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A Framework for the intergration of system engineering and functional analysis techniques to the goal and scope of life cycle assessment

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A FRAMEWORK FOR THE INTEGRATION OF SYSTEM ENGINEERING AND FUNCTIONAL ANALYSIS TECHNIQUES TO THE GOAL AND SCOPE OF LIFE CYCLE ASSESSMENT

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CERTIFICATE OF APPROVAL

M.S. DEGREE THESIS

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ABSTRACT

With the increased concern over the impact that products and processes have on the environment, tools such as Life Cycle Assessment (LCA) have been developed to assess environmental impacts. However, several issues are present in this tool; chief among them is the difficulty of comparing LCA studies. The attributed reasons for this issue are the lack of standardized assumptions and practices, the definition of the functional unit and the identification of reference flows. In this work, it is hypothesized that system engineering and functional analysis concepts are a promising approach to provide guidelines for system definition, system boundary definition, and reference flows identification. Based on this premise, this work delineates a framework to address some of the issues present in the early stages of LCA, and to ultimately help enable comparisons between different LCA studies. This framework was initially exercised with some simple examples to demonstrate the initial feasibility of the model. With the insights gained from these simple test cases, the proposed process was applied to a practical case study to assess the utility of the framework through the use of the SimaPro® software. The application of this framework through the case study demonstrated that the proposed approach holds promise. In particular, the case demonstrated that application of system engineering methods was a useful construct. Furthermore, the importance of decoupling consumer use from the reference flows and functional unit definition processes proved to be very useful. The implication of these two results is that the possibility of re-using already existing data, models, and projects becomes feasible since the framework creates an easy to adapt structure.

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1.0 Introduction

This first chapter provides the motivation for this research and summarizes the efforts by industry to clearly show the relevance of the selected research topic. It begins by providing background information regarding the Information and Communications Technology industry and the Print industry since the research topic was initially motivated by the current need in these industries. This is followed by an overview of Life Cycle Assessment (LCA). The problem statement is then introduced, followed by a detailed research roadmap. Along with the problem statement, the concrete research objectives are presented as are the specific questions that will guide the present work. To conclude this chapter, an outline of the thesis is presented.

1.1 Motivation to Work Towards Better Comparability of Life Cycle Assessment Studies

The need to improve the comparability between life cycle assessment (LCA) studies has been present for some time now. The fact that practitioners use the ISO 14040 and 14044 norms does not guarantee that studies of the same product or service conducted by different practitioners under different circumstances will be comparable.

Several initiatives have been undertaken in order to harmonize scope and assumptions of LCA studies. An example of this has been the work done by the National Renewable Energy Laboratory (NREL), with funding from the U.S. Department of Energy, which started the LCA Harmonization Project (Warner, Heath, & O'Donoughue, 2010). This project looks "to rigorously leverage the numerous individual studies (conducted in the electricity generation technologies field) to develop collective insights" (Heath & Mann, 2012). This work developed a meta-analytical procedure called "harmonization" which adjusted previously published greenhouse gas emissions estimates to ones based on a more consistent set of methods and assumptions (Heath & Mann, 2012). While the harmonization work successfully addresses the inconsistencies in methods and assumptions of previously published LCA estimates, it does not work towards nor does it propose a method that might enable better comparability. In addition, the meta-analysis applied only focuses on the energy field and on a selected impact category. It can then be said that this work does not address the methodological weaknesses of LCA, however, it is an excellent example of the present need in the industry to refine the LCA method and to help enable comparability of LCA studies.

Another example of the need to enable better comparability of LCA studies are the efforts being undertaken by the print industry as communnicated to the author by an industry practitioner (De-Vierno, 2012). A particular goal of this effort was to standardize assumptions and the functional unit for print technologies. The efforts were developed through the Environmental Product

Declaration (EPD) and Product Category Rules (PCR) aimed to consolidate the views of different stakeholders of the print industry. The EPD is a "certified environmental declaration developed in accordance with the standard ISO 14025" (The-International-EPDsystem). In addition, the ISO 14025 which covers the principles and procedures for environmental labels and declarations, defines an enviromental declaration as quantified environmental data for a product with pre-set categories of parameters based on the ISO 14040 standards, but not excluding additional environmental information (ISO, 2006a). Unfortunately, at the time of the discussion, a consolidated standardization for LCA practices specific to these classes of devices was not achieved and the project had not yet reached the desired goal.

Better comparability for the LCA methodology would improve collaboration and information sharing between different stakeholders and companies, regardless of the industry in which LCA is being practiced. It would allow more informed decisions for designers and product developers regarding the environmental impacts of the products and services being developed. Also, improved reporting would enable better communications from a marketing stand point and a more informed public. However, as the preceding examples illustrate, this is still an elusive goal.

