) used for product and process design; material requirements planning, advanced production, manufacturing execution, and enterprise resource planning systems (Material Requirement Planning (MRP), Advance Planning and Scheduling (APS), Manufacturing Execution System (MES), ERP) used for materials and production process planning; and supply chain management and customer relationship management systems (SCM, Customer Relationship Management (CRM)) used for data and communications management with customers and suppliers.

Overall, PLM in the modern era is sometimes interpreted as a "system of systems". Vendors defined as 'PLM suppliers' come from three diverse backgrounds and are adopting strategies to expand their past foci. These include [26]:

- Siemens and Dassault Systèmes, from the digital engineering world trying to connect to the operation management processes.
- SAP and Oracle, from ERP world attempting to connect to digital manufacturing and engineering tools and platforms.
- Windchill, from generic information and communications technology (ICT) world aiming at establishing collaborative environments for integration, basically using web technology.

2.3 Product Structure in PLM

A product model can be represented in different structures. Different users will also work with different structures. For example, engineering, accounting, production management, and assembly may all have different requirements for the BOM structures. For designer, throughout the development process, design changes, components are modified, products are restructured and project status is updated accordingly.

To efficiently consider environmental assessment during product development, a CAD-like product structure will be served as the foundation of the utilized model. The most important definitions for such a structure is listed below [27]:

- A product structure consists of assemblies, parts, and features.
- Assemblies, parts, and features are components of the product.
- Assemblies consists of subordinate assemblies and parts.
- Parts consist of features and have an assigned material.
- Features can be specialized to specific kinds of features.
- Each component can be subordinate to only one other component to ensure a hierarchical tree structure rather than a network.

Most product models that are used within modern 3D CAD systems follow these rules, sometimes with small deflections [28]. An environmental assessment that is based on the same structural items could easily transform and reuse existing product presentation directly from CAD or PLM systems.

2.4 Life Cycle Assessment (LCA)

LCA is a "cradle to grave" approach for assessing industrial systems. "Cradle to grave" means resources firstly must be extracted from earth and converted into material or components from which the product is made, infrastructure must provide its function to the plant and employees. When the product enter its end of life stage, the materials are to be recycled or returned to earth. LCA includes five stages of: raw material extraction, manufacturing, distribution, use and end of life. LCA evaluates all stages of a product's life cycle from the perspective that they are interdependent. It enables the estimation of cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more tradition analyses. By evaluating the impacts throughout the life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of environmental trade-offs in product and process selection [29]. It is a tool for relative comparison, thereby it can be used by decision makers to compare all major environmental impacts in the choice of alternative courses of action [30].

The International Standards Organization (ISO) started a standardization process for LCA [31]. Four standards were developed for life cycle assessment and its main phases and issued in ISO 14000 series of standards for Environmental Management. The framework for LCA is shown in Figure 2.3.

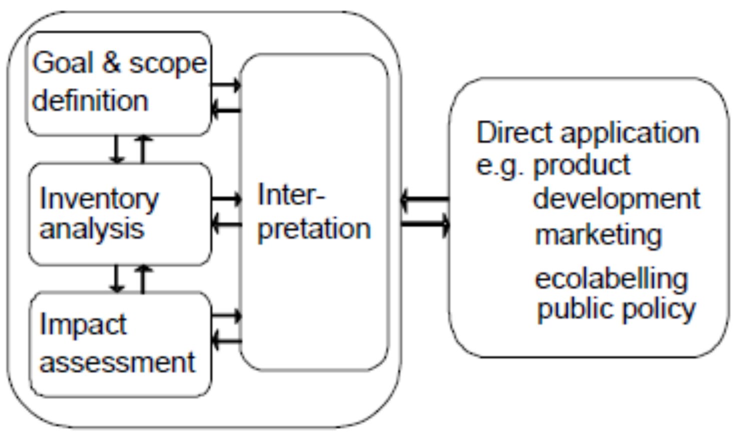


Figure 2.3 ISO 14040 Life cycle assessment framework

As illustrated in Figure 2.3 LCA is an iterative process.

- Goal and scope definition: goal and intended use of LCA is defined, and the assessment is scoped in terms of boundaries of the product system.
- Life Cycle Inventory (LCI): A life cycle inventory is a process of quantifying energy and raw material requirements, atmospheric

emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity.

- Life Cycle Impact Assessment (LCIA): the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the LCI. It attempts to establish a linkage between product or process and its potential environmental impacts.
- Interpretation: Interpretation is the phase of the LCA where the results of the other phases are interpreted according to the goal of the study using sensitivity and uncertainty analysis.

Computer-aided tools to support the application of LCA can be divided into two major groups [32]. Firstly, various general inventories are pre-compiled to be used to perform LCA later. Such inventories contain data sets related to general processes, like resource extraction, energy supply, material supply, chemicals, metals, waste management and transport services. Each data set contains general descriptive information along with the detailed input/output data, parameterized with respect to a reference unit. Examples of such database are Ecoinvent [33], ETH-ESU 96 [34], etc. Secondly, various types of analysis tools are developed and implemented. Such tools allow user to describe the process under investigation in terms of elementary processes, eventually clustered and related to each other, in order to define more complex processes. The user can then parameterize the different processes by setting the allocation values, and select the appropriate eco-indicator to be used to perform the impact assessment. Examples of such tools are SimaPro, GaBi and OpenLCA.

LCA software will significantly save time to collect, analyze and monitor a product's environmental performance. LCA software is developed to support the ISO framework. Since collection of data for the environmental exchange between processes and environment is normally labor-intensive. The database within LCA software stores data in a unit process which allows them to be used as building blocks in different life cycle models. The data is usually about the most important processes (manufacturing, transportation, recycle) and material (metal, plastic, etc.). As for the interpretation part, LCA software can give designers direct view through aggregation of numbers and graphs. Some also have scenario analysis which helps design to reduce environmental impacts by changing certain aspects of the product system that you modelled.

2.5 Overview of Sustainability and Sustainable Design Methodologies

Sustainability is not only about environment. It simultaneously addresses the social impacts, the environmental impacts, and the economic impacts of the company's activities as introduced in the concept of Triple Bottom Line (TBL) [35].

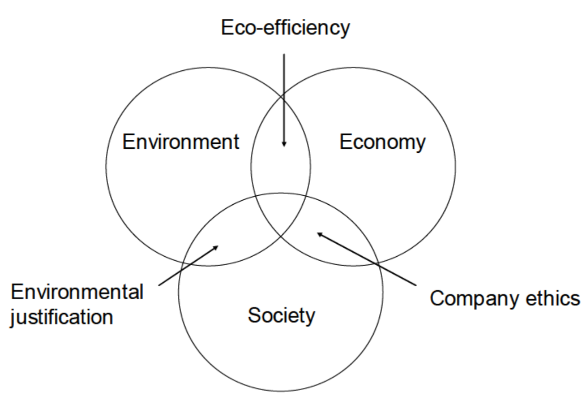


Figure 2.4 The dimensions of sustainability

As shown in Figure 2.4, the intersection of three spheres lies the most sustainable product that balance economic, social and ecological dimensions. Many organizations have adopted the TBL framework to evaluate their performance in a broader perspective to create greater business value [36]. Integrated sustainability triangle is one such tool that does not only provide a way to quantify sustainable performance of a product [37], but also introduces an appropriate instrument for the systemization and evaluation of the performance of a company regarding sustainability management [38].

However, traditionally businesses maintain a strong focus on factors that have a clear and direct effect on their economic performance. Several sustainable design methodologies, such as Life Cycle Design (LCD), Design for Environment (DfE), that try to balance between three aspects in TBL are developed. These methodologies use environment evaluation tools including LCA to determine the environmental performance of a product.

LCD is a term which has come to have a great deal of overlap with DfE [39]. It is an approach for more effectively conserving resources and energy, preventing pollution, and reducing the aggregate environmental impacts and health risks associated with a product system which integrates environmental requirements into the earliest phases of design and balances with other requirements like performance, cost, cultural, and the legal criteria. Concepts such as concurrent design, cross-disciplinary teams, multi-objective decision making, and total cost assessment are essential elements of it [40].

Table 2.1 Optimizing strategies on product life cycle

Life Cycle	DfE Strategies	Specific Strategies
Raw material	Material use optimization	Design for resource conservation - Reduction of material use - Use renewable material - Use recycled and recyclable Design for low impact material - Avoid toxic or hazardous sub. - Use of lower energy content
Manufacturing	Clean manufacturing	Design for cleaner production - Minimize the variety of material - Avoid waste of material - Select low impact ancillary material and process
Distribution	Efficient distribution	Design for efficient distribution - Reduce the weight of product - Reduce the weight of packaging - Ensure re-usable and recyclable Transport packaging - Ensure efficient distribution
Product Use	Clean use/operation	Design for energy efficiency Design for material conservation Design for minimal consumption Avoidance of waste Design for low-impact use/operation Design for durability
End of Life	End of Life optimization	Design for re-use Design for re-manufacturing Design for disassembly Design for recycling Design for safe disposal

Design for Environment (DfE) is a systematic consideration of design performance in terms of environment, health and safety objectives over the full product and process life cycle. Establishing an appropriate DfE strategy for designing a sustainable product is crucial in determining the environmental aspects of the product [41]. DfE requires the coordination of several design and data-based activities, such as environmental impact metrics, data management, design optimization and others [42]. Example of environmental impact metrics or methodologies for deriving them are given by Veroutis et al [43] and O'Shea [44]. There are also general guidelines for developing environmental friendly products, such as the "Ten Golden Rules" [45]. The environmental impacts of a product can be reduced through a set of DfE strategies of optimizing each stage of product life cycle as shown in Table 2.1 [46].

Despite the many existing DfE methods and tools, their use is still limited. Small and medium-size companies have experience with DfE projects, but they rarely lead to the use of DfE in ordinary product development [47]. Most companies do not treat DfE as a management issue. Finally, it is common that when a company does practice DfE, the focus is on environmental redesign of product instead of the development of new products. Given all this, the potential benefits of DfE have not been realized [48].

2.6 Multi-criteria Decision Making (MCDM)

As mentioned above, a sustainable design should balance environmental, performance, cost, cultural and legal requirements. The integration of environmental considerations must find its place among many other priorities considered in the development of a new product as shown in Figure 2.5. Usually, some of these criteria cannot be considered into a monetary value, because environmental concerns often involve ethical and moral principles that may not be related to any economic use of value. Selecting from many design alternatives often involves making trade-offs. Nevertheless, considerable research of MCDM has made available practical methods for applying scientific decision theoretical approaches to complex multi-criteria problems. MCDM method has been utilized to iteratively solve engineering problems [49]. The application of MCDM in engineering design can be found in many literatures [49] [50] [51].

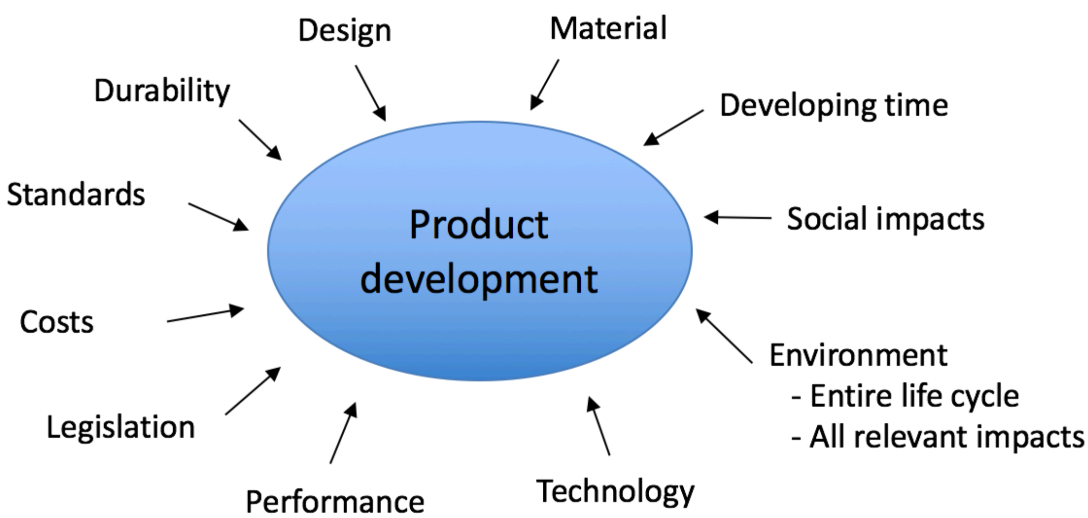


Figure 2.5 Design attributes considered in new product development

Multi-attribute utility theory (MAUT) or Analytical Hierarchy Process (AHP) are both decision-making techniques that being utilized to iteratively solve engineering problems. They employ numerical scores to communicate the merit of one option compared with others on a single scale. Scores are developed from the performance of alternatives with respect to an individual criterion and aggregate into an overall score. The goal of MAUT is to find a simple expression for decision-makers preferences. MAUT transforms different criteria (cost, environmental index, performance, etc.) into a dimensionless scale (0-1) of utility. Utility function for each criteria convert the criteria units into the 0-1 utility scale and are combined with weighting functions of the criteria within the overall decision to for a decision score for each alternative. MAUT relies on the decision maker's preferences. The goal of decision makers is to maximize utility [52].

Prior to this research, Hypothetical Equivalents and Inequivalents Method (HEIM) [53] was used for concept selection in sustainable design within the research group. Also, a method [54] that expands HEIM to handle multi-level and multi-attribute trade-offs was developed. These previous studies have proved the usefulness of HEIM in sustainable design. In this research, HEIM was also used for decision-making.

The selection of best concept in design decision-making depends on weights, same as MAUT and AHP. As it can be difficult for a decision maker to explicitly state their accurate preference, HEIM was formulated to determine the decision maker's true weights implicitly by ranking a set of hypothetical alternatives in order to assess attribute importance, and determine them directly from a decision maker's stated preferences [55]. When a preference is stated, such as "I prefer hypothetical alternative A over B", constraints are formulated and an optimization problem is constructed to solve for the attribute weights. The weights are solved by formulating the following optimization problem,

$$\begin{gathered} Minimize\ \ f(x) = \left(1 - \sum_{i=1}^{n} w_i\right)^2 \\ subject\ to\ h(x) = 0 \\ g(x) \leq 0 \end{gathered} \tag{2.1}$$

where, the objective function ensures the sum of the weights is equal to one. X is the vector of the attribute weights, n is the number of attributes, w_i is the weight of attribute i. The inequality constraints are based on a set of stated preferences from the decision maker. If the decision maker prefer hypothetical alternative A to alternative B, for example,

$$A > B \tag{2.2}$$

then, their value of alternative A is greater than that of alternative B, which can be expressed as

$$V(A) > V(B) \tag{2.3}$$

Finally, the inequality can be formulated as an inequality constraint for the optimization problem, as shown in Eq.2.4

$$\begin{gathered} V(B) - V(A) < 0 \\ V(B) - V(A) + \delta \leq 0 \end{gathered} \tag{2.4}$$

The δ in Eq. 2.4 is a small positive number included to transform the strict inequality to the more standard constraints representation (≤) while ensuring V(A) is still larger than V(B).

The equality constraints are developed based on stated preference of alternatives equally. Their value is equal, giving the following Eqn. 2.5

$$V(A) = V(B)\ or\ V(A) - V(B) = 0 \tag{2.5}$$

The value of an alternative (alternative A in this case) is give as

$$V(A) = \sum_{i=1}^{n} w_i r_{Ai} \tag{2.6}$$

where r_{Ai} is the rating of alternative A on attribute i.

Finally, the optimization problem in Eq. 2.1 can be solved in order to find the true attribute weights using Eqn.2.4, to determine a score for each alternative.

A normal process of executing HEIM includes: 1) Identify the attributes, 2) Determine the strength of preference within each attribute, 3) Set up hypothetical alternatives, 4) Normalize the scale and calculate the value for each alternative, 5) Formulate the preference structure as an optimization problem, 6) Solve for the preference weights, 7) Make a decision.

2.7 Decision Support for Sustainability in PLM

LCA has become an invaluable decision-support tool that can be used by manufacturers, suppliers, customers, policy-makers and other stakeholders [56]. However, application of LCA and its integration into decision-making processes have not been as widespread as expected. During the product development process, designers work in collaboration with different design participants, as a result, the development of a decision-support system (DSS) to support an eco-design approach must therefore consider the nature of the design work, the sequence of activities, the validation process and the share responsibilities within the corporation in order to be efficient [57]. PLM manages and stores product data. However, faced with a huge amount of information, the lack of decision support leaves designers looking for a proper way to make a decision instead of using past experience in most of the cases. Golovatchev et al. [58] also proposed a next generation PLM IT-architecture that supports PLM-process in the dimensions: Decision support, Operational support and integration of supplemental business applications. Thus, a decision-support system seems necessary to be used within the PLM environment.

The main purpose of a DSS is to gather and consolidate data in order to provide management with aggregated information on the product life cycle. They can help generate and guide the preference of stakeholders into organized structures that can be linked with other technical tools from risk analysis, modeling and cost estimations. They also provide graphical techniques and visualization methods to express the gather information in understandable formats. Few of them have been connected with PLM.

Poudelet et al. [59] asserts that designers not only require a tool to support the assessment of different alternatives, but they also need a database to store all of the already tested solutions. And they also set out several main requirements for such DSS:

- The tool should allow designers to compare different design alternatives in terms of environment and cost performances;
- The tool should be simple to use and fit perfectly into decision-making process;
- The tool will be based on rigorous environmental metrics supported by an LCA approach;
- The results obtained from the tool should be simple enough to be understood.

Even though proposing a DSS in PLM is not the focus of this research, the author is still a supporter of this thought. So in this work, a simplified decision support module using a spreadsheet uploaded into PLM is included in the integration system. The simplified DSS stores the design attributes of tested and untested alternatives. These attributes are either extracted from PLM or collect feedbacks from LCA. Then, these results are normalized and combined with weights calculated from HEIM. Optimal alternatives will be finally selected based on the preferences of the decision maker.

CHAPTER 3

STATE OF THE ART

This chapter introduces current solutions on PLM and LCA integration and also CAD/LCA integration, including interfaced approach and integration approach. Finally, besides LCA, some other ways of integrating environmental assessment in PLM are introduced.

3.1 Overview of LCA integrated with PLM/CAD

Normally, integrating two systems is through interface approach or integration approach. The interface approach is most common. It usually involves two standalone system exchanging information between each other, such as PLM and CAD system. One can use CAD system to build model, drawings. Through interface, models or drawings can be opened and modified in PLM system. In terms of integrating LCA with PLM, there is some research done both on the interface and integration approach. However, existing research outcomes seem to focus more on the integration of LCA with CAD rather than PLM.

3.1.1 Interface approach

Mathieux et al. have proposed the "DEMONSTRATOR" [60]. It is a prototype of tool based on feature technology in extracting CAD/PDM data, from CATIAv5 (CAD) to EIME (LCA). The identified benefits of this interface are: time saving, more data collected, data keyed-in only once. However, the limitations are that all the environmental data required by the LCA tool cannot be located in the CAD and PLM system, most of the data are related to product structure (component tree, mass…) rather than product & corresponding processes in other life cycle phases:

manufacturing , transportation, use, end of life. This work has demonstrated that a direct connection between CAD and LCA tools provides less information than using PLM but most of the additional collected data are not located in the PLM with a direct link. The information is in attached Word documents or expert applications [61]. Consequently, the necessary data to carry out a LCA study is not easy to obtain.

Pernexas and GreenDelta proposed and implemented an interface called "eLCA" [62] was developed that allows a dynamic access to the LCA tool from ENOVIA using two new PDM types: LCA Product System which makes the link with some product system defined in the LCA and LCA Container which makes the inheritance of a LCA product system for a part depending it part family. The limits are that data regarding each part are manually set through their two new PDM types and then a LCA result can be acquired. Also designers may be faced with a situation that a novel part does not belong to any product system defined in the LCA tool. In other words, environmental data about a part cannot be setup through simulation of how it will be made.