1.1.1 Initial Motivation for the Present Research: The Information and Communications Technology Industry and The Print Industry

The Information and Communications Technology (ICT) industry is currently defined as *"…an umbrella term that includes any communication device or application, encompassing: radio, television, cellular phones, computer and network hardware and software, satellite systems and so on, as well as the various services and applications associated with them, such as videoconferencing and distance learning"* (SearchCIO-Midmarket.com, 2003). Looking at historic and current trends it is correct to define it as one of the fastest growing industries (Branham-Group-Inc., 2011; Mendis, 2010; OECD, 2011; Oketola, 2012).

When looking at its environmental impacts, this rapidly evolving industry is characterized by its demands for high power resources. As mentioned in the Hewlett-Packard case study conducted by Hargadon (2011), 100 billion kW of electricity are annually consumed by computer networks. This makes the ICT sector responsible for two percent of global greenhouse gas (GHG) emissions; it is expected to reach four percent by 2020 (Hargadon, 2011). Given the size of the ICT industry, it is estimated that the use of the correct technology can deliver carbon savings of five times the industry's current total emissions by 2020 (The-Climate-Group, 2008).

Being aware of the impacts, the industry is conscious that the way to work towards a more environmentally friendly structure is through technology. The European Information Technology Observatory (EITO) (2002) analyzes the possibilities of the industry to improve through sustainable development by looking at the three characteristic pillars: economic, social and environmental sustainability. When addressing environmental matters, the paper demonstrates the important role of policies specifically in the long-term. In addition, considering how fast paced the development of ICT devices is, it is possible and important for these companies to include environmentally friendly attributes in their new products and strategies.

The print industry is encompassed within the ICT as what it is called "hardcopy peripherals", and these are mainly printers, multi-function peripherals and digital copiers (IDC, 2012).

Multi-function peripherals or multi-function devices (MFD) cover a wider range of functionality. These perform at least two different tasks, such as printing, copying, faxing and scanning (Wallener). As pointed out by Tatum, many offices and homes rely on the use of these MFDs and the most advanced devices can also include a collating tray and a stapler. The benefits of MFDs pointed out by Tatum are widely known and the increasing penetration that these have in the market (The-Recycler, 2011) demonstrates their success: having one MFD is more cost effective than having several single-function devices. In addition, MFDs utilize space in a more efficient way and can also save work-time (Tatum).

Hang & Shirer (2011) give a clear picture of the main players in the print industry. The main leader is HP which possesses 42.4 percent of the market share, Canon is the second-ranked vendor with 17.4 percent market share, and Epson holds the third place with 14.1 percent. It is important to note that most all of the companies that participate in this sector experienced growth in the first quarter of 2011, especially in the emerging markets (Hang & Shirer, 2011).

As pointed out by Bousquin, et al. (2011), the environmental impacts related to the print industry are not only related to energy use but also to the consumables such as paper and cartridges. In addition, the authors remark that consumer behavior is closely related to the environmental performance of a printer.

Several initiatives to measure the environmental impact of this specific industry have been proposed such as the Xerox's Green Calculator (Xerox, 2011) and HP's Product Environmental Metrics for Printers (J. Ord, Strecker, & Canonico, 2010), however these tools have been independently developed and are mainly for internal use within each company. A demonstration of the need to identify areas for environmental improvement within the digital printing industry is the

Green Scorecard developed by Xerox's researchers and engineers (Ebner et al., 2009). This tool serves as a guide to assess eco-efficiency of possible projects and facilitates the comparison and election of different opportunities.

When addressing concerns within the main players in this market, lack of standardization in environmental assessment practices is a key point since comparability among different devices is very hard to achieve as noted by Bousquin et al. (2011). In addition, the difficulty in obtaining concrete guidelines for the design process is also of concern among specialists. The need to work towards a more standardized practice of environmental assessment is a critical path that will need to be addressed in the short term (Bousquin et al., 2011).

1.2 Background on Life Cycle Assessment

Growing concerns on the environmental effects that current human practices, products and processes are having on our planet have resulted in the development of several and different methods to quantify these impacts. Environmental management heavily relies on measuring environmental performance and many organizations are showing growing interest in the measurement of the impact of their practices, products and processes (Viluksela, Kariniemi, & Nors, 2010).

Global trends show that environmentally conscious practices are now part of our everyday life (Battelle, 2008). Scientists and engineers are now responsible for the development of technologies that address the needs of a growing population while trying to minimize the impacts of the implementation of those technologies.

Several environmental management tools have been established and are currently in use, such as carbon footprint measurement, environmental performance evaluation, environmental auditing, and life cycle assessment among others (Fet, 2002). The approach each tool presents is different, and their calculations are based on close analysis of the systems under study.

Life Cycle Assessment or LCA is defined by the ISO 14040 (ISO, 2006b) as a method to better understand and address the environmental impacts of manufactured and consumed products[1]. Both the ISO 14040 and ISO 14044 are international standards developed to address the implementation of LCA studies. While the first one addresses the main principles and framework for practitioners, the second (ISO 14044) aims to fully detail the requirements and guidelines needed to conduct a practical LCA.

[1] For ISO, "products" includes both products and services (ISO, 2006b)

LCA is designed to address potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (ISO, 2006b). This life cycle perspective is of most importance when applying this methodology since it enables the identification of environmental burden trade-offs and shifts between life cycle stages or individual processes.

Each LCA study can be divided in four clear phases (Figure 1):

1. The Goal and Scope Definition phase

   This iterative phase sets the tone, goal and intended use of each particular study. This section includes the system boundary selection, definition of functional unit to be used, allocation procedures, assumptions and limitations, impact categories to be analyzed and interpretation methods to be used, among other items. It is an iterative process since various aspects of the scope may change to meet the original scope of the study. (ISO, 2006b, 2006c)

2. The Inventory Analysis phase

   This is an inventory of the input/output flows of the system under study. Collection, quantification, and allocation of data are of key importance for this phase. This process is also iterative since the more the product is analyzed, the more is learned. (ISO, 2006b, 2006c)

3. The Impact Assessment phase

   In this phase, the environmental impacts of each life cycle phase are evaluated. The results obtained from the previous section are needed to perform this assessment and data is related to specific impact categories and indicators, previously defined and aligned with the scope of the study. (ISO, 2006b, 2006c)

4. The Interpretation phase

   The final phase of a LCA study summarizes and discusses the findings, obtaining conclusions and making further recommendations for the system under analysis. (ISO, 2006b, 2006c)

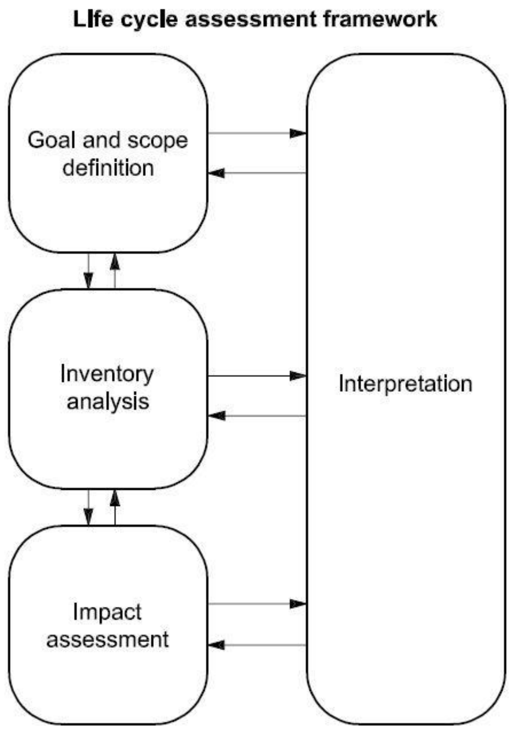


Figure 1 - Stages of a LCA study (ISO, 2006b)

Direct applications of LCA, stated by ISO 14040, include product development and improvement, strategic planning, public policy making and marketing. The review done by Bousquin et al. (2011) covered several LCA studies that were developed to address several of the previously mentioned applications. In addition, LCA can be applied by different stakeholders such as governmental organizations, industry in a wide range of sectors and non-governmental organizations (Rebitzer et al., 2004).

It can be said that one of the biggest strengths of LCA is the possibility to study a product system as a whole throughout its entire life cycle. As mentioned before, when possible changes or optimizations are evaluated it enables the identification of shifts in the environmental burdens of a life cycle stage to another one. It also provides a systematic approach and its international standards provide a robust base for practitioners to implement this methodology.

It is important to consider that LCA is only an environmental management technique and is not designed to address economic or social aspects of a product (ISO, 2006b). This is also mentioned as one of the methodological limitations of the tool by Reap, et al. (2008b).The authors remind practitioners that a study with focus on sustainability would not be properly undertaken by a thorough LCA study (Reap et al., 2008b).

The ISO guidelines also mention that the environmental impacts estimated by any LCA study cannot be understood as absolute or precise, not only because these are a relative expression to a reference unit but also because the data is not integrated over space and time and because of the inherent uncertainty in modeling such impacts (ISO, 2006b). Both the static evaluation and the high levels of uncertainty in the evaluation process are mentioned as unresolved problems in the literature (Millet, Bistagnino, Lanzavecchia, Camous, & Poldma, 2007; Ramani et al., 2010; Reap, Roman, Duncan, & Bras, 2008a). Considering that these two aspects are pointed-out not only by ISO but also in the literature, they can be considered as areas where the methodology could be refined.

LCA is known to be a relative tool since the impact assessment is always referred back to a functional unit. In addition, life cycle stages are generally compared to each other and normalization of results is commonly done in practice (ISO, 2006b).

The functional unit is defined by ISO as “the quantified performance of a product system for use as a reference unit” (ISO, 2006b). The standard states that its primary purpose is to provide a reference and therefore ensure comparability of LCA results. The norm also mentions that comparing the results of LCA studies is possible if the assumptions and context of the studies are equivalent and that this equivalence must be evaluated before interpreting the results (ISO, 2006c). It is important then to mention that the functional unit is critical to enable comparability; however it is not the only requirement to consider different studies as equivalent. Assumptions made and boundaries considered are key when analyzing and comparing LCA results. The system boundary of an LCA study “defines the unit processes to be included in the system” (ISO, 2006b). The elements modeled in each study are directly dependent on the goal and scope of the work, its assumptions, and its constraints. All of these are important when establishing equivalence between studies for comparability.

Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) call attention to the ISO definition for functional unit since it allows for different interpretations and therefore variability when conducting LCA studies. This has come to be an obstacle when comparing the environmental performance of different products throughout their life cycles. In addition, consumer behavior is often involved in the definition of the functional unit. This introduces a long list of variables that can change with geography and cultural practices. The definition of the functional unit is therefore impacted by decisions that depend on when and where the study is being conducted. Referring back to the formal definition of functional unit by ISO the question arises if consumer behavior should be considered a part of the functional unit definition or if it is related more to assumptions and boundaries of the study.

1.2.1 LCA within the Print Industry

The specific case of the print industry and the implementation of LCA studies raise many concerns among specialists in the field. There are not any criteria to define functional unit (Bousquin et al., 2011), and the presence of MFDs that cover different functions has made the practice of LCA more difficult.

Bousquin et al. (2011) identified the need to standardize practices after conducting a thorough review of different studies in the industry. In addition, the creation of a consortium involving different companies in the market with the objective of unifying practices suggests that this is not a trivial issue.

Pihkola et al. (2010) performed an extensive study analyzing the communication of environmental impacts in the print industry. After conducting a survey with different actors in the industry, they summarize the current main challenges as the comparability of LCA results (and carbon footprint calculations) and the lack of credibility when a company announces their results, among other obstacles that need to be solved in sustainability communication (Pihkola et al., 2010). These assertions, aligned with Bousquin et al.'s work (2011),point out the pressing need in the print industry to align practices. Considering that LCA comparability is enabled through the functional unit; then, standardization and guidelines for its definition are of critical importance.

1.3 Problem Statement

The stated primary goal of the functional unit in LCA is to ensure comparability of LCA results (ISO, 2006b), however, when reviewing literature and work done in the industry, LCA practitioners remark that comparing LCA studies is a very difficult task. The attributed reasons for this problem are the lack of standardized assumptions and practices, including the definition of the functional unit and reference flows (Bousquin et al., 2011; Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010b; Reap et al., 2008a, 2008b). Even though Reap et al. (2008a, 2008b) covered several unresolved problems present in LCA, as well as proposed some clear and actionable solutions to these problems, issues with functional unit definition still remain. In addition, when practicing LCA, experts do not follow a unified approach (Bousquin et al., 2011; Ramani et al., 2010).

A logical approach to consider to aid in the goal and scope of LCA is the introduction of system engineering principles and the practice of functional analysis. While system engineering principles and functional analysis have been extensively developed to aid design practitioners (Hirtz, Stone, McAdams, Szykman, & Wood, 2002; Hull, Jackson, & Dick, 2005; Stone & Wood, 2000), these approaches have not yet been effectively applied to the LCA domain.

Considering the above, the present work aims to delineate a framework that leverages system engineering principles and functional analysis in order to address some of the issues that have been identified with the early stages of LCA. The research conducted in this thesis will introduce system engineering and functional analysis concepts to the goal and scope definition phase of LCA in order to provide a framework for system definition, system boundary definition, and reference flows identification. The benefits associated with the proposed framework are expected to include improved comparability of LCAs, dynamic updating of LCAs, and the integration of LCA into early stage product development.

This Master's thesis will also characterize the stated problem. It has been noticed that various aspects of the problem have been discussed in the literature; however no work that we have found unifies these issues to create a comprehensive picture of why the goal and scope definition of LCA remains a persistent issue. More specifically, it has been seen that practitioners of LCA have not effectively integrated functional analysis into LCA, and practitioners of design theory and design methodology have not directly addressed the issues of functional unit development.

This characterization will create a basis for defining a process to systematically define boundaries, reference flows, and use behavior that leverages well established system engineering principles. Since this process will be grounded in the functional domain, issues around standardization and comparability can begin to be addressed. The inclusion of functional analysis is expected to be of key importance for the proposed process.

Finally, the application of the recommended framework on a detailed case study will be developed in order to fully evaluate the implementation of the recommended process, identify potential issues, and determine its utility.

1.4 Research Objectives

The main goal of this research is to develop a framework that integrates system engineering and functional analysis techniques to the goal and scope of LCA, with the final objective of providing a structured approach that will help enable comparability of LCA studies. Furthermore, this thesis will apply the proposed model to a specific LCA study example in order to evaluate the practical execution of the developed framework.