Marosky et al. [63] presented the structure of an algorithm that allows a mutual transfer of data between CAD and LCA, this transfer is based on extracting data from CAD model. They proposed that data formats of CAD and LCA have to exchangeable. Data about product specifications that cannot be provided by the product model but is needed as data input for LCA, should be provided by the LCA database. In the same way, Cappelli et al. [64] proposed a framework that is based on the analysis of the tree structure of CAD project composed of assemblies, subassemblies, parts and features, and consider that features represent data associated with assembly model that can be stored in CAD files or in a specific database. After that, they developed “EcoCAD”. The information input way for environmental assessment makes it not to study the overall impact of a complex product but rather prevent most of the worse environmental errors during the virtual design phase.

Similarly, Computer-Aided Life Cycle Inventory (CALCI) tool [65] was developed to provide architecture and a user interface to associate entities of PLM system components with entities of LCA software and life cycle databases. However, use of Simplified LCA (SLCA) and missing life cycle stages make results accuracy remain to be seen. Morbidoni et al. [66] develops a new software tool which integrates data from different design supporting system using SLCA. The difference from CALCI is that it consider the assessment of the complete product lifecycle.

3.1.2 Integration approach

Currently, there is no LCA that is embedded within PLM. There are many researches on LCA integrated with CAD system. Otto et al. [67] introduced a framework for the integration of data from a product model and an LCI database. It allows efficient data retrieval of LCI relevant product information and provides a tool for practical evaluation of digital product models and process models.

Dassault Systèmes SolidWorks includes SolidWorks Sustainability and SolidWorks SustainabilityXpress to provide a complete dashboard of LCA information for determining the environmental impacts of part or assembly drawn. It allows LCA analyses in real time on parts or assembly and replacement of comparable materials in real time to see how they affect environmental impact [68].

Also, EcologiCAD [27] works as a standalone assessment system that in conjunction with CAD system for ecological assessment during development stages. The lack of this solution is his dependence to the CAD system used in this work.

The drawbacks of currently CAD integrated with LCA systems are that they use Simplified LCA (SLCA), which neglects the whole lifecycle (in particular use and end of life) and lack of detailed estimation on material used and manufacturing cycle impact. Literature shows that SLCA system based on integration of CAD tools with LCA databases are deeply inaccurate, compared with dedicated LCA tools. Hochschorner et al. [69] evaluated two simplified LCA methods and compared to the results of a quantitative LCA. They conclude that a simplified and semi-quantitative LCA can provide information that is complementary to a quantitative LCA. They suggest that a simplified LCA can be used both as a pre-study to a quantitative LCA and as a parallel assessment, which is used together with the quantitative LCA in the interpretation.

3.1.3 Several Concepts of LCA Integrated with CAD/PDM/PLM

Except for the existing interfaced or integration systems, there are also many concepts proposed for the integration of LCA with different systems.

A framework is introduced for the integration of CAD models, EDM/PDM databases and LCI databases [70]. Efficient and semantically mapping of CAD models data into LCI-relevant data is realized by using LCI process-relevant attributes and feature technology.

Knowledge-based approximate life cycle assessment system (KALCAS) [71] is developed with aim of improve design efficiency by managing high-level product information. It consists a product information module, LCA module, database and knowledge-based approximate LCA module. It proves the information exchange of different domains can be feasible and valuable to the decision-making of design alternatives by emphasizing the collaborative design environment.

A four-layered structure Energy-saving and Emission-Reduction LCA system was proposed based on Internet of Things and BOM [72]. The concept of big BOM is proposed, which can facilitate the effective data integration and exchange between the proposed system and existing information system, such as PDM, ERP, and SCM. They proposed big BOM is a combination of the existing data in each stage of the product life cycle, and the LCI-relevant data generated in the process of each stage from design BOM, manufacturing BOM to use BOM and disposal BOM.

3.2 Other Ways of Integrating Environmental Assessment in PLM

Besides the achievements mentioned above, several methodologies about integrating environmental assessment in PLM have been proposed. Yousnadj et al. argues full LCA study is not applicable in the early stages of design due to lack of information. They proposed a methodology of connecting a simplified LCA tool with PLM and ERP to evaluate an entire product portfolio [73]. Januschkowetz et al. describes how an LCI on a product can be compiled using an ERP system. It shows that the environmental data can be integrated into ERP systems, which facilitates the registration of environmental data and decreases time of gathering LCI data [74]. Eigner et al. proposed a concept for an intuitive and interactive eco-efficiency assessment which can be fully integrated in PLM solutions. It enables that the increased complexity due to environmental factors remains manageable and environmental potentials for a product can be identified and influenced early [4].

CHAPTER 4

CHALLENGES

4.1 Design Paradox of Considering Environment

In order to prevent late changes, use of non-hazardous materials and the environmental impacts should be monitored and evaluated as early as possible. However, as shown in Figure 1.1, the paradox of eco-design between knowledge of the product, potential environmental improvement and design solutions usually prevents the use of LCA at early design stage due to data unavailability. As a result, a full LCA will be unfeasible for the study of alternatives that substantially differ from the originally assessed product [15]. By the time the products are mature and enough LCA-relevant data are available for a complete environmental evaluation, much of the design space is locked-in. Simplified or streamlined LCA are developed to mitigate this issue. But it turns out to be inaccurate due to exclusion of some life cycle stages. It only allows for qualitative comparisons of alternatives at early design stage. To maintain accuracy, a complete life cycle should be considered.

There are researchers who propose that a new full LCA is not required for a new product if intended environmental evaluation is implemented in the early design stages [75]. During redesigning a product, previous model of product can be deployed. LCA results should be scalable if new features are added in the newer model in order to calculate the LCA results of the newer model. In case a new dependent product is developed, a 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.

Thus, a reference product of the similar type or the last generation product of the company can be used to solve the information unavailability at early stage, since many parts within a product can be reused. Also, a reference model will help designers to identify environmental "hot spots".

4.2 Different Representation of Product in LCA and PLM

A product can be represented using different kinds of models. Process and product model are models, which are used in LCA and product development with CAD. They describe the product from a different point of view as listed in Table 4.1 [63].

Table 4.1 Differences between process and product model

Differences	Process Model	Product Model
Main objective	Description and guidance on processes of a product's life cycle	Description of a product's construction structure and specifications of the product
Levels of structure	Processes of a product's life cycle	Assembly of a product
Methodological origin/main area of application	LCA methodology/LCA software tools	Product development/ CAD software tools

In LCA software tools, each assessment requires manual remodeling of product data, and the manual assignment of ecological datasets. Very basic principles of utilized methodology approaches in existing solutions prevent, or at least restrict the digital integration into existing infrastructures. Structural items like assemblies, parts, and features, which represent the frame of virtual product data, are not considered as they are used in CAD, PLM systems, as shown in Figure 4.1. Instead, material and process are used for the main system structure.

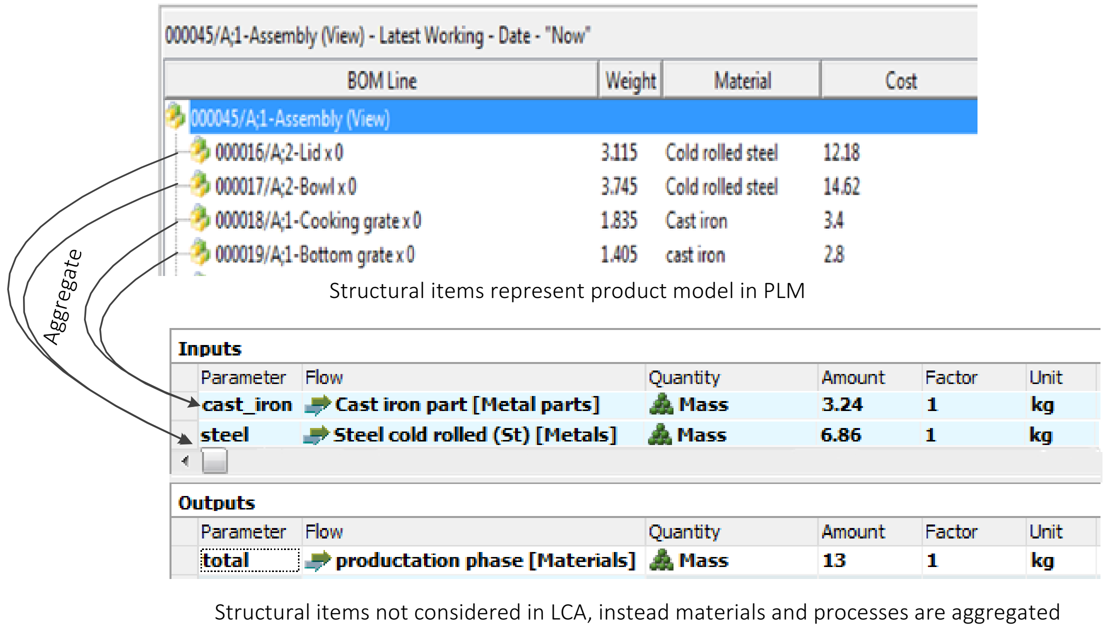


Figure 4.1 Different presentation of product model between PLM and LCA

Many current LCA software do not consider the definition of an individual lifecycle for each component, and the normalization of a function unit by the definition of an individual lifetime for each component. This results in huge complexity when dealing with a complex product system. Since materials and processes are aggregated during remodeling process, identifications of environmental “hot spots” regarding components within product system become difficult. What’s more, the remodeling of the entire life cycle of a product increases developing time caused by complexity of remodeling process and data keyed twice due to poor interconnection of LCA with other design tools.

Thus, LCA and PLM software tools shall be linked, data structuring needs to be consistent. Then, product model in PLM can be easily migrated to LCA and lifecycle-relevant information is extracted to complete the life cycle of that product model.

4.3 Proper mappings from PLM to LCA

The next barrier is the collection of data from PLM system and connection to LCA. The BOM information from PLM need to be as complete, error-free and consistent as possible under give constraints and must be in a readable format by LCA [76]. The work of Theret et al. [61] asserts that a direct connection between CAD and LCA tools provides less information than using PLM. Data, such as material type and weight, are defined in CAD system. Additional data, such as usage and end-of-life treatments, are usually attached to Word documents or expert applications, which is hard to be located in the PLM with a direct link. Consequently, the necessary data to carry out a LCA study is not easy to obtain.

Thus, proper mappings need to be built in order for LCA to extract right data from the right place. Currently, the formats used in CAD/PLM and LCI are not exchangeable. Properties of the product, such as materials and processes, need to be mapped to data from LCI database to be used in LCA. Other information that defined in embedded files needs to be machine-readable. However, this operation can be hard in terms of complicated end-of-life treatment scenarios for example. Manually inputs should be allowed to complete the life cycle. If data is missing for carrying out the LCA, it should be asked to provide this data by selecting missing processes.

4.4 Lack of comprehensive LCI database and Static Nature of LCA

In order to perform a LCA study, a database including the ecological balances of various materials, manufacturing processes, sources of energy production, modes of transportation, end-of-life treatment, etc., is required. These data, when they are not directly measured, are often presupposed conditions of the data issued from regulatory reports and industrial studies [13]. Although there are some Life Cycle Inventory (LCI) database, like Ecoinvent, NERL U.S. LCI database, it is still hard sometimes to find proper material types or processes to describe the life cycle of developing product. Time and money are still invested to find the right data filling into the proper place. Another important problem concerns the data updating; the static nature of LCA data can impede new product design and innovation [77]. Facing the unavailability of reliable actualized data, thorough studies of the missing ecological data, and other impediments, are essential.

But thanks to LCA become more important due to either government regulations or demands of highly competitive markets, one argument increasingly heard is that LCA will be required in the near future for every product and process [78]. This can potentially result in more ecological data to be developed to solve the problem of data insufficiency.

4.5 Designers Lacking Knowledge of Eco-design

Another problem is the designers lacking expert LCA knowledge and time [15]. All the design participants have their own bundle of knowledge. In addition, some of them may have a basic understanding of other specific domains. In order to help all the design participants to integrate the environmental impact in their design activities. They will need additional knowledge. However, a general lack of environmental skills is noted at each stage of design process [79]. Consequently, it is difficult to use the appropriate software and to share a global understanding about the way the environment should be integrated in the design process. The lack of coherence between the environmental stakes as understood by participants from different departments and by its providers, raises the question of the environmental management strategy [80].

In such case, these environmental results should be apparent and understandable to designers. Researchers [75] proposed that a key success factor to bring LCA to early design stages is the way the results of environmental evaluation should be visualized, similar to FEA modules integrated with CAD, where some parameters need to be specified to obtain visualized and understandable results. In terms of selecting optimal alternatives, quantitative results representing the environmental performance of an alternative should be obtained accompanied by the completion of design parameters and ready to use directly without overburden designers.

CHAPTER 5

PROPOSED SYSTEM

In this chapter, one way to solve different representation of product model in LCA and PLM are introduced by analyzing features of assembly tree. Then, LCAatPLM-a Life Cycle Assessment conceptual framework is proposed to transform product model used by PLM into process model used by LCA while maintained the product structure. Then, a substance compliance module is also proposed to make sure environmental regulations are checked early. Then LCA framework and substance compliance compose the Sustainability Module. A system architecture including Sustainability Module, PLM and other design supporting tools is shown at the end.

5.1 Opening Product Model from PLM to LCA

The operations and representations in the two systems are different. In order to integrate them, firstly a common representation of product model must be used. However, the aggregated materials and processes in LCA do not clearly indicate which part is a “hot spot” and are difficult to change when another alternative is worked out. The main goal is to let LCA to receive structural items and use them to perform a LCA study.

In section 2.3, product structure usually used in PLM is introduced. A product structure includes assembly, parts and features. Assembly consists of sub-assembly and parts. Parts consist of features. Each part or sub-assembly can be subordinate to only one other assembly to ensure a hierarchical tree rather than a network [27].

A hierarchical tree structure comprises of four entity types, namely the root, nodes, leafs and features. Such a data structure basically resembles a product tree consisting of root representing product and a set of assemblies (tree nodes), parts (tree leafs) and attributes (process features).

Analyzing each entity in the tree structure, each type may reside in different LCA phases with different type of processes. For example, a part, i.e. a leaf, is defined as a node with no child. It is produced by intermediate materials through production LCA phase. These intermediate materials are transformed from raw materials through raw material extraction LCA phase. Then, it is assembled with other parts using energy to form an assembly, i.e. a node. In this case, the node can be associated to production LCA phase. Both assemblies and parts need to be transported to certain places. So both node and leaf has transportation LCA phase. Finally, parts are disposed or recycled individually or within an assembly. They finally have end of life LCA phase.

Morbidoni and associates conclude that actual data entities of those type can be associated to process types and life cycle phases as shown in Table 5.1 [65].

Table 5.1 Entity, Life cycle and process type

Entity	LCA phase	Type of processes
Root	Production Use End of life	Assembly Transportation Energy production
Node	Production End of life	Assembly Transportation
Leaf	Production End of life	Material Transformation Transportation
Feature	Manufacturing	Machining

After defining each entity in the hierarchical tree structure associated to five LCA phases, a product model using structural items can be opened in LCA directly received from PLM.

5.2 Complete the Life Cycle Information Extracted Through Proper Mappings

After the entities within a product model can be associated with different life cycle stages, the next step is to extract proper materials and processes in order to complete the entire life cycle of the product. Actual data of individual allocation parameter are extracted mainly from PLM or design supporting systems integrated with PLM. Mappings could be built through programmed procedures to allow automatically extraction from multiple places. For example, features like material and volume should be linked to material transformation processes. This information can usually be found in a CAD or PLM system. Features like manufacturing methods are available in CAM or manually select and assign. Other features such as, transportation modes and distance, end of life treatment scenario, can be found in embedded documents attached to each structural item in PLM. For those embedded documents, a machine-readable format shall be enabled for auto extraction. If recycle or reuse is considered, complete end-of-life treatment scenarios shall be developed. For the missing processes to complete a life cycle, manually selection from an LCI database is combined with an auto-extraction process. Table 5.2 shows requirements of life cycle stages to complete a LCA study and places to extract them.

Table 5.2 Required information for life cycle and extraction places

Life Cycle	Requirements	Extraction places
Raw material Extraction (Transformation)	• Material •Geometry • Volume	CAD, PLM
Production	• Manufacturing process • Energy • Machine selection	CAM, CAPP, PLM
Transportation	• Transportation modes • Distance	PLM
Product Use	• Energy • Resources • Parts	PLM
End of Life	• End-of-life treatment scenarios	PLM

Finally, a product model used by PLM and other Computer-aided technology (CAx) can be kept using its original structure and life cycle information associated with different entities are mapped from PLM to five life cycle stages that linked to these entities. Figure 5.1 shows the concept of such mappings from PLM to LCA.

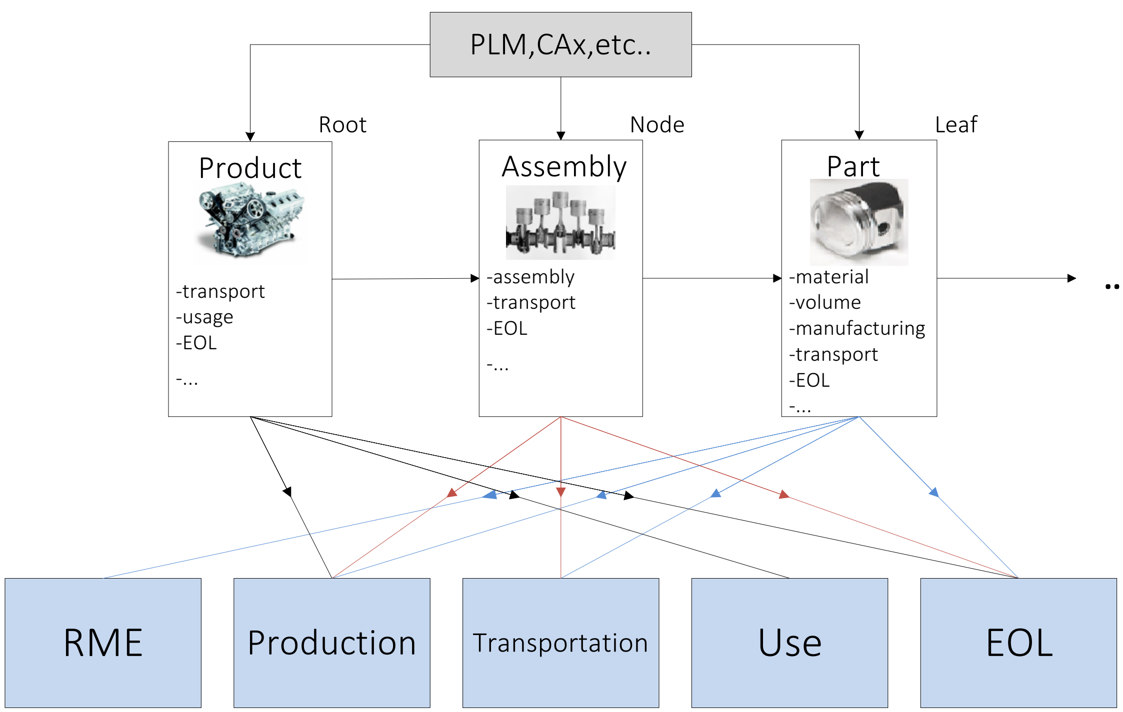


Figure 5.1 Mapping concept from PLM to LCA

5.3 Proposed LCAatPLM

A concept of a LCA framework that incorporates five life cycle stages is proposed to receive product model directly from PLM. It keeps the form of a product tree and extracts relevant information from PLM and other design supporting tools. Then, these information is filled into five life cycle stages including Raw Material Extraction (RME), Production, Transportation, Use and End-of-life (EOL). Through this means, no effort is used for remodeling the entire life cycle of a product by building a complete LCA model.