The specific points to be developed during this research can be defined as follow:

- Reconcile the literature on functional unit and LCA weaknesses in order to fully understand the present gap and set a path forward to propose a new process to help enable LCA comparability

- Looking at the functional unit definition by ISO, its implications with reference flows and functional analysis, develop a recommendation to unify and guide the goal and scope definition of LCA
- Apply the proposed approach to a concrete case study

Some of the research questions that will guide the process for developing the proposed framework are listed below:

1. What is a functional unit? How is it defined in practical LCA?
2. What do the detractors of LCA say regarding weaknesses of the methodology and implications of functional unit?
3. Are there any proposed solutions to unify functional unit definition? What are their strengths and weaknesses?
4. How does LCA contribute to the product design process? (Most practitioners do not consider LCA as a tool for product development; however ISO mentions this as one application for the method)
5. Can functional analysis aid the process of examining the function and reference flows of a product in order to enable comparability among different product structures?
6. How can study boundaries and assumptions be approached in order to contribute to LCA comparability?
7. ISO standards are open to future improvements in the state-of-the-art technique, is it an option to contribute to the development of the standard and LCA practice?
8. Looking at a case study, analyze the implementation of the proposed method

1.5 Outline of Thesis

The present chapter describes the motivation and importance of the topic being researched. Background information on LCA is given and the opportunity of including system engineering and functional analysis techniques into the goal and scope of LCA is presented. Finally, the problem statement and research objectives are delineated. The remainder structure of this thesis is organized as follows:

Chapter 2 covers the relevant literature research conducted on this topic. Reviews on the application of LCA are covered, and issues identified by different authors are presented. The problems in finding an adequate functional unit are also reviewed. The basic premises of functional analysis are also covered, and its implications in product design are explained including some

applications of functional analysis and LCA. In addition, different environmentally friendly tools developed for designers with a life cycle view are revised.

Chapter 3 describes the research methodology used in this Master's thesis. Different study phases are defined and explained.

Chapter 4 characterizes the problems in LCA by consolidating the identified issues in groups. In addition, the implications of these issues are defined. The grouping of these concerns aims to facilitate the identification of how the proposed framework addresses some of the identified problem areas.

Chapter 5 details the framework recommended by this research. The use of system engineering and functional analysis principles is of key importance, and the use of the framework is detailed in four distinct steps. In addition, some initial applications of the framework and presented and explained. The application of these examples was of importance since they enabled the refinement of the approach.

Chapter 6 covers the case study application. The process of selecting a Paper Shredder as a case study is explained as is the theory of operation of the selected product. The process of applying the proposed framework is detailed with the use of SimaPro® software (PRé-Consultants, 2011) to demonstrate the compatibility of the theoretical framework previously presented in Chapter 5 with the practical application of LCA. Finally, other technologies to fulfill the same function that the paper shredder provides are analyzed in order to show that the new approach provides a basis to compare different use patterns and completely different solutions.

Finally, Chapter 7 discusses the main points covered in this research. The need for future work is identified in this section, detailing some topic areas that need further development.

1.6 Summary

As previously presented, the research is motivated by the need to improve comparability among LCA studies. Although some initiatives have been undertaken in specific industries, no general approach regarding the LCA methodology has been developed. The combination of system engineering principles and functional analysis and its integration to the goal and scope of LCA is a promising notion that could provide a unified framework for practitioners.

The research will provide a characterization of the problems encountered in LCA practice, and using both systems engineering and functional analysis, a framework for system definition, system boundary definition, and reference flows identification will be proposed.

The benefits associated with the proposed framework are expected to include improved comparability of LCAs, dynamic updating of LCAs, and the integration of LCA into early stage product development.

2.0 LITERATURE REVIEW

The present literature review covers several views on the application of LCA, the definition of functional unit and the work being done in this area, the efforts encountered to develop functional analysis, and its applications in product design coupled with LCA. Finally, some tools developed to aid designers in developing more environmentally friendly projects and products are also reviewed.

2.1 APPLICATION OF LCA AND FUNCTIONAL UNIT DEFINITION

LCA is widely accepted in the industry and it can be said it is the most used tool to assess environmental impacts throughout the entire life cycle stages of a product or process (Ramani et al., 2010; Reap et al., 2008b; Rebitzer et al., 2004). The results and analysis obtained are generally highly insightful and useful; however it is also known that the process of conducting an LCA is very data intensive and time and resource consuming (Bousquin et al., 2011; Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010b; Devanathan, Ramanujan, Bernstein, Zhao, & Ramani, 2010; Ebner et al., 2009; Ramani et al., 2010). While ISO has developed extensive standards to guide the process of conducting an LCA study, a two-part survey has been published by Reap et al. (2008a, 2008b) which criticizes the process, and even suggests improvements. This extensive review identifies the unresolved problems in LCA. The two publications reconcile the issues and limitations encountered in LCA analyzing each specific LCA phase. In their work, Reap et al. (2008a, 2008b) identify 15 specific problem areas. After assessing the severity and the adequacy of available solutions for each issue, the authors rate each problem area resulting in six critical issues that, in the authors' opinion, need particular and critical attention. These important issues are the following:

1. Functional Unit Definition – affects goal and scope
2. Boundary Selection – affects goal and scope
3. Allocation – affects the inventory phase
4. Spatial Variation – affects the impacts assessment phase
5. Local Environmental Uniqueness – affects the impacts assessment phase
6. Data availability and quality – affects all four phases

Looking at the first phase of an LCA, the functional unit definition and the boundary selection are in need of attention since these form the base of any study. In the inventory phase, allocation refers to the distribution of environmental burdens of a multi-functional process amongst its functions or products. In the impact assessment phase, the spatial variation of local environment sensitivities is considered to be overlooked and misevaluated and therefore a serious matter that

needs improvement. In addition, the authors also consider that local environmental uniqueness and sensitivity is poorly covered in current LCA practices. The final critical problem that the authors discuss is the poor data availability and quality that affects all four phases. The key outcome of this survey is the observation that for the first three critical issues there are no available and agreed upon solutions and/or improvements proposed.

Reap et al. (2008a) consider functional unit definition, boundary selection, and allocation to be of high priority, and therefore propose the development of LCA archetypes in order to guide practitioners. In addition, dynamic modeling is also recommended in order to improve the spatial variation and local environmental uniqueness problems. Finally, peer-reviewed and standardized databases and the development of model bases are proposed to address the data availability and quality issues (Reap et al., 2008a). Reap et al. (2008a, 2008b) succeeded in compiling most of the issues that many authors mention in different opportunities, and their recommendation of LCA archetypes encourages researchers to keep working towards the development of recommendations and procedures to guide functional unit definition, boundary selection, and allocation. This present work will attempt to define a path for those critical problems.

The work done by Millet, et al. (2007) reviews and questions the applicability of LCA in the product design process. For their research, several environmental tools such as Design for Recycling (DfR), Design for the Environment (DfE), and LCA, among others, were analyzed to determine how well they were integrated into the internal business processes of the different companies. An assessment of the usefulness of LCA as a tool was performed, both in the short term and the long term.

Millet et al. (2007) argue that the methodology is not an adequate tool for designers since it is based on the analysis of existing or well defined products. Even though scenario analyses can be done to alleviate the fact that some information is missing during product development, it is argued that it increases the complexity and uncertainty of the results. During their work, several issues already mentioned by Reap et al. (Reap et al., 2008a, 2008b) are covered such as problems with data availability and homogeneity, the static nature of LCA, the complex process of defining a functional unit, and the different categories of impact which mostly focus on global interactions with long-term effects among others. In addition, in the long term view, the authors criticize the lack of applications the tool has, arguing that, within a company, it is hard to create awareness of it. Their recommendation is that, for the product design field, LCA should be dedicated to the strategic evaluation of new concepts and should be considered only as a specialized tool managed by the environmental stakeholders. The authors make the important mention of using LCA as an indirect

means to aid designers in generating methodological principles to guide the development of (better) environmentally friendly products. An example of this point can be the work by Telenko and Seepersad (2010) which will be further reviewed in this literature research.

The main view point raised in this study is the fact that LCA cannot be used as a design tool in the sense of a cross functional tool that generates concepts or ideas. The authors imply that the tool is good as a complement for the design process, and that it should be limited to an expert tool. These statements are not insignificant since the tool sometimes falls under the label of "design tool" when it is really supposed to be a support method for product design. The ISO 14040 suggests that the tool has a direct application in product development (ISO, 2006b), but Millet et al. (2007) make the straight-forward case of LCA's shortcoming in this respect.

A deeper look into the problems of specifying functional units and reference flows was done by Cooper (2003). The fact that no requirements for defining functional units and reference flows are present in the ISO standards is the starting point of this work, and the main objective is to suggest a process for defining the functional unit and reference flows for comparative LCAs.

The suggested process covers the proper inclusion of lifetime, performance, and system dependencies of the system under analysis. A case study was developed in order to show the feasibility of the use of the proposed requirements. This work demonstrates the importance of considering system and interfacing materials, and energy flows. Its main conclusion is that, through the use of the proposed set of requirements, it is possible to account for differences in materials and energy flows in a transparent manner, improving the assessment and interpretation phases of LCA. An important highlight is that this approach is a good attempt to provide concrete steps or requirements for practitioners to follow when defining functional units. Finally, the main point to be considered from this work is that, as mentioned earlier, it includes the issues related to lifetime, performance, and system dependencies; however this is done through the inclusion of these into the definition process itself. The use scenarios and lifetime considerations are then not decoupled from the functional unit and reference flows definition, leaving uncertainty on how to quantify and model these important factors.

The problem of defining an adequate functional unit was also covered in detail by Hischier and Reichart (2003) but, in this case, the discussion was specific to the issues encountered when multifunctional devices are under study. A thorough and astute analysis was performed in order to identify a proper functional unit to compare an internet newspaper, a TV news cast, and a traditional newspaper. Their development is based on the comparison of different functional units, and the main stated conclusion establishes that different functional units lead to different results.

The authors claim that when basing the functional unit on functional equivalence of the analyzed products (or services), the functional unit does not resemble the options of the consumer in the real world making the LCA comparison not relevant (Hischier & Reichart, 2003). However, the article lacks a fully detailed definition for functional equivalence and the functional unit derived from the equivalence analysis can be questioned for lack of abstraction. In the present research, this specific case will be considered and the process proposed using functional analysis will be tested..