An example of product tree in Figure 5.2 is used to show how product model and lifecycle-relevant information are used in the LCA framework. In this case, A is the root representing a product, B is node representing an assembly, and C, D, E are leafs representing single part.

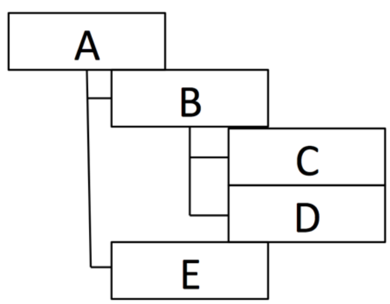


Figure 5.2 Example of a product in assembly tree

5.3.1 Raw Material Extraction Phase

In the Raw Material Extraction (RME) block, types of material and other geometrical properties are required. As shown in Table 5.1, leafs in the assembly tree have life cycle processes of material, transformation, transportation and end of life. So within this block, only leafs have input place. Available information can be found from properties defined during CAD design phases or from PLM.

Optimal material selection early in the design process will improve the overall impacts of products. Ljungberg [81] argued that material selection is one of the most important factors that affect the quest to achieve more sustainable products. Here a material selection library is proposed to be used with PLM to provide material information to the designers. Final RME block concept figure is shown below using the example.

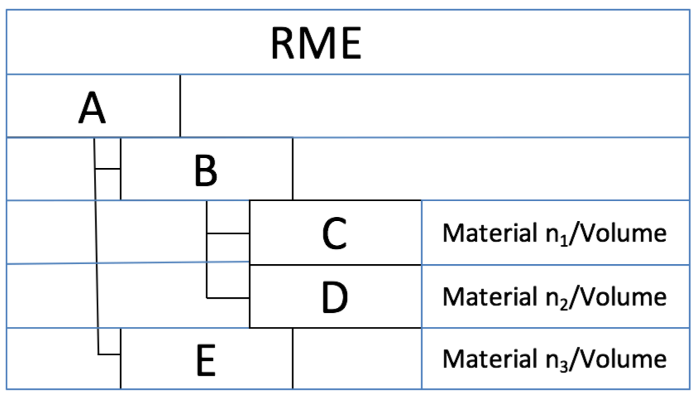


Figure 5.3 RME in proposed LCA framework

5.3.2 Production Phase

In the production block, manufacturing processes and energies are needed to manufacture the intermediate materials from RME block to the finished parts. This is the feature of leafs. Besides leafs, tree root and nodes also have input areas. The assembling of different parts into an assembly or a root may require energy. LCI database contains most of the current manufacturing processes and energy consumption which can be enough for an evaluation. Not only one process but also multiple processes ca be selected or extracted based on the design information.

There is also a need to build a machine database that contains a list of processing machines available in the company, with specific consumption [82]. By a combination of selection of multiple processes and machines a company owns, it is possible to model the correct and real manufacturing process. One challenge mentioned above that LCI databases which are never sufficient can be mitigated by a customizable LCA database which continuously update the latest LCI by adding processes, and adding or adjusting the available machines. A conceptual figure of Production block is shown below.

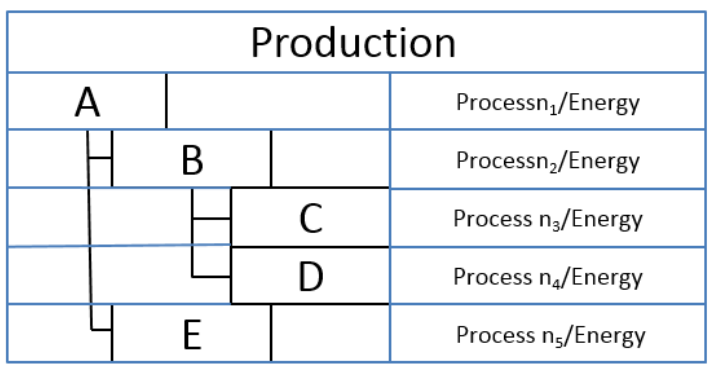


Figure 5.4 Production in proposed LCA framework

5.3.3 Transportation Phase

In the Transportation block, transportation modes and distance are required to complete this stage. All the entities in the tree structure can be associated to transportation phase as shown in Figure 5.5.

Traditionally, when remodeling this stage using LCA software or methods, an aggregated estimation of modes and distance is used to represent the whole product transportation stage. However, by separating the entire product structure into each part, in other words, separating the one entire life cycle of a product into one life cycle for each part, every entity in the tree structure can have its own transportation modes and distance. This will help to understand how the selection of supplier influences the final ecological impacts. This is rather important in real world. Since nowadays, one product is seldom produced in one place. The selection of supplier while considering the cost and also environmental impacts becomes a problem.

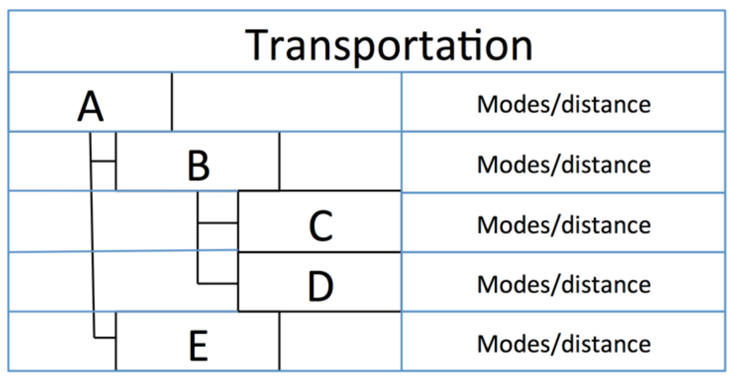


Figure 5.5 Transportation in proposed LCA framework

5.3.4 Use Phase

The Use phase can sometimes contribute most to the environmental impact of a product. The use of the finished product includes use of resources or energy and use of components. Firstly, the use of energy or resources can be selected processes from LCA database and assign them the product. Secondly, due to the degradation of the components and their subsequent substitution or maintenance, the replacement and repair have a relevant contribution and computation of two or more of them. So in the Use column, it enables multiple selections from processes like the consumption of electricity, water, to components to allow the maintenance and replacement phases to be considered. Only root can be associated with the Use phase as shown in Figure 5.6.

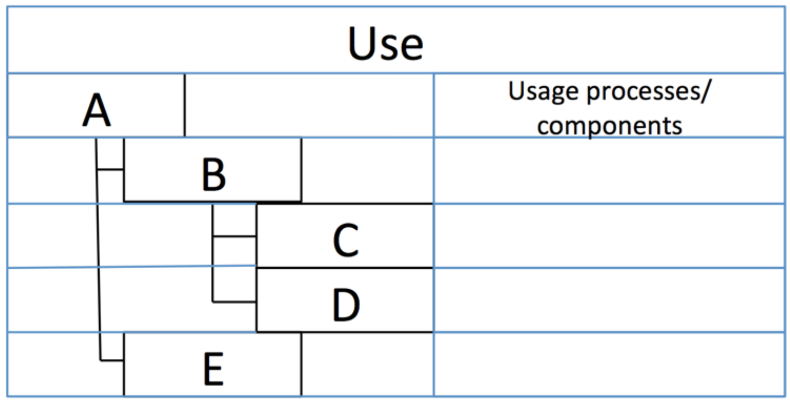


Figure 5.6 Use phase in proposed LCA framework

5.3.5 End-of-Life Phase

Finally, the End-of-Life stage is little more difficulty than the former stages. First barrier is that usually during the design stages, the final end-of-life treatment scenarios are not decided. It is necessary to envisage every possible End-of-Life treatment scenarios and this process is usually time-consuming. The second issue is there is a tendency for sustainable products sliding from a cradle-to-grave approach to a cradle-to-cradle one [83]. This can be seen from several regulations, such as End-of-Life Vehicle (ELV) [refer] which is designed to promote collection, reuse and recycling of vehicles. Usually a closed-loop industrial system implies that manufacturers do not only take care of product manufacturing and use, but also of how products can be taken back and treated at their end-of-life or re-included in new lifecycles [84] [85]. Reuse, remanufacture and recycle are of great importance to lower the environmental impacts of a product. Gehin et al. [86] introduced 3R strategy for closed-loop system named after a mix of the three EOL scenarios : Reuse, Remanufacture and Recycle. For example, if the component i is recycled in a closed-loop system (it is assumed that the recycled material is used for manufacture the same type of components) or remanufactured, or reused, then for each usage cycle between 2 and u_i 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 u_i 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. So in the proposed EOL column, each component has four choices: Reuse, Recycle, Remanufacturing and other treatment (Disposal, incineration, Landfill, etc.). Morbidoni et al. [66] provides an approach to solve EOL treatment scenarios. In their paper, they proposed firstly in the Reuse choice, the reuse times can be specified for the calculation of environmental impact, a component can be reused more times during the product life cycle, after it cannot be used, the other three choices can be selected. Secondly in the Recycle choice, the user can select “closed loop” or “Generic recycle” as recycle types, the first case the material is reused for the same component production, in the other case the material is used for other applications. In the Remanufacturing choice, percentage of components that can be effectively remanufactured is defined as well as remanufacturing times. After components can no longer be used, recycle and other treatment choices can be selected. In the last choice, Other Treatment, an EOL process (Incineration, Landfill, etc.) can be selected from LCA database. To save time, these four choices can be assigned to parts, assemblies and the whole product. It is not necessarily to define EOL for each part. EOL stage unlike other stages strongly depends on the types of the product. Usually for less complex product, Other Treatment choice is sufficient. But for products like vehicle or electronic devices, a mix of all four choices will be selected and defined. By defining all the EOL treatment like this, a direct view of End of life phase will be acquired for analyzing product against strict environmental regulations during the design stage. An illustrative figure of EOL column is shown below, each EOL can be opened and select from four choices and define relevant data to complete EOL stage.

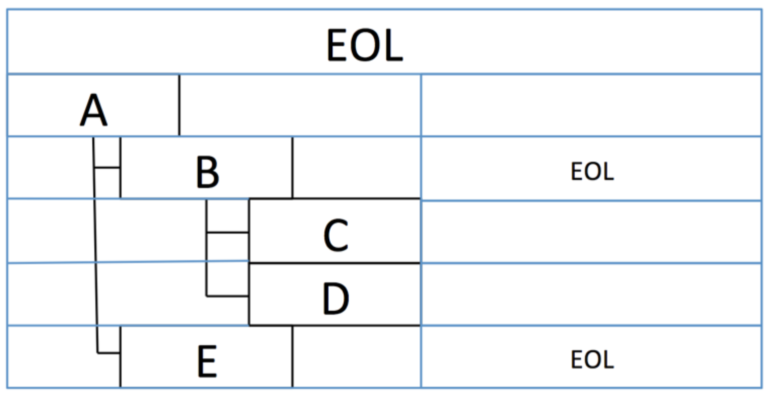


Figure 5.7 EOL in proposed LCA framework

5.3.6 Overall LCA Framework

After introducing five blocks of the proposed LCA framework, the overall LCA framework in Sustainability Module within PLM is shown in Figure 5.8. Each block can be opened separately for information input in order to complete the life cycle. The idea of making environmental impacts as a dependent property attached to assemblies or parts is introduced. Designers can perform a LCA study just after an assembly is designed. The results will be used for quick add to the product and comparison with other assembly design. When a revision of assembly or product is worked out, a new LCA result will be attached to the revision. By this means, the designers can monitor the environmental impacts directly. The dependent property can be visited directly during the calculation of a complete product, which significantly save computing time when dealing with a complex product structure.

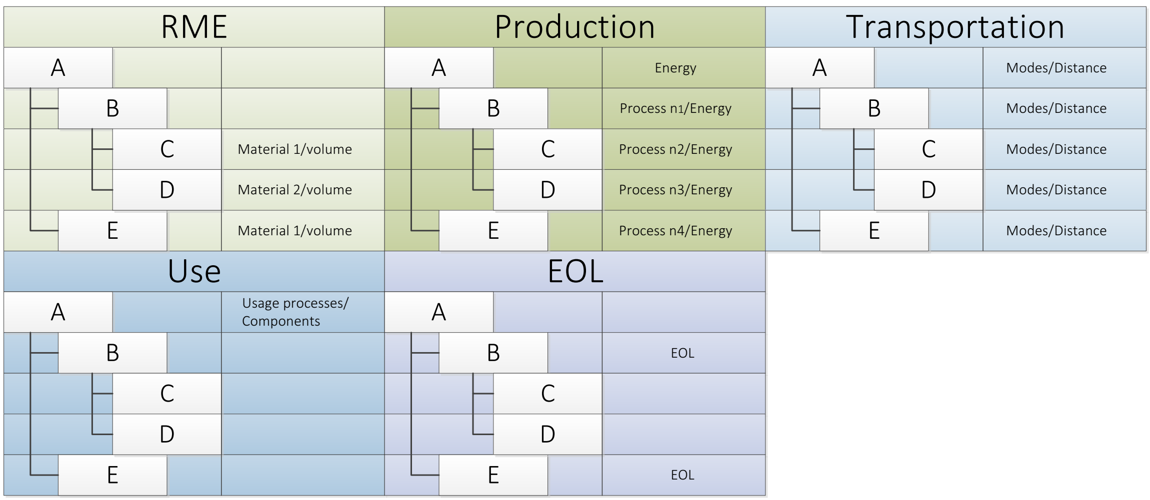


Figure 5.8 Overall proposed LCA framework

Several works on LCA integrated with CAD [27] [64] [65] used a common idea that components in a product tree can be associated with different life cycle phases. This idea established the fundamental basis for this work. However, these fundamental works developed a user interface that connects a CAD system and LCA, and input life cycle parameters one component after another by visiting each entity in an assembly tree in CAD system. Thus, they are still two stand-alone systems. Some of them excluded certain life cycle stages for simplification.

This work proposed a LCA framework used in a PLM system in order to retrieve data that cannot be provided by an assembly tree used in a CAD system.

What's more, this work integrates a product model and a process model, and brings them in the same interface. This feature gives designers a direct view on components associated with their life cycle stages and allows them to easily select and modify different processes. Also, this framework covers a complete life cycle, which guarantees more accurate environmental performance of the product. Many features, including process management and integration with design supporting tools, provided by PLM beyond a single CAD system can not only bring design participants of different expertise into one place but also provides more comprehensive information of a product.

5.4 Proposed Substance Compliance Module used in PLM

The environmental concern usually starts with "complying with regulations". A certain product belongs to a certain category that might fall under restrictions. Sometimes, they are even more important than a lower environmental impacts. Falling to comply with these regulations makes product unable to enter market for the worst case.

A review of some of the environmental regulations found they focus on different life cycle stages. RoHS, also known as, Lead-Free, stands for Restriction of Hazardous Substances. It restricts the use of six hazardous materials found in electrical and electronic products. REACH also aims to protect human health and environment through the identification of the intrinsic properties of chemical substances. Regulations of such focus on earlier life cycle stages in order to maintain the product do not consist of restricted materials. However, in recent years, more and more focus has been on the reuse, recycling and recovery of the products after they are disposed. Responding to constantly more demanding European legislation, notably for electrical and electronic equipment, worn-out vehicles or hazardous substances, manufacturers have to develop End-of-Life (EOL) strategies [83]. For example, the European Union's End-of-Life Vehicle (ELV) Directive, which came into force in September 2000, aims at making dismantling and recycling of ELVs more environmental friendly. It sets clear quantified targets for reuse, recycling and recovery of the ELVs and their components. Waste of electrical and electronic equipment (WEEE) also focus on the end-of-life stages by setting targets of collection, recycling and recovery for all types of electrical goods.

Current solutions on these matters includes Environmental Compliance and product sustainability module used in Teamcenter from Siemens, Windchill Product Analytics from PTC and product compliance software from Thinkstep. BOM combined with information provided from suppliers enable them to track and manage the compliance of products very early. With Bill of Substance (BOS) acquired from BOM and suppliers, it is easier to check the use of hazardous materials at very start. Compared with REACH and RoHS, ELV and WEEE target mainly on the end of life phase. In the proposed LCA framework, detailed scenarios can be set for each part or assembly. After an alternative is worked out, designers can have a directly view on the End-of-Life phase by generating a disassembly report, recovery rate or other ways. Even though these settings may not be final ones, its main aim is to improve the knowledge of the product at the earliest time for designers.

Finally, as the complying with regulations is the start of the eco-design process, the substance compliance module will be serve as a gate of YES and NO. New alternatives that comply with the relevant regulations after checked by substance compliance module will continue their design processes. New alternatives that violate the regulations after checking will be marked and returned no matter how good their LCA results are. This process keeps all the developing new alternatives comply with regulations from the start to the end of development process.

5.5 Proposed System Architecture

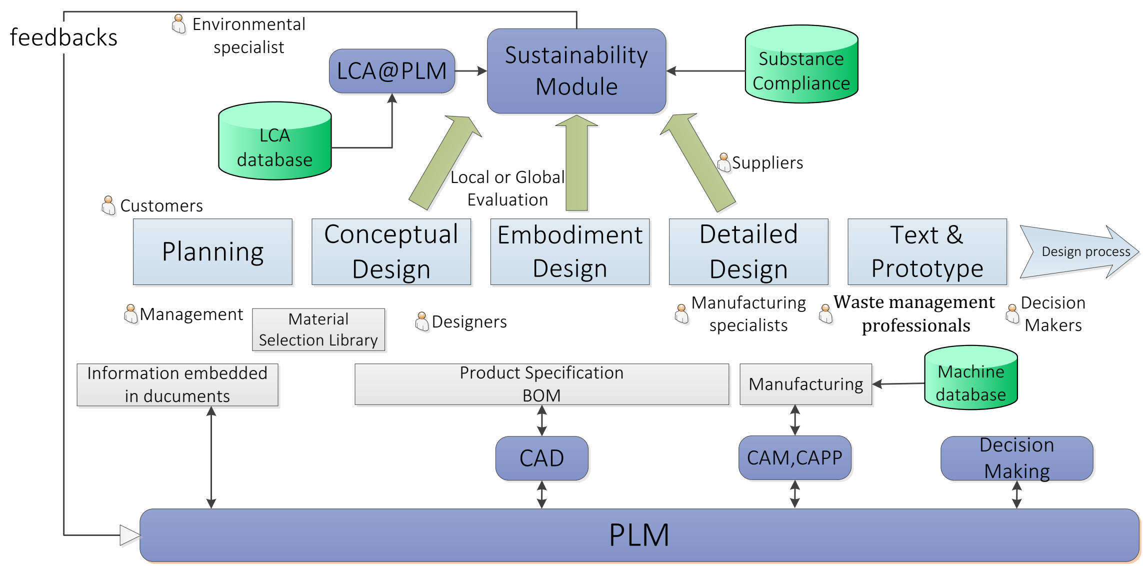


Figure 5.9 Proposed system architecture

The Sustainability Module will be like other integrated applications within PLM like CAD, CAM, etc. A proposed system architecture is shown in Figure 5.9. The PLM serve as the foundation for all by managing information from all source to maximize information sharing and interoperability. Information that are embedded in the documents helps translate needs into design goals and complete life cycle information that cannot extract from CAx. A decision-making module is added at the end for design attributes collection and comparison of alternatives. Since a decision-support system is lack in PLM, in this case a spreadsheet is attach to PLM for decision making.