It is important to separate the difficulty in defining a proper functional unit for a product in general regardless of its technology, and the difficulty presented in defining a proper functional unit for multifunctional devices. While the former issue looks to establish a robust functional unit and reference flows to compare different products that perform the same function utilizing different technologies, the latter refers to the use of LCA for comparing products that perform multiple and different functions. Even though both issues are in need of improvements, it seems logical that once a clear procedure to define functional unit and reference flows for any type of product has been established the analysis can be rolled out to outline guidelines for the use of functional unit and LCA for multifunctional devices.

When specifically looking at the print industry, Bousquin et al. (2011) performed a comprehensive review of LCA studies conducted within the industry. This review covered not only studies performed on printers but also studies performed on consumables, print products, design methodologies, and calculators. Common practices, limitations, areas of improvement, and opportunities for standardization were identified. In addition, the importance of consumer behavior and the fast-paced technological advances in these devices were also identified as factors that increase the complexity of LCA and several sources of discrepancy among studies were noted. Similarly to the review performed by Reap et al. (2008a, 2008b), the lack of reliable data in the reviewed studies is mentioned and the suggestion of increasing transparency in the studies is identified as a way to tackle this problem.

The main outcome of this review is the conclusion of the lack of standardization in assumptions and practices in the reviewed LCA studies performed by and for the print industry. The functional units used were sparsely defined, contributing to the lack of comparability among studies. Even though several LCAs addressed the same type of product, printers, the functional unit employed in each study was completely different. This points out the need for some type of procedure or guideline that helps practitioners align functional units, and therefore contribute to comparability between studies. By addressing the pressing need of the print industry to determine the feasibility

of meaningful LCA comparison, Bousquin et al.'s (2011) review serves as a starting point to work towards this goal by identifying the most important areas to focus on future work.

In the same line of research, Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) developed an interesting concept to contribute to the standardization of functional unit: the Fuon theory. Remarking that the ISO standards allow for high variability between practitioners when defining a functional unit, and considering the pressing need of aligning this important part of the goal and scope phase, the authors introduce a systematic approach based on the abstraction of a product. Fuon stands for Functional Icon and they are based on the essential functions of a product. A specific Fuon represents the set of products that share the parameters for that function's flows. The objective of this approach is to aid practitioners in the correct definition of a functional unit, and therefore enable life cycle comparison.

It is important to mention that the work done in the functional analysis area by Stone and Wood (2000), and Hirtz et al. (2002) was reviewed by Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) and they concluded that this work has not been used in LCA.

The presented theory is based on obtaining parameters that represent the main function of the product under analysis and that will ultimately enable scaling. In the reviewed paper, Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) develop two Fuons, shown in

Figure **2**, "Physical Container" and "Logistics-intensive Element" with its specific types of functional unit parameters (FUp's) and explain the process to obtain these.

The authors establish that the functional unit has to be defined as a delimited set of parameters which they call FU parameters (FUp's). Many of these parameters are physical magnitudes, which are the main functions of the product, and are represented by FUp^{p}. Other parameters represent constraints to design or an additional function that the product must fulfill, such as aesthetics or intangible added value. These are called functional constraints, and are represented by FUp^{c} (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010a). By selecting a specific Fuon, the possible scaling parameters that define that class of products are determined.

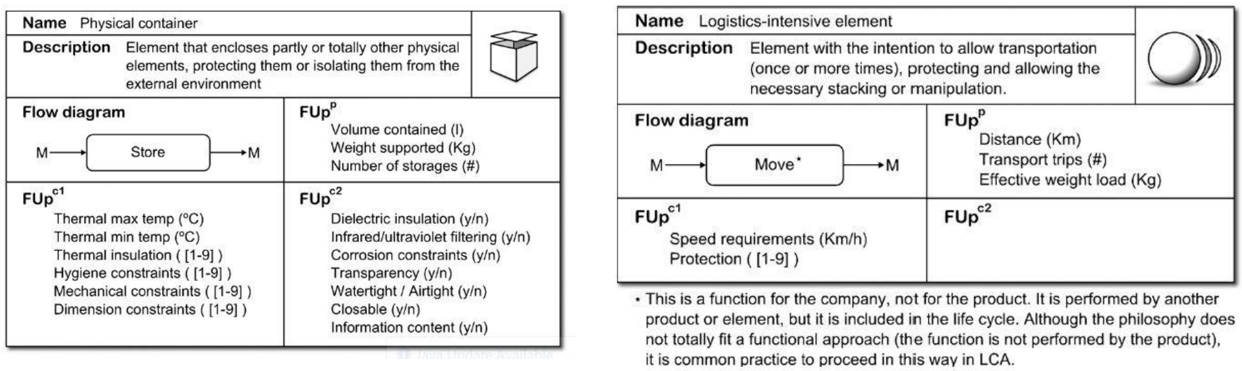


Figure 2 - Fuons Developed by Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b)

The full development of these Fuons was based on conducting the life cycle inventory of 52 products and assessing cumulative energy demand. The authors proved their validity by performing a regression model with the environmental impact as dependent variable and the chosen functional unit parameters as independent variables. When scaling was proved suitable, then those variables were set as the parameters that correspond to the Fuon being developed.