This architecture includes two levels. Firstly, the horizontal level is a normal product design process. Different from the definition of life cycle in PLM, i.e. from ideation, design to service, this architecture mainly emphasizes its use during design stages. Usually the boundary between phases are vague. The design process is not a phase after phase procedure. Sometimes a detailed design alternative may go back to planning phase and restart. The most sustainable design meets all the criteria defined at the start, balancing cost, performance, environmental impacts and so on. However, during the real implementation, there are always trade-offs. In order to get a more optimal design, the vertical level will help. After design alternatives are worked out, they will send to Sustainability Module for identifying “hot spots”, check substance compliance and generate an environmental report. These information are feedback to PLM to notify designers on the environmental performance of that alternative for future modifications. These reports are also attached to each alternative and fill into the decision-making module. Since there is no boundary between design stages, designers can make local or global evaluation and do not have to wait only after the life cycle information of an alternative is complete. Local evaluation means designers can evaluate finished assembly or parts, while global evaluation means evaluate of full product in terms of the environmental impacts.

Also, after evaluation, instant feedback is sent back to PLM. Through constant feedbacks, products in terms of environmental impacts are well monitored. Combined with other design attributes gathered from PLM and other places, all design attributes are stored in decision making module for a holistic consideration of all design attributes.

Another feature of the architecture is the participation of people from different fields. Bring all design participants into one place is crucial for shorten developing time, maximizing information sharing and interoperability. There certainly are roles which are not shown in the framework, however, the basic idea is that people ranging from customers, suppliers to designers of different departments should have their roles in the right place at the right time.

CHAPTER 6

DESIGN METHODOLOGY

A sustainable design methodology is proposed using the concept of proposed Sustainability Module integrated within PLM. The design methodology combined with LCAatPLM mainly tries to solve the challenges mentioned in Chapter 4. Some design steps use of capability provided by a PLM system. The main design process of the methodology is shown in Figure 6.1 followed by a detailed illustration of each process. We illustrate this methodology is used at early design stages, where potential design goals and alternatives are established for comparison.

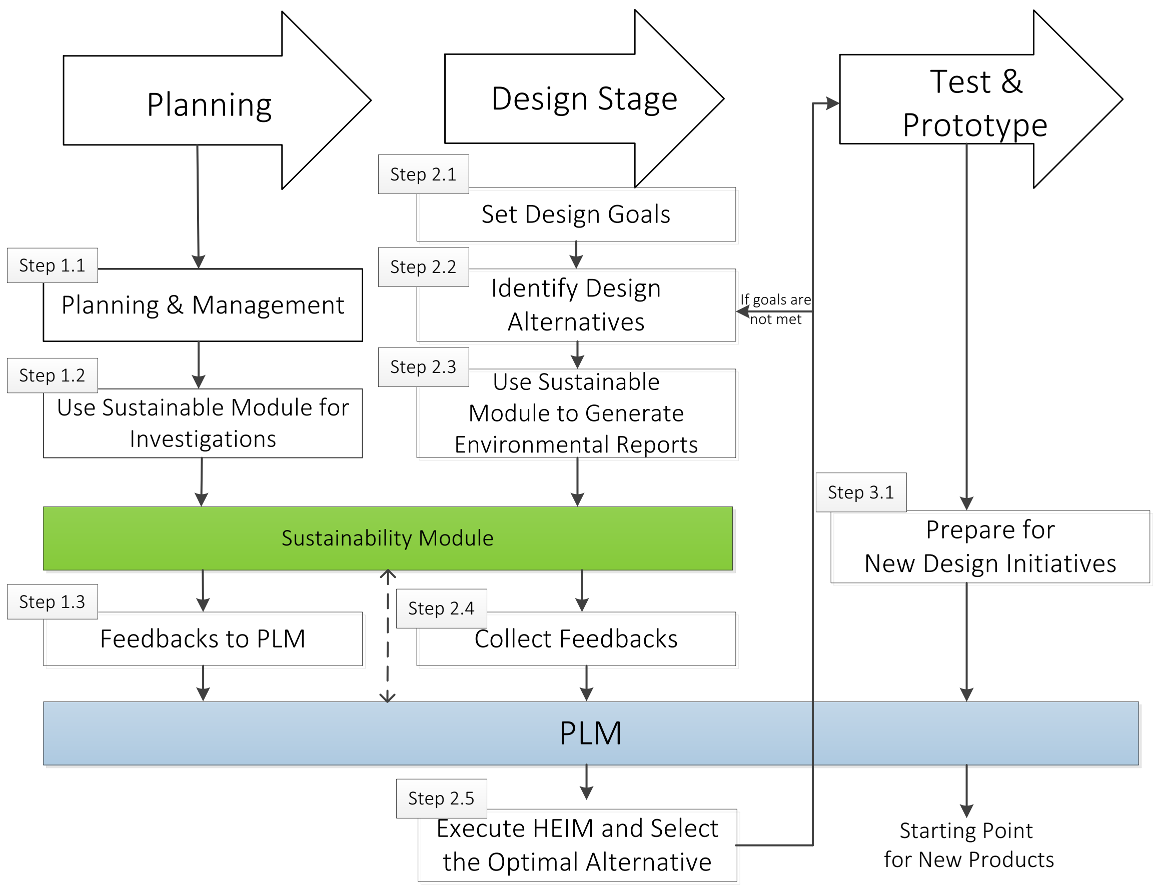


Figure 6.1 Proposed design methodology

6.1 Before Design Stage

As shown in Figure 1.1, a PLM system has capability of data management, process management and integration with other design supporting tools. It is also a collaborative backbone allowing people of different fields to work together effectively. Some of the features provided by PLM are helpful for executing eco-design processes. Thus, many authors agree that PLM is the key concept for the establishment of eco-design processes [4] [5] [6] [7].

Before design stage, planning phase exerts a major influence on all phases of development. Team coordination, strategies, need analysis and baseline are all need to support design projects. In the sections below, planning phase makes full use of capabilities of PLM.

6.1.1 Step 1.1: Planning and Management

Firstly, PLM's project management is critical to product development either in terms of collaborations or developing time. PLM can help building an eco-design team from different fields in a project. When the skills and knowledge of many disciplines are available during all stages of a project, members within the team are not overwhelmed by the task of including environmental criteria in their design. Project management also can help to create schedule with milestones and deliverables so that project are finished efficiently and on-time since everyone throughout the product lifecycle has what they need to get their work done effectively.

Secondly, PLM's requirement management can document design requirements from different sources from governmental regulations, standards and customer needs and determine whether these requirements are satisfied.

Formulating requirements is probably most critical phase of design. Requirements should be stated in detail for design team to translate needs into solutions. After formulating design alternatives, they can be evaluated on how well they meet requirements. It is important to spend enough time to develop proper requirements.

Thirdly, PLM's document management can help manage all types of files from specification, 2D/3D drawings to spreadsheets and technical publications. With this feature, design requirements are well documented, based on which different design alternatives are formulated. In this methodology, comprehensive environmental profiles are also stored in the form of a document. A spreadsheet, used as a decision-making module, is uploaded to be used for collecting design attributes and decision-making.

Besides using these features, some more work need to be done during the planning phase. Needs Analysis is usually performed off the system. Needs come from many sources, including customers, researches, or existing product systems. In any case, the need which a design commits must be clearly stated and existing options for meeting the need must be assessed.

The focus of this research is to pursue the most sustainable pathways for addressing needs. Baseline analysis of existing products and benchmarking competitors may indicate opportunities for improving a product's environmental performance. For a redesigning process, components and subassemblies are already available in the reference model. Wenzel and colleagues refer to already existing components and subassemblies as reference products, and assume that environmental information is already available for these systems [87]. In this case, a reference model of a company's last generation product or product of similar family could be used for analysis and solving the data unavailability at early development stage. Usually, product data have already been stored in PLM and ready for use. Environmental profile of the reference model will be instantly available using Sustainability Module.

However, for completely new products with little information is readily at hand, there are two solutions that can solve information unavailability at early design stage. Firstly, since new product are usually based on existing technologies in new compositions, it is possible to compose a useful reference product by putting existing units and technologies together to form a fictive model. The second solution is the idea of LCA-comparison product families (LCP-families) [88] as a set of products whose LCA shares a common behavior and can be compared in some practical way. Even though the starting phase will take some time for a completely product, once the design process is finished, future development will become much easier and faster.

6.1.2 Step 1.2: Use of Sustainability Module for an Initial Investigation

The initial investigation includes three parts. Firstly, an environmental profile of the reference product will be generated. All information about the reference product are stored in PLM in the form of hierarchical tree with detailed BOM and other LCI-relevant information. LCAatPLM will receive product model from PLM and extract relevant information from multiple places to complete the life cycle of the reference product and fill into the five LCA blocks. Much information can be automatically extracted, while designers can also manually select LCI to complete the life cycle.

However, the environmental profile of a product is a summary of all environmental impacts throughout the product's life cycle. Making these impact categories clear to non-environmental experts is quite critical if environmental attributes are to be used early. In an attempt to simplify the LCA output for decision-making, the greatest environmental impacts have been considered for simplicity. Through normalization, characterization and weighting, multiple environmental impacts categories are transformed into an environmental index that indicate the overall environmental performance of the product. Such a quantitative number requires no environmental expertise and can be easily understood and used by designers. The overall environmental profile will be helpful to analyze the product improvement in terms of environment. The single environmental index is used for purpose of supporting decision-making process.

Secondly, a substance compliance report will be generated. The substance compliance in Sustainability Module will help to check whether the reference model complies with the existing environmental regulations in order to identify the restrictions. It will make sure all the components within the reference model can be reused and assembled into a new product. The success of this step greatly depends on the communication with suppliers. A direct view at end-of-life treatment of the reference product also can be acquired for analysis.

Thirdly, the most important sources of environmental impact in the reference model's life cycle (environmental 'hot spots') are pointed out in order to identify potential focus areas for the further product development. The LCA framework separate the whole life cycle of a product into each unique life cycle of a part or an assembly. Each unique life cycle will generate the component's LCA. Then, these component's LCA results are transformed into environmental indexes using the same characterization, normalization and weighting method as used above. These indexes will be attached to the components accordingly. The designers can compare all the components within an assembly according these environmental indexes and then determine which components are 'hot spots'. Also, the five life cycle phases will notify designers which stages of the reference model contribute most.

With an overall report regarding the environmental performance of the reference model, environmental requirements can be formulated. New alternatives can be identified by replacing the environmental 'hot spots'. The LCA results of reference model can be also served as a measure of success when it is compared with new sets of alternatives.

6.1.3 Step 1.3: Feedbacks to PLM

The generated environmental report including environmental profile, substance compliance report and environmental 'hot spots' are then fed back to

PLM to allow all the design participants to view. Management person can make new environmental policy and make environmental requirements on the future product.

The substance compliance report will notify designers whether all components within the reference model comply with regulations. If some of them are violets the regulations, they will help set design goals on solving that issue. For other components, they are safe to be reused.

All the design attributes of the reference product are also filled into the decision-making module in PLM. It will work as a baseline to evaluate the performance of the new alternatives.

6.2 Design Phase

This design process uses some of the ideas from NASDOP [19] developed by Dr. Eddy who is in cooperation with the author on this research. The NASDOP design process first identifies design alternatives based on design goals. Then, for each alternative, LCA and LCC (Life Cycle Costing) are used to account for all environmental and cost flows to determine the resulting environmental and cost attributes. Then uncertainties are accounted for due to significant uncertainty in environmental and cost data. HEIM (hypothetical equivalents and inequivalents method) is executed to find the weights of the attributes based on the stated preferences of the decision maker. Finally, MAU (Multi-attribute utility) value are computed for each design alternative and the alternative with greatest MAU value is chosen. If the design goals are not met, new sets of design alternatives are identified and repeat the processes until the design goals are met.

6.2.1 Step 2.1: Set Design Goals

After the planning phases, design requirements, need analysis are all formulated and stored in PLM. An initial investigation of the reference model is also performed to get environmental requirements. Then, design goals are firstly set in order to identify new alternatives that satisfy them.

6.2.2 Step 2.2: Identify Design Alternatives

After the environmental profile of the reference product is acquired, design goals including all aspects of the product such as, cost, environmental performance, feasibility, etc. must be taken into consideration to ensure the new alternatives at least get close to the goals. New functionalities can be added to the reference product in order to meet the current customer's needs.

Regarding the environmental performances, it is time to determine whether some of the environmental 'hot spots' can be moderated or removed by modifying or replacing certain solutions in the reference model. Through this means, environmental improvements compared to the reference model can be achieved if environmental reports from PLM are taken as an opportunity to rethink traditional solutions. As for those non-environmental 'hot spots', detailed information about them can be reused directly during the design phase.

Then, new alternatives are identified through modifying or replacing certain solutions, adding new functionalities and reusing components in the reference model. Materials, weight and processes are determined. All energy uses or parts are taken into account. Transportation processes are included. End-of-Life treatment scenarios are built up based on estimations.

6.2.3 Step 2.3: Use Sustainability Module to Generate Environmental Reports

After the strategies of identifying new alternatives are set, the BOM of each new alternative is formed with the use of design supporting tools, such as CAD, and stored in the PLM in the form of a product tree structure. Product properties, such as materials types and manufacturing processes can be found in the PLM. Information on life cycle stages, such as transportations, use and end-of-life, are included in the Word files or other types of documents uploaded into PLM.

With the availability of these product data, the entire life cycle of the alternative can be modeled in order to get an LCA result. However, the proposed LCAatPLM does not need the life cycle remodeling process. It keeps the product model and fills life cycle information associated with different components in the product tree into five life cycle stages. An environmental profile is generated through this. Also, another part, substance compliance, in the Sustainability Module will check these new alternatives at the earliest whether they comply with environmental regulations in order to redesign or exclude the bad alternatives to prevent late change.

If proper mappings are built from PLM to LCA, the LCA result will be generated in real-time. It changes the static nature of LCA and let LCA dynamically updated with the modifications in alternatives so that the designers are aware of how well new alternatives become compared with reference model in terms of environmental impacts.

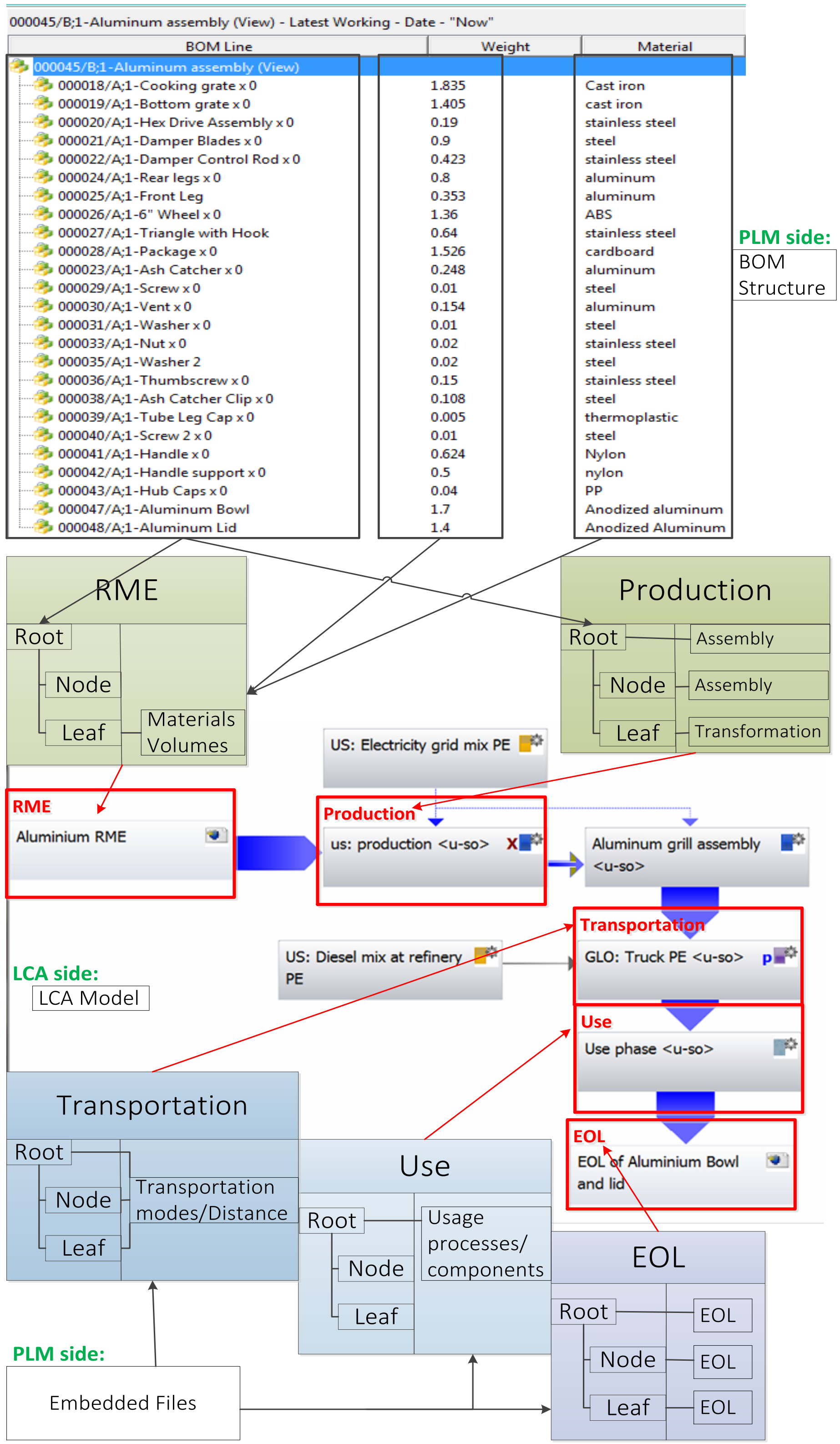


Figure 6.2 Information extraction from PLM to LCAatPLM to LCA

This step is better illustrated with an example. After a new alternative is identified, a BOM is created in PLM, as shown in Figure 6.2. This BOM will mainly provide life cycle information to the first two life cycle stages, RME and Production. Other information that cannot be represented using a product tree are embedded in Word files or documents to provide life cycle information to the rest stages, which are Transportation, Use and EOL. After proper mappings are built to connect PLM to this LCA framework, a life cycle of the product model is complete. Thus, LCA results will be available.

However, since this research does not yet involve any programming, its aim is to provide a concept on how LCA can be best used within PLM and a blueprint for software developers. Thus, this concept is achieved through other way first.

An LCA model is created with specific creating rules using a commercial LCA software. In Figure 6.2, five life cycle processes which are marked in red box are deliberately created to represent the five LCA blocks in LCAatPLM. Other processes are either selected directly from LCI databases to serve as inputs or for connection purpose. Through this means, a simulation of the proposed LCAatPLM is firstly achieved by using a LCA tool and a PLM system separately.

However, as mentioned above, the materials and processes are aggregated in LCA without considering the product tree. There is no way to get LCA results on each single part except for creating LCA models of each part one after another manually, which is significantly time-consuming. Thus, although the author simulates the operations in LCAatPLM by input product properties based on the product tree one by one, the same materials or processes are still added together in the end. Due to limited time, the LCA results of each part are not generated. Otherwise, they will make this research more complete on the aspect of identifying environmental ‘hot spots’ based on each part.

But that does not necessarily mean these ‘hot spots’ cannot be identified. The LCA tool enables detailed environmental analysis. Which life cycle stages contribute most to the environment can be easily identified. The identification of environmental ‘hot spots’ based on parts requires extra analysis by opening impact results of each life cycle stage. This process requires some time. The proposed LCAatPLM tends to make this process more apparent and easy.

Simulation of another part, Substance Compliance, in the Sustainability Module is achieved manually by analyzing the BOM against environmental regulations. Overall, the simulation of Sustainability Module is done by using LCA and PLM separately however based on certain rules. This section shows how a LCA tool is actually integrated with a PLM system.

6.2.4 Step 2.4: Collect Feedbacks

After environmental reports have been generated, PLM collects them. Different categories of environmental impacts, through normalization, characterization and weighting, are transformed into an environmental index and filled into decision-making module uploaded in PLM, in this case, a spreadsheet. They will be used as one of the design attributes for selecting the optimal. As the new alternatives are identified, other design attributes are set, such as cost, performance and other relevant attributes. The decision-making module also collects them and brings all the attributes into one place. It is straight forward for designers to view all the design attributes at the same time and execute the comparison process.

6.2.5 Step 2.5: Execute HEIM and Select the Optimal Alternative

At the step, the goal of this research is met, which is a holistic consideration of environmental impacts along this other design attributes at early design stage. New alternative and reference product are compared with each other from a holistic consideration of all design attributes. Qualitative and Quantitative comparison can both be applied to the decision-making process.

Qualitative analysis can be firstly used for excluding mostly unlikely alternative in order to save time for performing a quantitative analysis. If the cost, for example, is the only significant difference between different alternatives, the comparison of costs will not require any decision-making process. If more attributes are considered, the alternatives will be hard to tell from each other.

In this case, quantitative comparison using Multi-Criteria Decision Making (MCDM) method will be used. Multiple attributes have already been listed in the decision-making module including environmental impacts, cost and so on. They can then be evaluated as a MCDM process using HEIM. The preference among the design attributes are modeled using HEIM. Then an optimization problem is formulated based on the preference structure. The problem is solved for weights. Finally, the alternative with maximum value is the optimal one.

It should be noted that the largest environmental improvement potentials are not necessarily found among these "hot spots". The improvement potential can be zero if actual solutions have already been optimized to the best situation. This can be reviewed by monitoring the environmental improvements on the "hot spots" components in each alternative. If their results are not so different, the redesign process should focus on the less significant 'hot spots'. As the design processes, the selected alternative is developed with more details. The increase knowledge about the product may validate original assumptions made during the conceptual design stage, but it could also reveal that one or more of the requirements cannot be met. In such case, the design process requires an additional iteration.

6.3 After Design Phase

Based on the comparison of various alternatives with difference preferences, the optimal ones shall be selected. Minor problems revealed at this point can still be corrected. After formal approval, the establishment of the product can begin.

6.3.1 Step 3.1: Prepare for New Design Initiatives

The final details of the best alternative are worked out. Detailed drawing, engineering specifications, and final process design are then completed. When all details of the best alternatives have been settled, the final environmental profile of the product can be generated. Before implementation, the alternative is compared to reference model. Final evaluation should identify both strengths and weaknesses. From the sustainability perspective, the profile will serve as documentation for the environmental properties of the product and environmental advantages which have been achieved compared with the reference model.

However, the design action does not end at this point. Product development is a continuous process. After the product enters the market, feedbacks may be returned for opportunity of improvement. The existing products should be viewed as the starting point for new initiatives.

With all information stored and well setup in PLM, future development process can be significantly facilitated.

CHAPTER 7

CASE STUDY: CHARCOAL GRILL REDESIGN

In this chapter, a case study of redesigning a charcoal grill is performed to illustrate the design methodology and system. Since there is currently no LCA and PLM integration system, a simulation of the proposed concept is introduced using LCA and PLM separately. Two commercial LCA and PLM software are introduced and showed how they will be integrated to simulate the proposed LCAatPLM, as mentioned in Section 6.2.3. After the simulation, it is applied to a Weber charcoal grill that used by Choi [89] [90]. In their paper, the product lifecycle scenario for a baseline charcoal grill is defined based on realistic scenarios and assumptions.

7.1 Simulation of the Proposed System Concept

Since currently, there is no LCA software integrated with PLM. Two stand-alone software are used in combination to simulate the proposed system. GaBi 6 from Thinkstep is used for evaluating environmental impact and Teamcenter 10 from Siemens is used as PLM system. A spreadsheet is uploaded into Teamcenter to collect design attributes and helps the decision-making process.

The use of GaBi 6 requires remodeling process of an entire life cycle of a product by creating customized blocks. In each of these blocks, inputs and outputs that remodel the life cycle of the product will be defined. These inputs usually include material type, weight, energies and processes. The outputs are the final outcome, usually finished assembly or part, within that block. The last block's output serves as the input of the next block. Then they are all connected together to complete the whole life cycle. Overall, the remodeling process enabled by LCA software is rather open as long as the users follow certain rules.

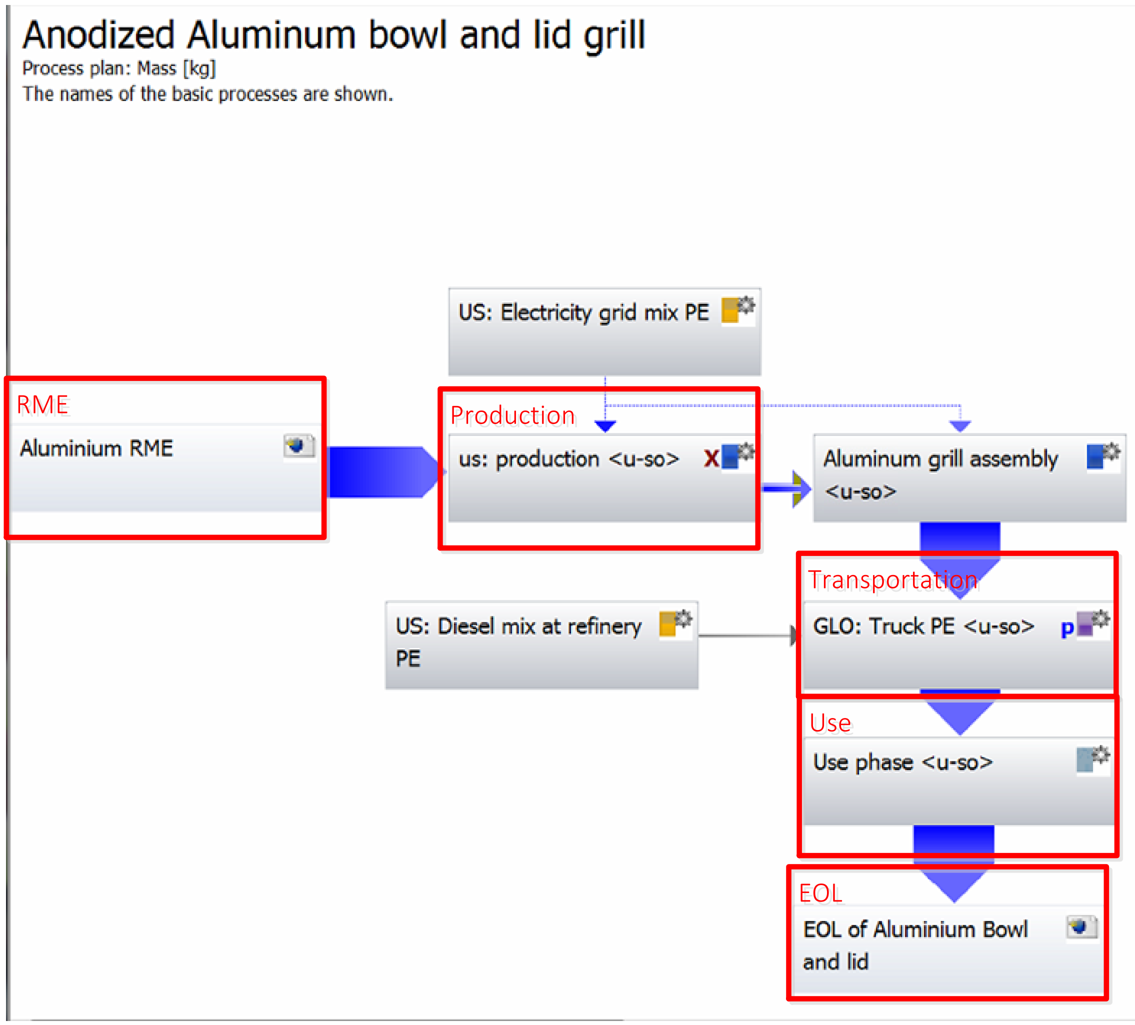
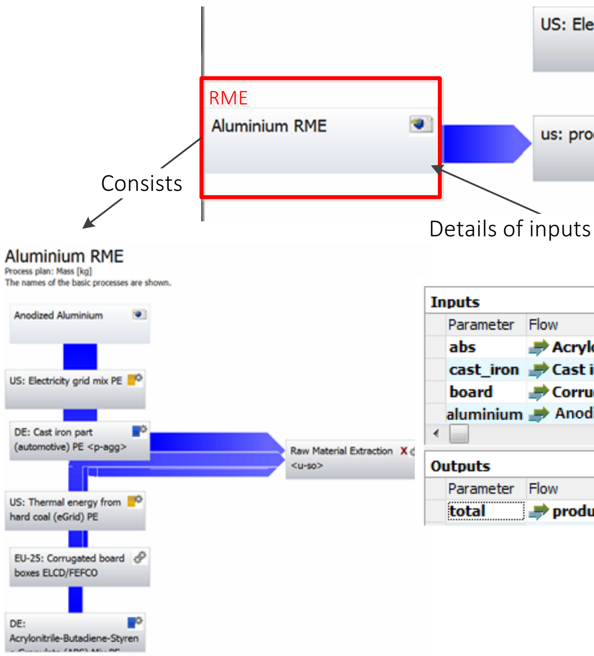


Figure 7.1 Simulation of LCAatPLM

However, in order to simulate the proposed LCA framework, those five indispensable life cycle stages that follows LCA 1400 series are prescribed on purpose. Those five stages, as introduced above, consists of RME, Production, Transportation, Use and EOL, as shown in Figure 7.1. The highlighted in red box are these five customized blocks that simulate the proposed LCA framework. In each block, inputs and outputs are defined based on product properties. For example, the

RME block is formed by several processes for producing the parts. The weight of these parts serve as inputs to RME, as shown in Figure 7.2. Other blocks are creating for connection purpose. They do not create any environmental impacts. All other LCA model of other alternatives will follow this creating rules.



Inputs

Parameter	Flow	Quantity	Amount	Factor	Unit
abs	Acrylonitrile-butadiene-styrene	Mass	1.36	1	kg
cast_iron	Cast iron part [Metal parts]	Mass	3.24	1	kg
board	Corrugated board boxes [Packa	Mass	1.53	1	kg
aluminium	Anodized aluminium [Metals]	Mass	3.1	1	kg

Outputs

Parameter	Flow	Quantity	Amount	Factor	Unit
total	productation phase [Materials]	Mass	9.23	1	kg

Figure 7.2 Inputs and Outputs in RME

The design process is mostly implemented in the PLM system. And all the information is stored there in the form of assembly tree, BOM and embedded files, as shown in Figure 7.3.

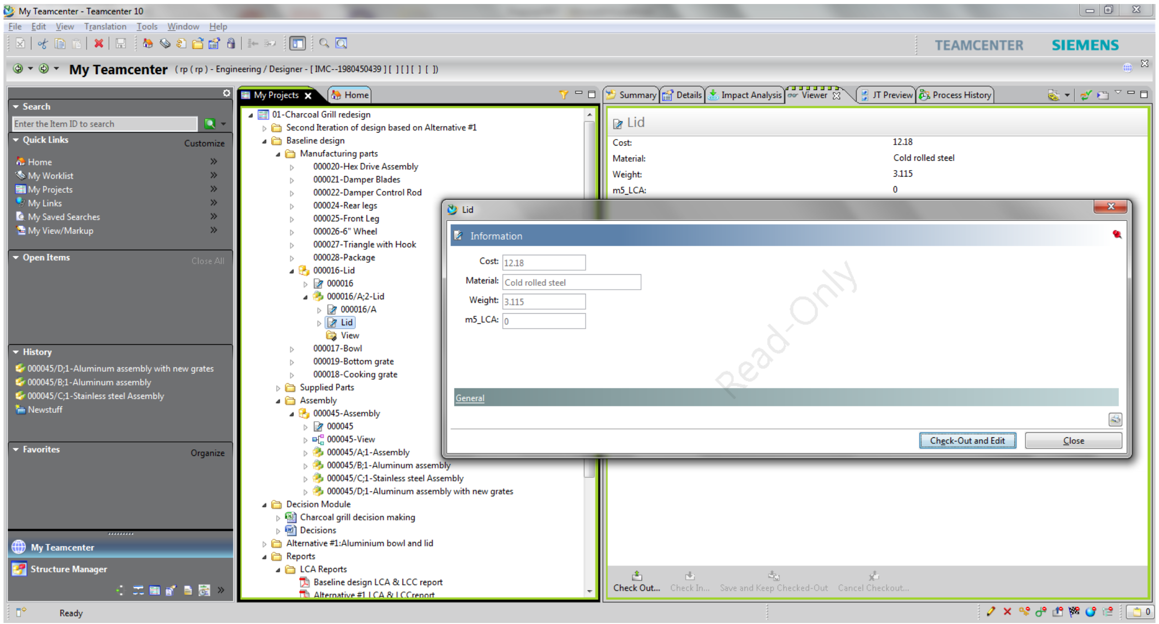


Figure 7.3 Design in PLM

Within each block, life cycle information of each entity type (root, node, leaf) associated with its life cycle stage are filled into these five red boxes. This mapping process is done manually by reading entity and its information in PLM and writing them into the LCA model created by GaBi. Through this process, the proposed concept is simulated.

Then environmental profiles will be generated and fed back from GaBi and stored in Teamcenter. Design attributes are input into spreadsheet uploaded in PLM. Other design processes, such as performance evaluation, decision-making, will be done off the proposed system.

7.2 Case Study: Before Design Stage

7.2.1 Step 1.1: Planning and Management

Firstly, a design team is formed. Since this case study is only for research purpose, only two roles are involved, which are a designer and an administrator.

The Administrator first creates a project in PLM called Charcoal Grill Redesign. Role of designer are assigned to the author and authority to access to different information. Requirements, design specifications are embedded in Word files and uploaded into PLM for sharing.

A reference product is acquired from Choi et al. [89] [90]. In their paper, well-defined information of a baseline charcoal grill is available including BOM, manufacturing process, use information and End-of-Life treatment scenarios. They propose a sustainable design methodology using the baseline charcoal grill. Other information include manufacturing, use and end-of-life can be found in their work [90].

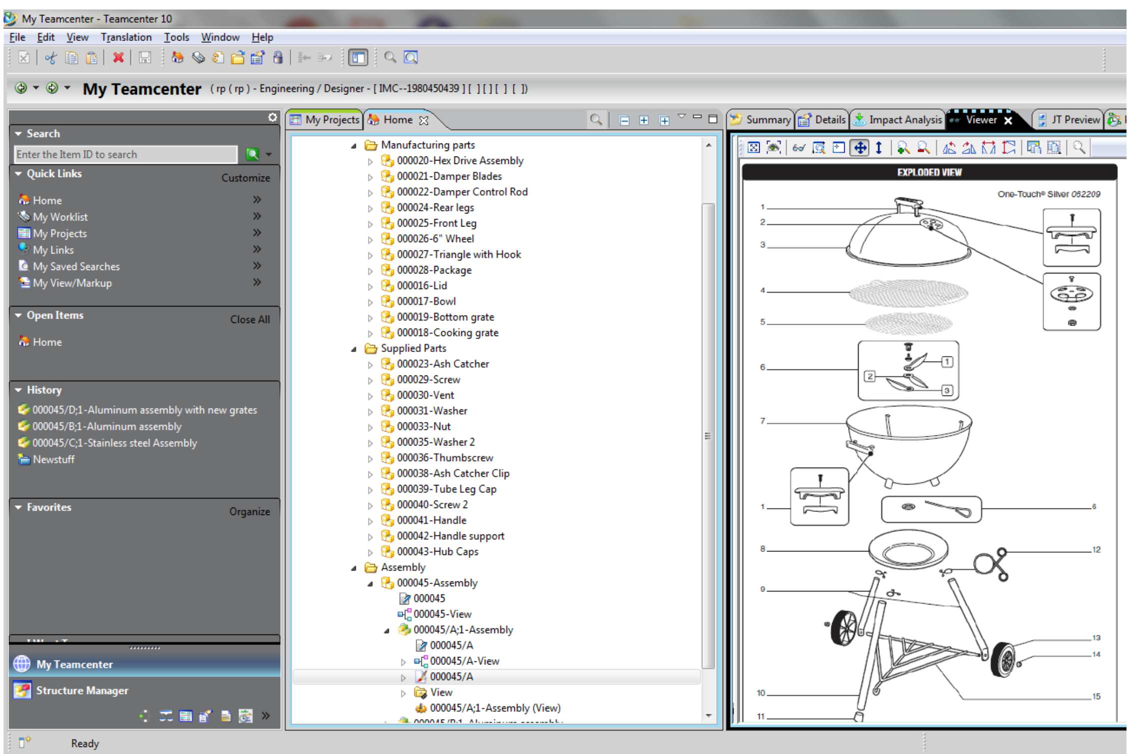


Figure 7.4 Reference product in PLM

Then, based on this baseline charcoal grill, all of the detailed information is input into PLM, as shown in Figure 7.4. The information that cannot be presented in the form of a BOM structure, are embedded in the Word files.

Then, general design goal based on customer analysis and other ways are concluded. Compared with gas grill or electronic grill, a metal charcoal grill should keep its price low to satisfy the marked. Its performance need to be upgraded. Three general goals are listed below:

1. Minimize the cost and keep it below $ 100
2. Minimize time to heat up the cooking zone to ideal cooking temperature
3. Minimize cooking time

7.2.1 Step 1.2: Use of Sustainability Module for an Initial Investigation

After all the information about the reference product is mature in PLM, use the Sustainability Module for an initial investigation. Again, since there is no LCA and PLM integration system, we will simulate the proposed LCA framework using GaBi 6 and fill each life cycle blocks based on the both BOM and embedded files from PLM. The mappings from PLM to the proposed LCA framework is illustrated using a part (Charcoal grill lid) from reference model in Figure 7.5

The material and processes to produce a charcoal grill lid is mapped from PLM to the proposed LCAatPLM as connected by black arrow. In the end, both LCA results will be generated on the lid part and the whole reference model. The lid LCA result will be sent back to the place where other properties of it are stored as a dependent property. In this case, its environmental impacts are transformed into an index. Thus, the idea of separating product life cycle into individual life cycle of per part or assembly will easily help to identify environmental 'hot spots'. However, this function is not achieved in this research. They are identified by analyzing the detailed LCA reports generated by GaBi. Additionally, the full product LCA will be sent back to PLM, including different categories of impacts.

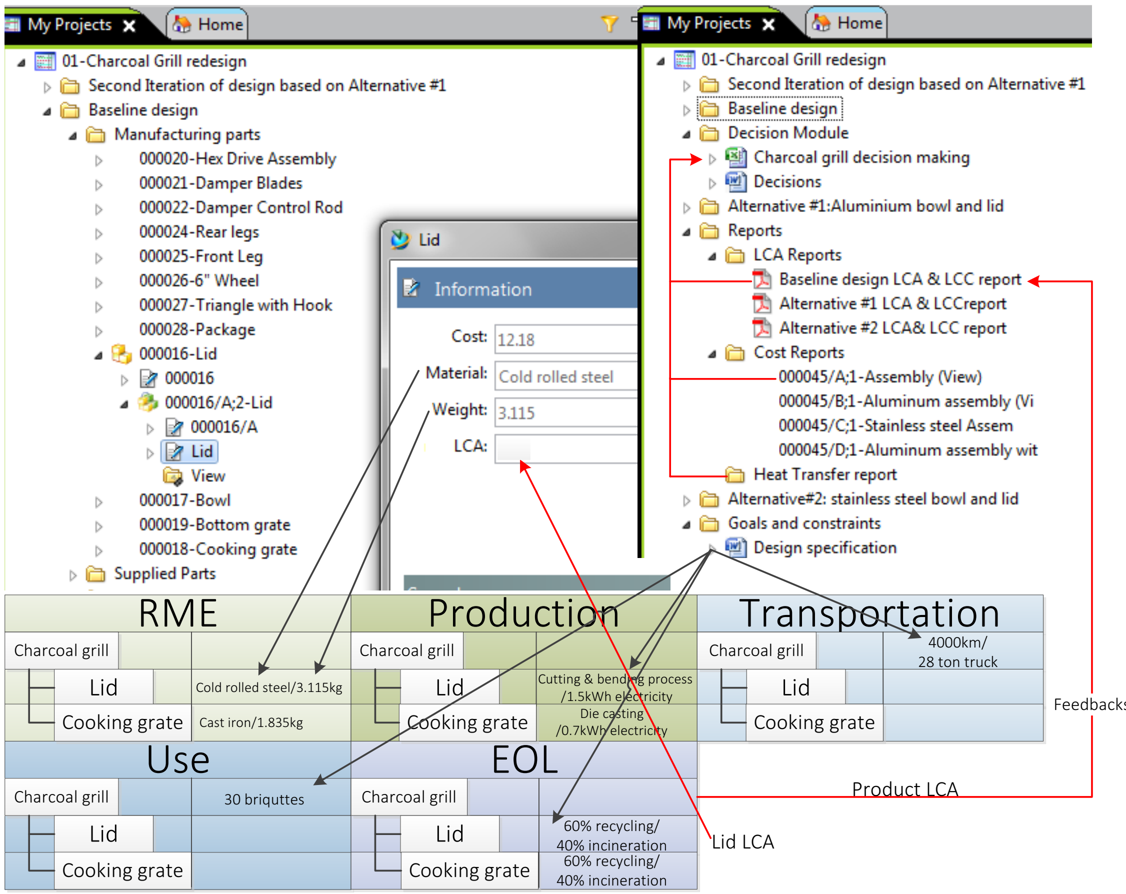


Figure 7.5 Example of mappings from PLM to LCAatPLM

To simulate the LCAatPLM, an LCA model of the baseline charcoal grill is created. Same as the LCA model mentioned in Section 6.2.3, it incorporates five life cycle stages representing five life cycle blocks proposed in LCAatPLM, as marked in red in Figure 7.6. Again, other life cycle stages in the Figure are either served as input to the stage or for connection purpose. They do not produce any kinds of environmental impacts. Within each of life cycle processes in the LCA model, inputs and outputs are setup all based on the information based on the reference model from PLM. Users can click all these life cycle processes to set and view inputs and outputs, same as shown in Figure 7.2. Due to the length of this thesis, only the LCA models of all new alternatives will be shown in this research. Finally, a simulation of LCAatPLM is illustrated with Figure 7.6. The figure shows how the life cycle information is firstly mapped from PLM to the proposed LCA framework, then use a commercial LCA tool to simulate the framework.

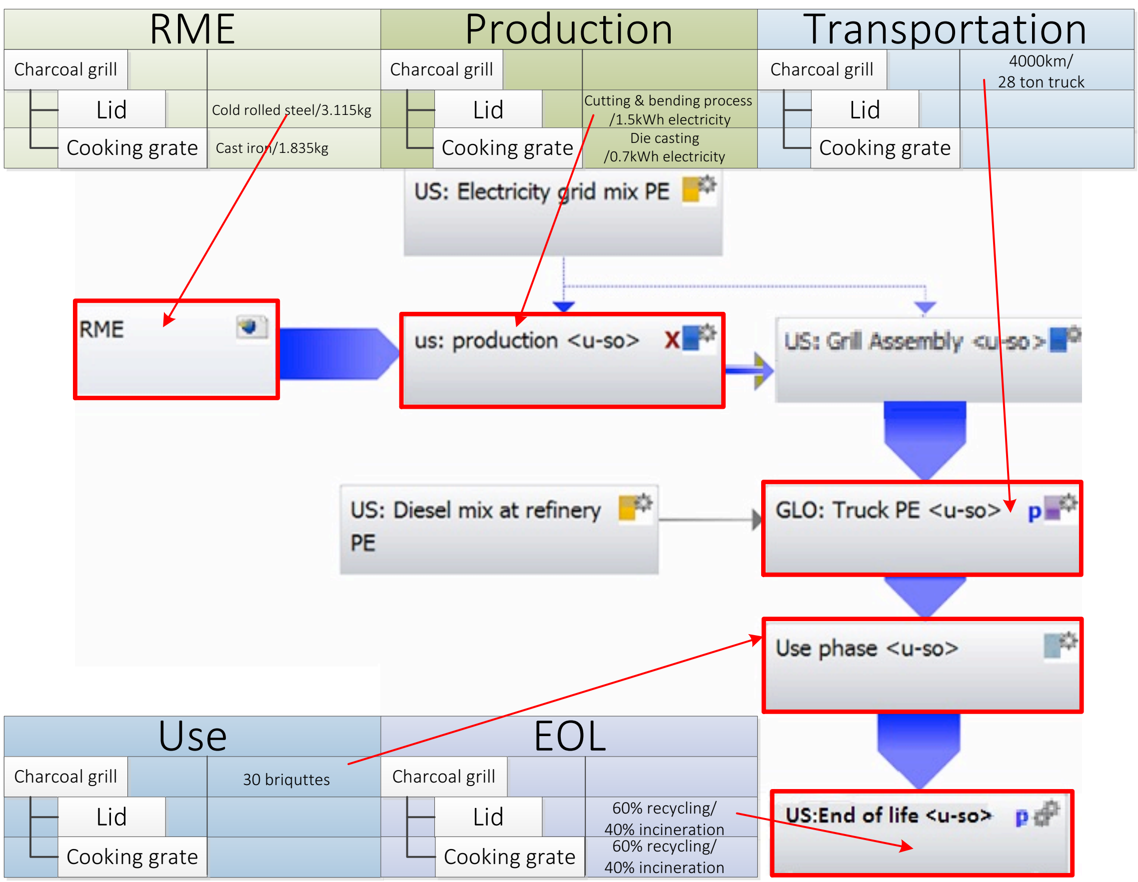


Figure 7.6 Use LCA to simulate LCAatPLM with an example

After LCA model is created and filled with life cycle information, an environmental profile can be generated. Current LCA software is able to generate comprehensive environmental reports that cover different categories of impacts. However, in order to solve the challenge of designers lacking environmental knowledge, the categories of impacts should be easy and representative. The environmental impacts are simplified for decision making purposes. Traci 1.08 provided by GaBi 6 which includes six categories of environmental impacts is used. Those categories include: Global Warming Potential (GMP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Layer Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP) and Human Toxicity Potential (HTP). The referenced charcoal grill environmental impacts are shown as Table 7.1.

Table 7.1 Environmental impacts of baseline

	CML2001 - Apr. 2013, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	CML2001 - Apr. 2013, Acidification Potential (AP) [kg SO2-Equiv.]	CML2001 - Apr. 2013, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	CML2001 - Apr. 2013, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	CML2001 - Apr. 2013, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	CML2001 - Apr. 2013, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]
Old charcoal grill LCA	669.93	3.85	0.08	0.00	1.07	9.40
EOL	-2.84	-0.02	0.00	0.00	0.00	-0.95
Raw Material Extraction	25.50	0.09	0.01	0.00	0.01	8.65
GLO: Truck PE <u-so>	3.89	0.03	0.01		-0.01	0.07
US: Assembly <u-so>						
US: Diesel mix at refinery PE	0.72	0.00	0.00	0.00	0.00	0.58
US: Electricity grid mix PE	3.49	0.01	0.00	0.00	0.00	0.20
US: Production <u-so>						
US: Use phase <u-so>	639.18	3.73	0.06		1.07	0.84

Then the environmental regulations are checked at this time. Regulations like REACH and RoHS can be checked based on Bill of Substance (BOS). Since a charcoal grill does not contain electrical parts, regulations like WEEE is not applicable to it. If it is electrical product or a vehicle, since the end-of-life treatment scenarios have been already setup in LCAatPLM, a disassembly report will be generated to give designers direction knowledge on the percentage of recovery and treatments. Besides environmental regulations, there are also some design regulations of a charcoal grill, like European Standard EN 1860-1: 2013 - Appliances, solid fuels and firelighters for barbecuing - Part 1: Barbecues burning solid fuels - Requirements and test methods [91, 92, 62, 92, 92, 92, 62, 62, 36, 36]. These regulations are not in the concern during this research. After approval, no restricted materials are used. All parts can be reused in the future alternatives.

The redesign process in this research mainly focuses on modifying or replacing environmental 'hot spots' in order to moderate or remove them. However, the functionality of identifying these 'hot spots' is not achieved. It is achieved through an analysis of impacts in different life cycle stages in LCA. Table 7.2 shows a portion of the whole LCA report. We can easily identify that use phase contributes to the environment most. Environmental 'hot spots' are identified by extending these categories of impacts and performing analysis on them. In this research, four environmental 'hot spots' are identified, which are grill bowl, lid, bottom grate and charcoal grill. These parts make up most of the charcoal grill's weight. Thus, the redesign process focus on these four parts towards impact reduction.

7.2.3 Step 1.3: Feedbacks to PLM

In the PLM, specific folders are created to store reports from different places. Also a spreadsheet is used for decision-making.

As shown in Figure 7.5, both part LCA and product LCA are fed back to PLM. Then design attributes are collected from PLM and sent to the decision-making module upload in the PLM. In this case, the environmental impacts as well as the index, after normalization, characterization and weighting, are stored in "Baseline design LCA" file. Then the environmental index is filled into the decision-making module. The cost of the product is generated using BOM report feature of PLM and then also sent to decision-making module. As the heating performance is also another design criterion, the performance of the reference model is evaluated. A quantitative result representing the performance is filled too. These attributes will be compared with new alternatives. The contents is shown in Table 7.3.

7.3 Case Study: Design Stage

7.3.1 Step 2.1: Set Design Goals

Firstly, the general design goals are mentioned above:

1. Minimize the cost and keep it below $ 100
2. Minimize time to heat up the cooking zone to ideal cooking temperature
3. Minimize cooking time

Then, based on the environmental profile obtained above, use stage and raw material extraction stage are identified to be the phases that contribute most to the environmental. Thus, two strategy of new alternatives are worked out shown in Table 7.2.

Table 7.2 Strategies of new alternatives and goals

Strategy number	Description of Strategy	Design Goal
#1	Components from renewable resources	50% more recycling and half greenhouse gas impact
#2	Efficient during use	1/3 less energy during use and 2% more materials and manufacturing impacts

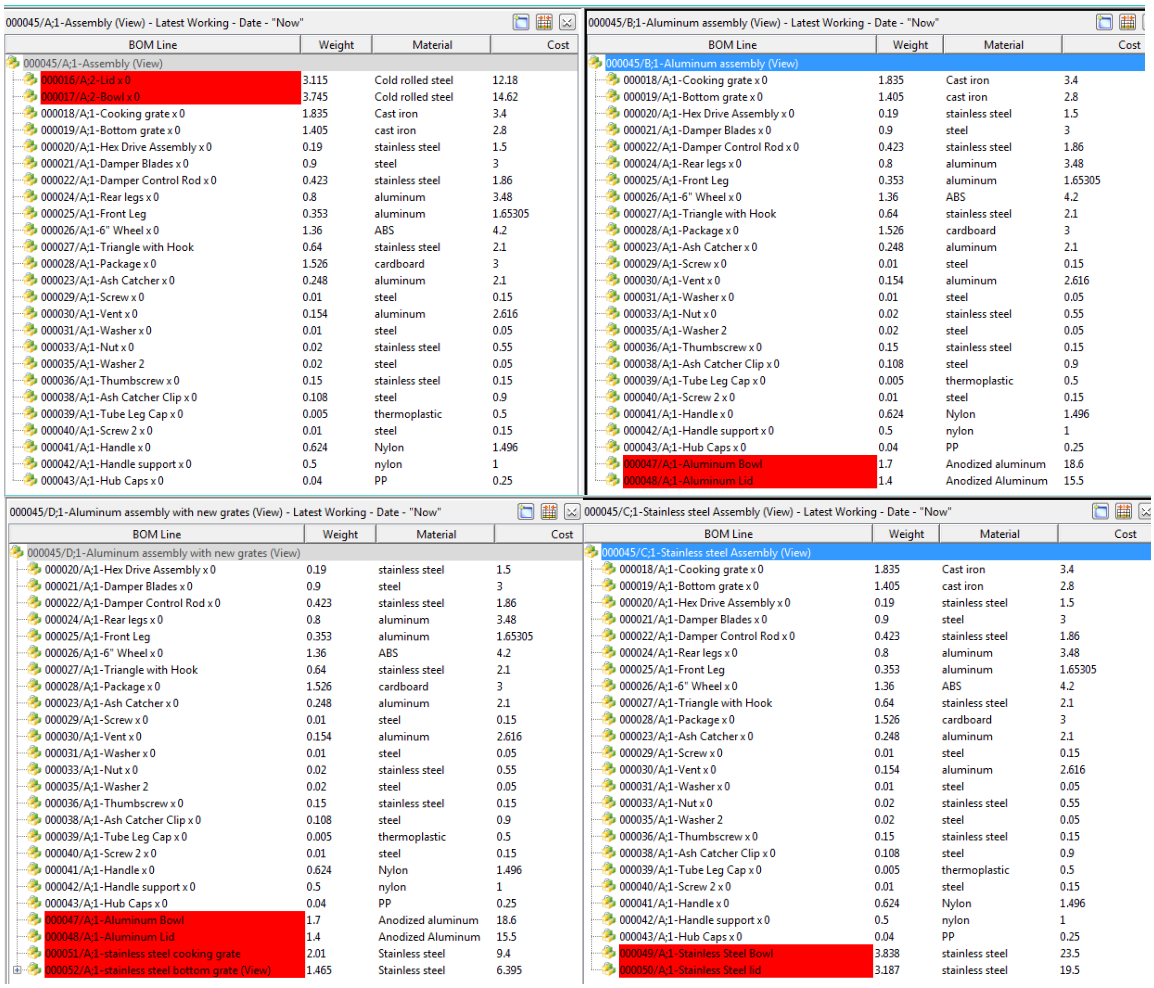
7.3.2 Step 2.2: Identify Design Alternatives

Regarding the environmental "hot spots" identified early and largest impacts from them, they will be redesigned towards the design goals. For strategy one, more recyclable materials will be chosen for components. Aluminum is a more recyclable material but has a higher thermal conductivity, which means it cannot maintain heat within the grill. Aluminum oxide on the other hand seems a perfect material to keep heat. Thus, surface treatment of anodic oxidation is applied on the aluminum bowl and lid to increase heat insulation. For the second strategy, material with much lower thermal conductivity is selected for maintain heat. Thus, to achieve the same performance of the baseline design, less charcoal is used. Several potential materials are stainless steel, cast iron, ceramic, etc. Considering the design goals, stainless steel is selected as the second alternative.

Regarding the heating performance, for a direct cooking process, lid and bowl maintain heat to enable the internal space reach ideal cooking temperature faster. The cooking grate conduct heat directly to meat. Since a normal grill has a rather long life cycle, replacing the parts, especially grates, are inevitable. Cast iron grates tend to rust. In the entire life cycle of a charcoal grill, several cast iron grates are needed if they are not kept well. This will potentially increase the environmental impacts for one charcoal grill. Stainless steel is one of the materials that do not need extra care and easy to be manufactured. Thus, stainless steel is used for new material as cooking grates and bottom grates. Thus, four conceptual alternatives are identified using different combinations of materials mentioned above. Table 7.3 shows these four alternatives.

Table 7.3 Main components of new alternatives

Alternatives	Main Components
Alternative #1	Anodized aluminum bowl and lid with cast iron grates
Alternative #2	Stainless steel bowl and lid with cast iron grates
Alternative #3	Anodized aluminum bowl and lid with stainless steel grates
Alternative #4	Stainless steel bowl, lid and grates.



000045/A;1-Assembly (View) - Latest Working - Date - "Now"

BOM Line	Weight	Material	Cost
000045/A;1-Assembly (View)			
000016/A;2-Lid x 0	3.115	Cold rolled steel	12.18
000017/A;2-Bowl x 0	3.745	Cold rolled steel	14.62
000018/A;1-Cooking grate x 0	1.835	Cast iron	3.4
000019/A;1-Bottom grate x 0	1.405	cast iron	2.8
000020/A;1-Hex Drive Assembly x 0	0.19	stainless steel	1.5
000021/A;1-Damper Blades x 0	0.9	steel	3
000022/A;1-Damper Control Rod x 0	0.423	stainless steel	1.86
000024/A;1-Rear legs x 0	0.8	aluminum	3.48
000025/A;1-Front Leg	0.353	aluminum	1.65305
000026/A;1-6" Wheel x 0	1.36	ABS	4.2
000027/A;1-Triangle with Hook	0.64	stainless steel	2.1
000028/A;1-Package x 0	1.526	cardboard	3
000023/A;1-Ash Catcher x 0	0.248	aluminum	2.1
000029/A;1-Screw x 0	0.01	steel	0.15
000030/A;1-Vent x 0	0.154	aluminum	2.616
000031/A;1-Washer x 0	0.01	steel	0.05
000033/A;1-Nut x 0	0.02	stainless steel	0.55
000035/A;1-Washer 2	0.02	steel	0.05
000036/A;1-Thumbscrew x 0	0.15	stainless steel	0.15
000038/A;1-Ash Catcher Clip x 0	0.108	steel	0.9
000039/A;1-Tube Leg Cap x 0	0.005	thermoplastic	0.5
000040/A;1-Screw 2 x 0	0.01	steel	0.15
000041/A;1-Handle x 0	0.624	Nylon	1.496
000042/A;1-Handle support x 0	0.5	nylon	1
000043/A;1-Hub Caps x 0	0.04	PP	0.25

000045/B;1-Aluminum assembly (View) - Latest Working - Date - "Now"

BOM Line	Weight	Material	Cost
000045/B;1-Aluminum assembly (View)			
000018/A;1-Cooking grate x 0	1.835	Cast iron	3.4
000019/A;1-Bottom grate x 0	1.405	cast iron	2.8
000020/A;1-Hex Drive Assembly x 0	0.19	stainless steel	1.5
000021/A;1-Damper Blades x 0	0.9	steel	3
000022/A;1-Damper Control Rod x 0	0.423	stainless steel	1.86
000024/A;1-Rear legs x 0	0.8	aluminum	3.48
000025/A;1-Front Leg	0.353	aluminum	1.65305
000026/A;1-6" Wheel x 0	1.36	ABS	4.2
000027/A;1-Triangle with Hook	0.64	stainless steel	2.1
000028/A;1-Package x 0	1.526	cardboard	3
000023/A;1-Ash Catcher x 0	0.248	aluminum	2.1
000029/A;1-Screw x 0	0.01	steel	0.15
000030/A;1-Vent x 0	0.154	aluminum	2.616
000031/A;1-Washer x 0	0.01	steel	0.05
000033/A;1-Nut x 0	0.02	stainless steel	0.55
000035/A;1-Washer 2	0.02	steel	0.05
000036/A;1-Thumbscrew x 0	0.15	stainless steel	0.15
000038/A;1-Ash Catcher Clip x 0	0.108	steel	0.9
000039/A;1-Tube Leg Cap x 0	0.005	thermoplastic	0.5
000040/A;1-Screw 2 x 0	0.01	steel	0.15
000041/A;1-Handle x 0	0.624	Nylon	1.496
000042/A;1-Handle support x 0	0.5	nylon	1
000043/A;1-Hub Caps x 0	0.04	PP	0.25
000047/A;1-Aluminum Bowl	1.7	Anodized aluminum	18.6
000048/A;1-Aluminum Lid	1.4	Anodized Aluminum	15.5

000045/D;1-Aluminum assembly with new grates (View) - Latest Working - Date - "Now"

BOM Line	Weight	Material	Cost
000045/D;1-Aluminum assembly with new grates (View)			
000020/A;1-Hex Drive Assembly x 0	0.19	stainless steel	1.5
000021/A;1-Damper Blades x 0	0.9	steel	3
000022/A;1-Damper Control Rod x 0	0.423	stainless steel	1.86
000024/A;1-Rear legs x 0	0.8	aluminum	3.48
000025/A;1-Front Leg	0.353	aluminum	1.65305
000026/A;1-6" Wheel x 0	1.36	ABS	4.2
000027/A;1-Triangle with Hook	0.64	stainless steel	2.1
000028/A;1-Package x 0	1.526	cardboard	3
000023/A;1-Ash Catcher x 0	0.248	aluminum	2.1
000029/A;1-Screw x 0	0.01	steel	0.15
000030/A;1-Vent x 0	0.154	aluminum	2.616
000031/A;1-Washer x 0	0.01	steel	0.05
000033/A;1-Nut x 0	0.02	stainless steel	0.55
000035/A;1-Washer 2	0.02	steel	0.05
000036/A;1-Thumbscrew x 0	0.15	stainless steel	0.15
000038/A;1-Ash Catcher Clip x 0	0.108	steel	0.9
000039/A;1-Tube Leg Cap x 0	0.005	thermoplastic	0.5
000040/A;1-Screw 2 x 0	0.01	steel	0.15
000041/A;1-Handle x 0	0.624	Nylon	1.496
000042/A;1-Handle support x 0	0.5	nylon	1
000043/A;1-Hub Caps x 0	0.04	PP	0.25
000047/A;1-Aluminum Bowl	1.7	Anodized aluminum	18.6
000048/A;1-Aluminum Lid	1.4	Anodized Aluminum	15.5
000051/A;1-stainless steel cooking grate	2.01	Stainless steel	9.4
000052/A;1-stainless steel bottom grate (View)	1.465	Stainless steel	6.395

000045/C;1-Stainless steel Assembly (View) - Latest Working - Date - "Now"

BOM Line	Weight	Material	Cost
000045/C;1-Stainless steel Assembly (View)			
000018/A;1-Cooking grate x 0	1.835	Cast iron	3.4
000019/A;1-Bottom grate x 0	1.405	cast iron	2.8
000020/A;1-Hex Drive Assembly x 0	0.19	stainless steel	1.5
000021/A;1-Damper Blades x 0	0.9	steel	3
000022/A;1-Damper Control Rod x 0	0.423	stainless steel	1.86
000024/A;1-Rear legs x 0	0.8	aluminum	3.48
000025/A;1-Front Leg	0.353	aluminum	1.65305
000026/A;1-6" Wheel x 0	1.36	ABS	4.2
000027/A;1-Triangle with Hook	0.64	stainless steel	2.1
000028/A;1-Package x 0	1.526	cardboard	3
000023/A;1-Ash Catcher x 0	0.248	aluminum	2.1
000029/A;1-Screw x 0	0.01	steel	0.15
000030/A;1-Vent x 0	0.154	aluminum	2.616
000031/A;1-Washer x 0	0.01	steel	0.05
000033/A;1-Nut x 0	0.02	stainless steel	0.55
000035/A;1-Washer 2	0.02	steel	0.05
000036/A;1-Thumbscrew x 0	0.15	stainless steel	0.15
000038/A;1-Ash Catcher Clip x 0	0.108	steel	0.9
000039/A;1-Tube Leg Cap x 0	0.005	thermoplastic	0.5
000040/A;1-Screw 2 x 0	0.01	steel	0.15
000041/A;1-Handle x 0	0.624	Nylon	1.496
000042/A;1-Handle support x 0	0.5	nylon	1
000043/A;1-Hub Caps x 0	0.04	PP	0.25
000049/A;1-Stainless Steel Bowl	3.838	stainless steel	23.5
000050/A;1-Stainless Steel lid	3.187	stainless steel	19.5

Figure 7.7 Detailed BOM of alternative #3 in PLM

After the identifications, the design process is mainly performed in PLM to build BOM and other life cycle information for each new alternative. For the alternatives that use cast iron grates, three pieces are assumed to be used in one life cycle of a charcoal grill. For alternatives that uses stainless grates, one is assumed for one life cycle. Finally, all BOM are built, as shown in Figure 7.7. PLM's 'BOM compare' lights up the part within each alternative in red to show the differences from reference product.

7.3.3 Step 2.3: Use Sustainability Module to Generate Environmental Reports

After the design is finished, these alternatives will be sent to Sustainability Module instantly to get real-time environmental reports. Same as the process of performing an environmental study on the reference product using Sustainability Module, LCA models of the new alternatives are created with the same rule which uses five main life cycle processes to simulate the five life cycle blocks proposed. Two LCA models are shown here in Figure 7.8 and 7.9.

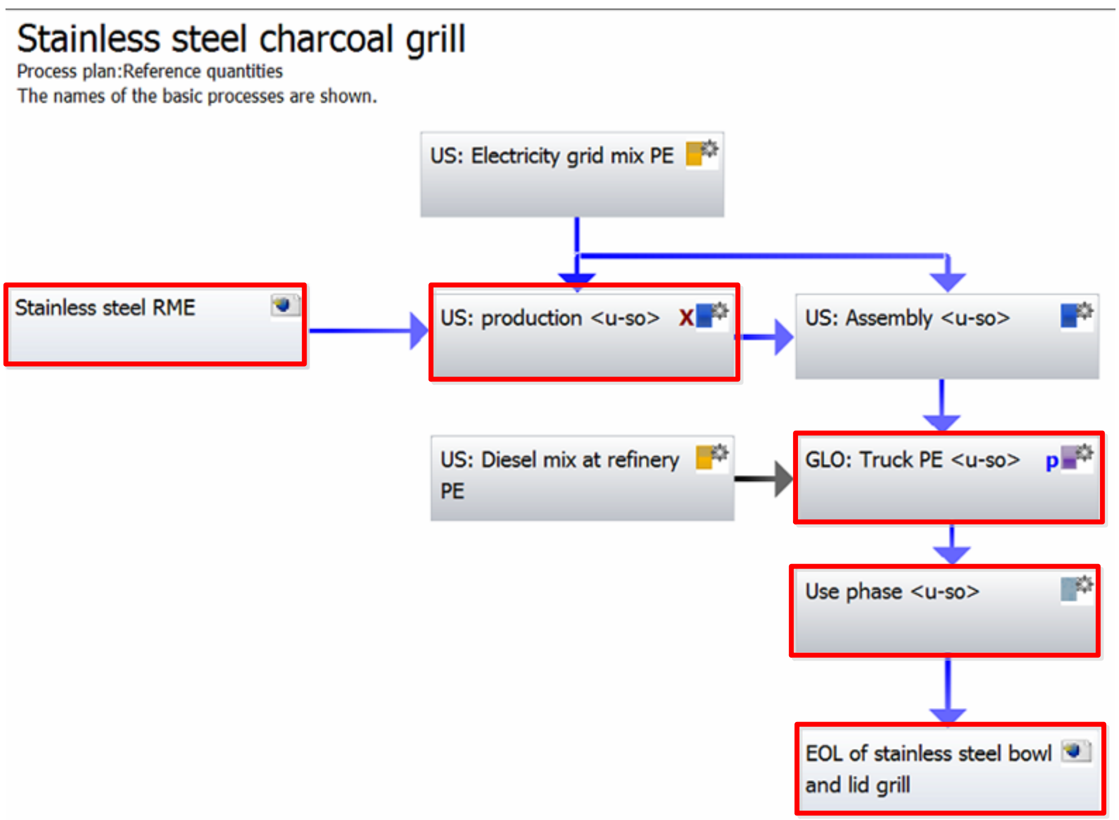


Figure 7.8 Simulation of LCA framework on alternative #2

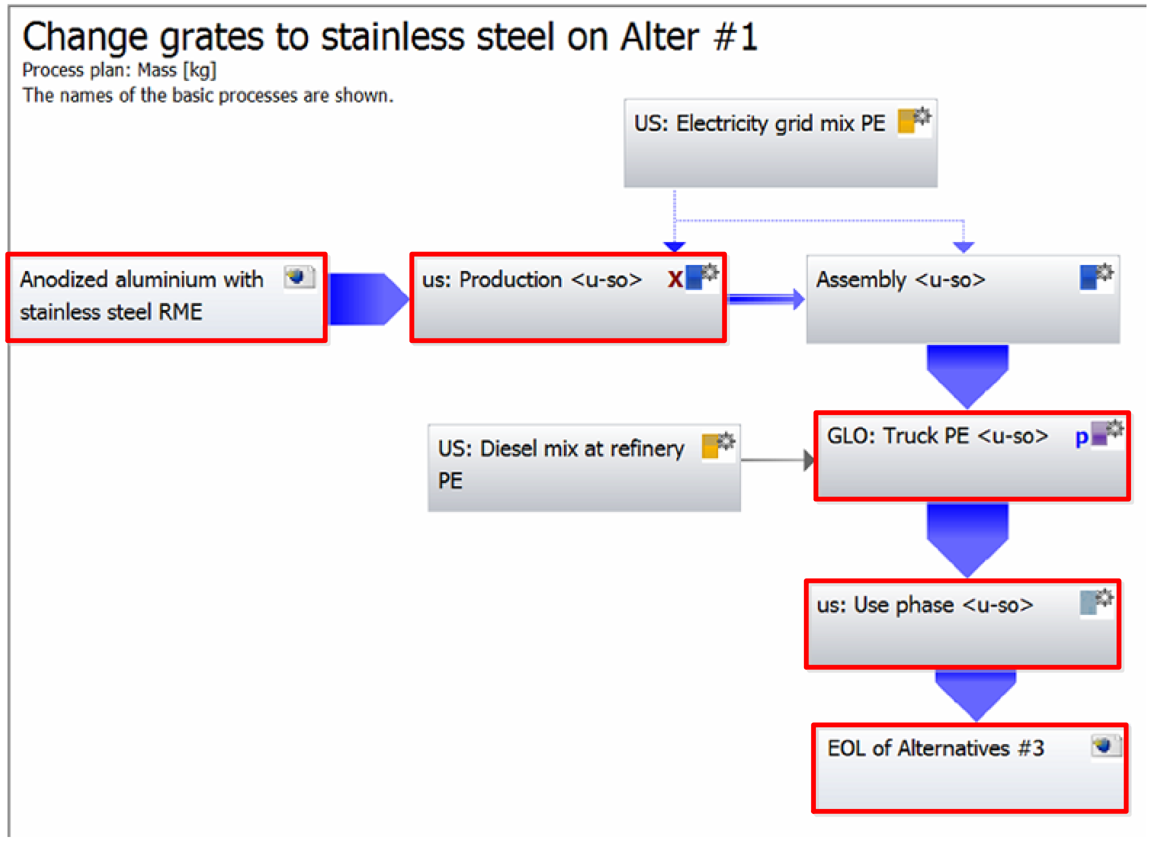


Figure 7.9 Simulation of LCA framework on alternative #3

After analyzing all the generated environmental reports, no restricted uses of materials are found. The environmental 'hot spots' are still identified as those four parts. Some of them increase the impacts compared with reference model, while some of them moderate the 'hot spots'.

Since most of the parts can be reused, the environmental dependent property significantly saves computing time. The instant environmental reports also reduce development time and make environmental performance of alternatives available at early design stage.

7.3.4 Step 2.4: Collect Feedbacks

Then, the environmental reports are fed back to PLM, same as the process of reference model sending reports back to PLM. Comprehensive environmental reports are stored in specific folder as well as other design attributes. Then the environmental index of each alternative is filled into the decision-making module. These quantitative numbers are apparent to designers and can be used directly in the decision-making process. The production cost attributes are acquired using BOM report in PLM. The heating performance is evaluated using comparisons against the baseline design. It is calculated based on a normal direct cooking process which means placing the meat on the grate after the internal temperature reaches ideal temperature with lid closed at first. For simplification, the exact cooking time is not calculated. Instead, the cooking time is set to T second. The other alternative's cooking time is calculated accordingly. Finally, the performance attributes of four alternatives are 0.74T, 0.58T, 2.294T and 1.798T respectively. Then all these quantitative numbers are collected by decision-making module, as shown in Table 7.4.

Table 7.4 Design attributes in decision-making module

	LCA	Production cost ($)	Performance (s)
Reference	0.7282	76.15	T
Alternative #1	0.6061	83.46	0.74T
Alternative #2	0.5060	92.35	0.58T
Alternative #3	0.5681	80.65	2.294T
Alternative #4	0.5058	89.545	1.798T

7.3.5 Step 2.5: Execute HEIM and Select the Optimal Alternative

At first glance, in terms of environmental impacts, all these alternatives have lower impacts compared with baseline. Due to better materials are used and its manufacturing process, the production cost have increased and the performance varies, too. In summary, all alternatives have their trade-offs. Since most of the information are already in detail and reflect the true aspects of the product, the execution of the methodology is best accomplished by an accurate and computationally efficient decision model. HEIM (Hypothetical Equivalents and Inequivalents Methods) was used on in this case that involve selection from multiple attributes having various advantages and disadvantages. However, the selection of the optimal alternative largely depends on the preferences of the decision maker. An under constraint optimization problem is firstly formulated to compare the wining alternatives under different preference. Then, more constraints are introduced based on the author's preference, a single robust alternative is found. The process of modeling preferences resulting in different optimal alternatives will increase the product knowledge so that they will be used for future development, which will be illustrated in the final design step.

The main execution of HEIM is executed as follows. Firstly, the attributes are identified mainly as shown in Table 7.4. Next step is to determine the strength of Preference within attributes. Here, we assume risk averse decision making for LCA results, slightly risk prone for cost and risk prone tendency for the performance attributes. We will use the strength of preferences as shown in Figure 7.10.

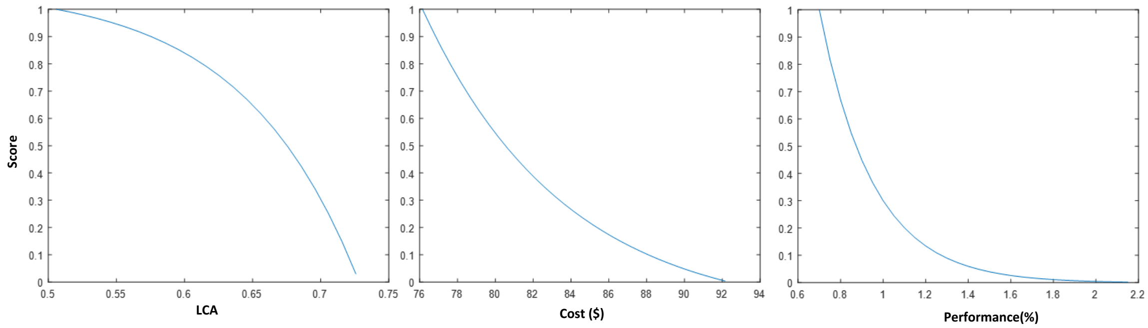


Figure 7.10 Strength of preferences

Then a set of hypothetical alternatives are established. Kulok and Lewis [93] deployed a three level L9 orthogonal array to solve a design problem with three attributes. The standard utility values in each cell correspond to the normalized most desirable, least desirable and mid-level desirable for each single attribute. Thus, the attribute values at each level correspond to single attributes utility values of 1 (most desirable), 0 (least desirable) and 0.5. The weights of LCA, production cost and performance are represented with

ω_1, ω_2 and ω_3 respectively. Table 7.5 shows the hypothetical alternatives with their corresponding attributes values.

Table 7.5 Normalized score for hypothetical alternatives

Hypothetical alternative	LCA	Production cost	Performance	Total values
A	0	0	0	0
B	0.5	0.5	1	$0.5\omega_1 + 0.5\omega_2 + \omega_3$
C	1	1	0.5	$\omega_1 + \omega_2 + 0.5\omega_3$
D	0	0.5	0.5	$0.5\omega_2 + 0.5\omega_3$
E	0.5	1	0	$0.5\omega_1 + \omega_2$
F	1	0	1	$\omega_1 + \omega_3$
G	0	1	1	$\omega_2 + \omega_3$
H	0.5	0	0.5	$0.5\omega_1 + 0.5\omega_3$
I	1	0.5	0	$\omega_1 + 0.5\omega_2$

The real values corresponding to the hypothetical alternatives is shown in Table 7.6.

Table 7.6 Real values of hypothetical alternatives

Hypothetical alternative	LCA	Production cost ($)	Performance (s)
A	0.7282	92.35	2.294T
B	0.6753	80.53	0.58T
C	0.5058	76.15	0.823T
D	0.7282	80.53	0.823T
E	0.6757	76.15	2.294T
F	0.5058	92.35	0.58T
G	0.7282	76.15	0.58T
H	0.6753	92.35	0.823T
I	0.5058	80.53	2.294T

After the preference strengths have been determined in order to avoid the flaws of assuming a linear preference structure, normalization is carried out, as shown in Table 7.7.

Table 7.7 Normalized alternative scores

	LCA	Production cost	Performance
Reference	0	1	0.1855
Alternative #1	0.8223	0.5089	0.5268
Alternative #2	0.9998	0	1
Alternative #3	0.9148	0.6893	0
Alternative #4	1	0.151	0.0007

Next step is the formulation of preference structure as an optimization problem. Here, the preference structure is assumed as C>B>A, E>F>D, G>I>H. By using the values shown in Table 7.5, six constraints can be created. Therefore, the complete optimization problem can be formulated below:

$$Minimize\ \ f(x) = [1 - (w_1 + w_2 + w_3)]^2$$

$$subject\ to \qquad G_1 = -0.5\omega_1 - 0.5\omega_2 + 0.5\omega_3 + \delta \leq 0$$

$$G_2 = -0.5\omega_1 - 0.5\omega_2 - \omega_3 + \delta \leq 0$$

$$G_3 = 0.5\omega_1 - \omega_2 + \omega_3 + \delta \leq 0 \tag{7.1}$$

$$G_4 = -\omega_1 + 0.5\omega_2 - 0.5\omega_3 + \delta \leq 0$$

$$G_5 = \omega_1 - 0.5\omega_2 - \omega_3 + \delta \leq 0$$

$$G_6 = 0.5\omega_1 - \omega_2 - 0.5\omega_3 + \delta \leq 0$$

Where $\delta = 0.001$

The solution for the preference weights are obtained using optimization technique. However, this is an under constraint optimization problem. Different starting points will result in different weights. After calculation, baseline design, alternative #1 and alternative #3 are all possible winners depending the chosen set of feasible weights as shown in Figure 7.11. The mean value of weights resulting in different wining alternatives are shown in Table 7.8.

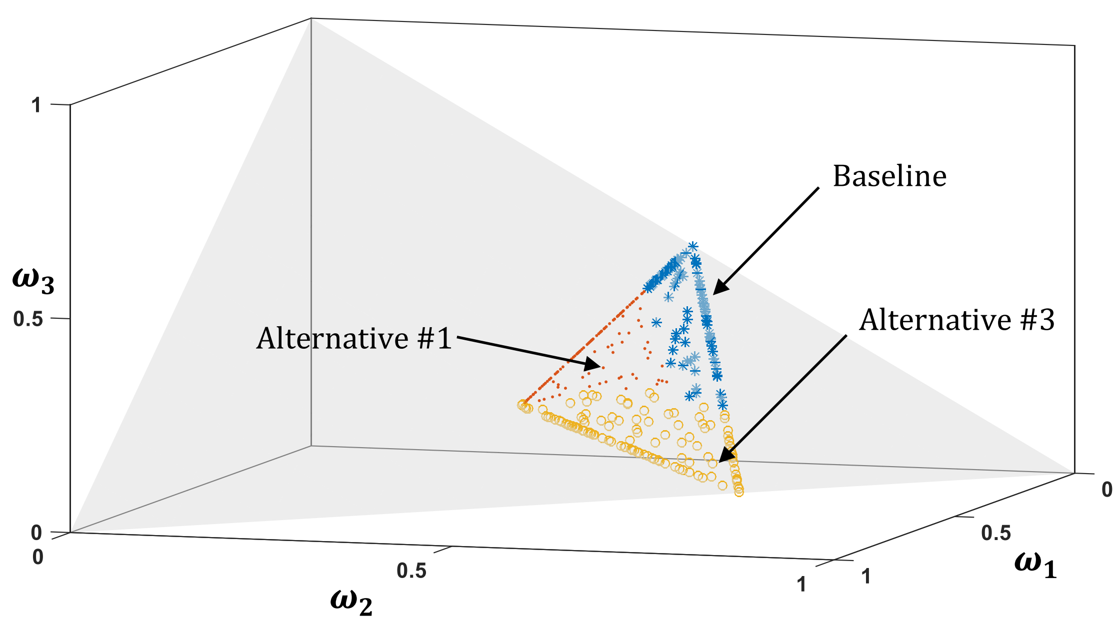


Figure 7.11 Feasible weights and winning alternatives

Table 7.8 Attributes weights

	Mean value of weights		
Attributes Weights	Baseline	Alternative #1	Alternative #3
$\boldsymbol{\omega_1}$	0.1016	0.2542	0.3353
$\boldsymbol{\omega_2}$	0.5238	0.4508	0.5416
$\boldsymbol{\omega_3}$	0.3746	0.2950	0.1234

Local weight that lead to baseline design having the greatest utility score are colored blue, those that lead to alternative #1 winning are colored orange, and those lead to alternative #3 wining are colored yellow. The grey triangle plane represents the sets of local weights that sum to one. The minimum, maximum and mean value are calculated for each attributes and recorded in Table 7.9. The mean value are used for calculating the utility score of each alternative and the total utility score for each alternative is shown in Table 7.10.

Table 7.9 Attributes weights

Attributes Weights	Minimum	Maximum	Mean
ω_1	0.002	0.3982	0.2446
ω_2	0.4010	0.6656	0.5044
ω_3	0.0013	0.4980	0.2510

Table 7.10 Utility score for each alternatives

	Baseline	Alternative #1	Alternative #2	Alternative #3	Alternative #4
Utility Score	0.5510	**0.5901**	0.4956	0.5714	0.3225

In order to further constrain the design space so that only one winner is found, constraints must be added which separate the three regions of the space that lead to a different alternative winning [53]. Three new pairs of hypothetical alternative are created in order to place constraints between any two of the regions.

The boundaries between the regions are located where the values of the two alternatives are equal as defined by

$$V(Baseline) = V(Alternative\ \#1)$$
$$V(Baseline) = V(Alternative\ \#3) \quad (7.2)$$
$$V(Alternative\ \#1) = V(Alternative\ \#3)$$

By such definition, the boundary line can be determined and converted into a preference constraint. For example, the value functions for baseline and alternative #1 are:

$$V(Baseline) = \omega_2 + 0.1855\omega_3 \quad (7.3)$$

$$V(Alternative\ \#1) = 0.8223\omega_1 + 0.5089\omega_2 + 0.5268\omega_3 \quad (7.4)$$

Therefore,

$$V(Baseline) = V(Alternative\ \#1) \quad (7.5)$$

$$\omega_2 + 0.1855\omega_3 = 0.8223\omega_1 + 0.5089\omega_2 + 0.5268\omega_3 = 0 \quad (7.6)$$

To create new hypothetical alternatives, the terms in Eq. 7.6 are rearranged, as in Eq. 7.7

$$0.8223\omega_1 + \omega_3 = 0.4911\omega_2 + 0.6587\omega_3 \quad (7.7)$$

It is important to note that Eq. 7.7 is just one possible rearrangement. The right and left hand side of Eq.7.7 are two value functions that correspond to two different hypothetical alternatives. The rest of the four alternatives are developed in the same way. Using the strength of preference of Figure 7.10, the six alternatives are unnormalized and presented in Table 7.11.

Table 7.11 New Unnormalized hypothetical alternatives

Hypothetical alternative	LCA	Production cost ($)	Performance(s)
J	0.6061	92.35	0.58T
K	0.7282	80.63	0.68T
L	0.5681	92.35	2.294T
M	0.7282	83.21	T
N	0.5058	78.64	0.77T
O	0.5718	80.53	0.58T

Now, in order to achieve a robust winning alternative, preferences are stated over the new sets of hypothetical alternatives from J to O. In this case, we assumed that J>K, M>L, O>N for the preference structure.

The additional constraints made from the comparison are added to the set of inequality constraints and new optimization problem is formulated in Eq. 7.8.

$$\begin{aligned}
&\textit{Minimize}\ \ f(x) = [1-(w_1+w_2+w_3)]^2 \\
\textit{subject to}\quad & G_1 = -0.5\omega_1 - 0.5\omega_2 + 0.5\omega_3 + \delta \le 0 \\
& G_2 = -0.5\omega_1 - 0.5\omega_2 - \omega_3 + \delta \le 0 \\
& G_3 = 0.5\omega_1 - \omega_2 + \omega_3 + \delta \le 0 \\
& G_4 = -\omega_1 + 0.5\omega_2 - 0.5\omega_3 + \delta \le 0 \\
& G_5 = \omega_1 - 0.5\omega_2 - \omega_3 + \delta \le 0 \\
& G_6 = 0.5\omega_1 - \omega_2 - 0.5\omega_3 + \delta \le 0 \\
& G_7 = -0.8223\omega_1 + 0.4911\omega_2 - 0.3413\omega_3 + \delta \le 0 \\
& G_8 = 0.9148\omega_1 - 0.3107\omega_2 - 0.1855\omega_3 + \delta \le 0 \\
& G_9 = -0.0925\omega_1 - 0.1804\omega_2 - 0.5268\omega_3 + \delta \le 0
\end{aligned} \tag{7.8}$$

where $\delta = 0.001$

The optimization problem is solved again using optimization technique. Figure 7.12 shows that all the feasible points now lead to alternative #1 as being the robust winning alternative.

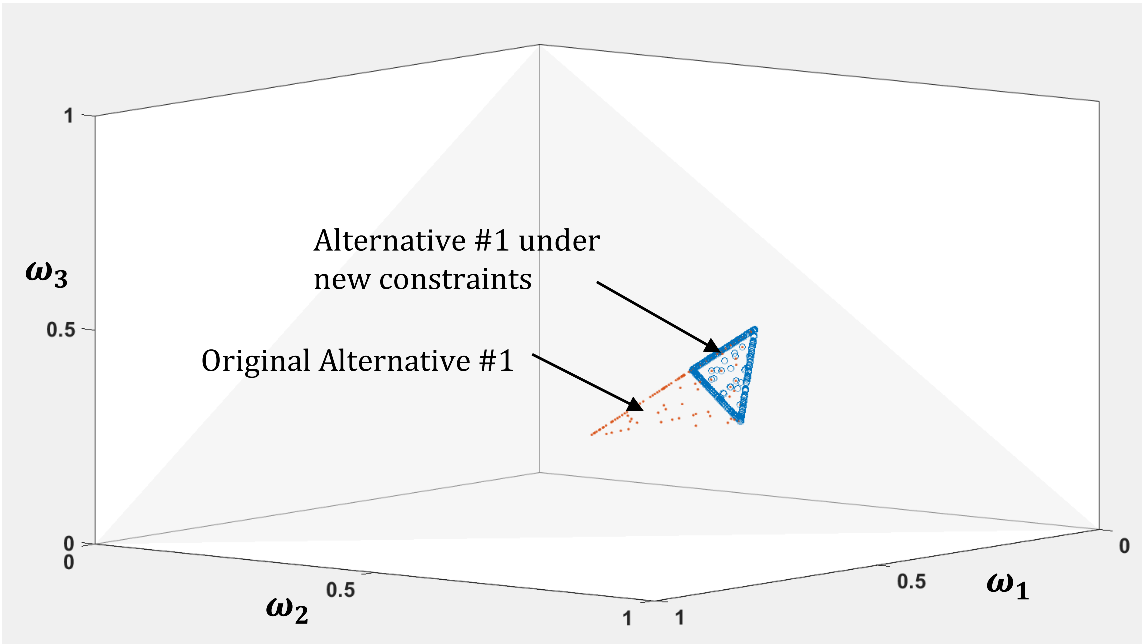


Figure 7.12 Feasible weights and one robust optimal alternative

The minimum, maximum and mean are again calculated for each attributes weight and recorded in Table 7.12.

Table 7.12 Final attributes weights

Attributes Weights	Minimum	Maximum	Mean
ω_1	0.117	0.2293	0.1937
ω_2	0.4459	0.5413	0.4816
ω_3	0.2294	0.4164	0.3247

The mean value for each weight in Table 7.13 is used for calculating utility scores for the three attributes. The utility score on each attribute is found in Table

7.7. Finally, the total utility score of each design alternative is found in Table7.13. In this case, alternative #1 has the greatest utility score and is the most preferred. There is no change in the winning alternative based on their utility score, while the utility score does change after more constraints are added to the optimization problem. The important different between using the additional constraints is the greater confidence that the decision maker has after making three additional pairwise comparison.

Table 7.13 Utility score for design alternatives

	Baseline	Alternative #1	Alternative #2	Alternative #3	Alternative #4
Utility Score	0.542	**0.575**	0.518	0.509	0.267

Finally, we assume that alternative #1 is the optimal alternative based on our preference. It will be selected to proceed the development to the next phase other than design stage, which is not the research focus of this thesis. Again, it is compared with design goals. If they are not met, we should go back to Step 2.2 and identify new alternatives. In this case, aluminum parts can be recycled more than 50%. Global warming potential has been reduced by 24%. For alternative #3, aluminum parts and stainless steel part enable more than 50% recycle rate. The global warming potentials has been reduced by 20%. For alternative #2, 24% less energy is used and 50% more manufacturing and material impacts. With proper End-of-life treatment which let the stainless steel to be recycled to 50%, total 5% more manufacturing and material impacts compared with baseline design. In summary, since the greenhouse are mainly produced during use, especially for a charcoal grill, the design goal of half global warming potential may be a little aggressive. But the new alternatives have half met that goal. Thus, to some extent, the design goals are 75% met. If the design goals are less aggressive, we assume that the new alternatives basically met them.

7.4 Case Study: After Design Stage

7.4.1 Step 3.1: Prepare for New Design Initiatives

An analysis is performed on the results after the decision-making to select potential alternatives for the new product development. In order to illustrate this step, we assume that all the results are based on our preference structure.

Firstly, alternative #1 is selected to be the optimal one. Thus, its product properties will be detailed in the rest of the development phases and stored in PLM served as the reference model for the new product development in the future. For the rest of the alternatives, especially for baseline design and alternative #3, they are found that with the similar preference over production cost, different preferences on the other two attributes result in different winning alternatives. If we assume environmental impacts over performance, alternative #3 wins. If we assume performance over environmental impacts, baseline design is better than the rest ones. For alternative #1, the choice of weights more tends to balance the three attributes while a little more emphasis is put on production cost. Thus, the design of choice is different based on different point of view over attributes. Finally, the developed conceptual alternatives provide product knowledge about how to improve the design performance in terms of LCA, production cost and product performance, separately. Thus, alternative #3 is critical to the new product development with goals of more environmentally friendly. Baseline design is critical to new product development with goals of better performance.

The Figure generated after HEIM showing all the feasible alternatives and winning alternatives are added to future development folder. The figure showing alternative #1 is the optimal solution is attached to the "Alternative #1: Aluminum bowl and lid" folder as the preferred scenario. Then, all the information combined with alternative's BOM will all be saved in PLM as future alternatives for the new product development, as shown in Figure 7.13.

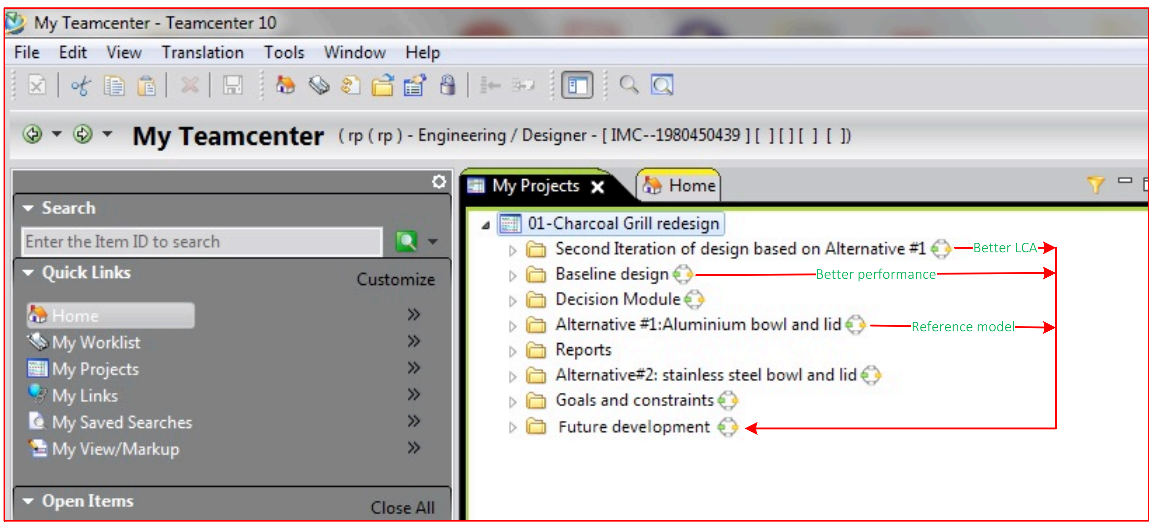


Figure 7.13 Developed alternatives stored for future development

CHAPTER 8

DISCUSSION

8.1 Summary

This thesis identified the several challenges of preventing current LCA software from integrating with PLM. These challenges include paradox of eco-design, different representation of product in PLM and LCA, difficulties of extracting information from PLM to LCA, lack of comprehensive LCI database and designers lacking knowledge of eco-design. Thus, a concept of a LCA framework, LCAatPLM including five life cycle blocks, is proposed which keeps the product model used by PLM in the form of a product tree and perform an environmental assessment that is based on the same product model. For completing the life cycle information, entities in the product tree representing product, assembly and part, can be associated to the five life cycle blocks in LCAatPLM. These information is either provided by design supporting tools or PLM. It transforms LCA from an evaluation tool used after a design is already completed to one that can guide designs earlier within the PLM environment. In order to check the environment regulations early to prevent late change, a substance compliance module is also proposed. These two parts formed Sustainability Module to be better used within the PLM environment. Then, a system architecture is shown that uses PLM as the foundation of information collection and sharing. A sustainable design methodology is proposed to be used at early design stage for a holistic consideration of environmental performance along with other design attributes over a complete life cycle. Combined with Sustainability

Module, it integrates the use of PLM and LCA to facilitate the design process toward sustainability.

A case study is performed through a simulation of the proposed system and proposed methodology. The results reveal that the environmental profiles of the product alternatives are available just after all the product properties are defined for each new alternative in PLM. To be apparent for designers at early design stage, environmental index is used to provide a simplified and quantified number that can be used along with other quantified design attributes for decision making using HEIM at early design stage. After executing HEIM, product knowledge is acquired about different preferences resulting in different alternatives. These alternatives will be saved in PLM as conceptual alternatives for the future product development.

8.2 Limitations

In order to get the environmental performance of alternatives at the earliest time for designers, the proposed LCA framework sacrifices some to achieve that goal. Thus, there are several limitations of this new concept.

Firstly, waste are not considered. The proposed LCA framework reads the BOM information directly from PLM and maps the information of exact weights, materials or processes of the assembly into five life cycle blocks and calculates a LCA result. In a real remodeling life cycle of a product with LCA, inputs and outputs are setup in each life cycle stage and they sometimes do not equal with each other. It will introduce deviations depending on the percentage of raw material to be manufactured into final part, when compared with LCA remodeling using LCA tools

In addition, faced with insufficient LCI database, a missing process or material that cannot be selected directly could increase additional burden to designers. During the implementation of the case study, since an anodizing process is not available, the author spends additional time remodeling it. Such situation appears too when dealing with the End-of-Life treatment scenario in LCA. Thus, a complete LCI database should be the foundation for easy selection and assigning to proper places.

Finally, this LCA framework is only proposed to be used by designers for the consideration of environmental impacts along with other design attributes at early design stage. It only aims to get an environmental indictor used for comparison among other alternatives. In order to get a comprehensive LCA result, specialized LCA tools are still necessary after all the detailed product properties are defined usually at late design stage. However, this framework aims to prevent late change to the large extent.

8.3 Benefits

This research mainly reveals that the environmental impacts can be considered along with other design attributes at early design stages by prescribing a way to integrate LCA into PLM. Besides that, the new concept also introduced many benefits. These benefits make it significantly useful during design stages, especially at early design stage for designers.

Firstly, designers do not need the expertise and time to remodel the entire life cycle of the product in order to get the environmental performance. The product data are keyed once and then extracted from PLM into LCA framework directly. An environmental profile becomes available just after an alternative is finished. It significantly reduces the development time if environmental impacts are considered during design.

Then, it helps constantly monitor the environmental improvements of alternatives through real-time feedbacks to PLM. As conceptual alternatives are filled with more details, feedbacks of environmental performance are constantly send back to PLM and documented. Designers can have an improved knowledge about product towards sustainability. This feature changes the static nature of LCA into a dynamic number that changes with design alternatives. The environmental impacts of alternatives are considered along with other design attributes at the earliest time.

The concept of LCA framework introduced the idea of separating entire life cycle of a product into unique life cycle of each part or assembly based on the assembly tree. And after calculation, make environmental impacts as a dependent property that attached to that component to save computing time. This allows the quick identification of environmental “hot spots”.

The proposed system also allows for local or global comparison in terms of environmental impacts. Global comparison enables designers to compare whole product, while local comparison enables to compare assembly, subassembly or single part. Quick evaluations of subassembly or part enable the lowest-impacts components to be used in the full assembly.

Compared with existing solutions of LCA integrated with PLM or CAD, more accurate LCA results can be got representing more accurate environmental performance of the alternatives. Although this concept can still not be able to compare with detailed model of life cycle of a product using LCA software, it selects five most important life cycle stages without missing any stages as done with Simplified LCA.

Combined with the Substance Compliance Module which constantly checks the restrict use of material in the early stage and provides direct view on End-of-Life stage, it is better prepared for ever stricter existing and future regulations.

Finally, the development of a new product becomes much easier. Since the last generation product is detailed in PLM along with environmental profiles, parts can be reused to the maximum. These components already have documented environmental impacts so that they can be extracted directly and ready to use in the new assembly. The environmental profile will also notify current environmental performance and "hot spots". Thus, it will serve as a new reference product and provide guidance on the identification of new alternatives.

8.4 Future Work

The work described in this thesis provides a concept of how LCA can be best used in the PLM environment. By doing this, environmental impacts can be considered during design phases at the earliest time. However, sacrifices have been made to achieve this goal. Thus, this concept still has several limitations. The future work could mainly focus on several places mentioned below.

Firstly, waste should find a way to be considered in order to get a more accurate life cycle of the product. A specific holder can be built to store the information of residues and let these residues to enter End-of-Life stages directly after the Production phase. Then the LCA framework should not be limited to only five life cycle blocks. They should be customized to meet the needs of different products. Finally, research can be done for other ways to consider environmental impacts early in the design process in order to design more sustainable products.

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