While this methodology presents an interesting approach, it is not clear how the life cycle inventory was quantified and how the functional units used in the original LCIs were defined. The developed theory does not explicitly state if and how a functional unit was defined for each LCI conducted, thus it is not clear to the reader what the regression response variable is. Furthermore, because these Fuons are developed absent of their context, or more accurately, they attempt to account for a large variety of contextual scenarios, the number of scaling parameters generated is relatively large making the possible use of Fuons confusing. In addition, since there is no way to ensure that they are exhaustive, there is little guidance provided on how to deal with a new context. The proposal is valuable, however, since it addresses the need for guidelines in the LCA practice.

2.2 Functional Analysis in Product Development

Several efforts to develop functional analysis and an integrated approach in this area have been published (Hirtz et al., 2002; Stone & Wood, 2000). The work done by Stone and Wood (2000) proposes a unified language for the application of functional design. Considering the importance of functional modeling in product design, the authors recommend the use of an aligned design language among engineers. Their proposal, called Functional Basis, covers an extensive portion of the mechanical design space and is characterized by the use of the 'verb-noun' format.

The overall concept behind this approach is the use of functional analysis for engineering design, allowing practitioners to describe the overall functionality of an artifact without relying on the physical structure and allowing for more openness when it comes to solutions. Functional design can be used in many different spaces such as developing product architecture and function structure generation. The research done by Hirtz et al. (2002) follows the initial work done by Stone and Wood (2000) since it reconciles the language proposal aforementioned with the one suggested by the National Institute of Standards and Technology (NIST) to recommend an evolved functional basis. A profound analysis is done covering the differences and similarities between these previous efforts and a more comprehensive design vocabulary is finally suggested.

The main advantage of a common design language is that it enables a formal repeatable level of detail and semantic consistency between engineers and projects. The relevance that this approach can have to the definition of functional unit is clear since a common problem found in LCA is that practitioners use their own language contributing to high variability in functional units (Bousquin et al., 2011). It is important to mention that no work that extends the use of Functional Basis and functional analysis premises to formal LCA and functional unit definition has been found (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010b), and the integration of these two areas is an outstanding opportunity.

One use of functional analysis with the integration of LCA is studied by Bohm et al. (2010). Through the use of a design repository, Bohm et al. (2010) can estimate the LCA impacts of a general artifact through developing its functional model. Different virtual concepts were modeled with the use of a design repository that archives extensive product design knowledge. Once these options were presented, the virtual concepts were environmentally assessed through LCA and then compared to the LCA impacts of similar real-life products (Bohm et al., 2010). The focus of this research was mainly to demonstrate that there is a possibility of estimating LCA in the design phase since it is known that as much as 80% of a product's environmental impact is defined during this phase (Bohm et al., 2010).

The research successfully demonstrated the use of functional modeling and the design repository, illustrating that a rough estimate of life cycle environmental impacts can be achieved in the design phase. The approach generates a virtual bill of materials that is later used as source inputs in the LCA simulation. When comparing the results obtained through the repository to the results obtained by simulating actual physical products, it was determined how close the LCA estimates for the virtual concepts were. While the study shows the influence and potential that the design repository has in estimating environmental impacts, it does not explicitly address the

concerns identified above in defining a functional unit. Since the comparison and modeling in the reviewed work starts from the same functional decomposition, both the virtual concepts and real-life products being modeled use the same functional unit for comparison. The use and the tool presented in this study are of high relevance for designers since it integrates LCA into early design stages thereby enabling environmental assessment of concepts that have not really been locked in on, however it does not contribute to a robust practice of LCA.

2.3 Environmentally Friendly Tools for Designers

Telenko and Seepersad (2010) successfully incorporated reverse engineering and functional decomposition to identify environmentally conscious guidelines that can be further implemented in the design phase of a class of products. Their methodology includes the use of LCA to validate the guidelines that result from the proposed process. The method addresses a set of functionally related products and therefore the identified guidelines can be considered and applied without repeating the process every time. The uniqueness of the proposed methodology lies in that it explores impacts through a life cycle approach rather than a one life cycle stage focus as most guidelines for design for the environment (DFE) do (Telenko & Seepersad, 2010).

Even though the approach is useful and interesting, since it addresses the need of evaluating environmental impacts in the design stage, the methodology only uses LCA as a validation tool, thus the issues of functional unit definition were not explicitly addressed. In this paper, when performing LCA, the functional unit is defined through surveys and common uses for the product under analysis and the authors do not cover any of the pressing concerns regarding functional unit definition. While a comprehensive functional decomposition is performed, even at the black box level, none of the information obtained in this process is used to define functional unit. As mentioned before, there is space for connecting robust practices for functional unit definition with functional decomposition and the reviewed study does not address this opportunity.

A methodology proposed by Devanathan et al. (2010) addresses the environmental assessment in early design through the use of a function impact matrix (FIM). The FIM correlates environmental impacts (results from LCA) with the functional decomposition of a product. This semi-quantitative tool is mainly proposed as part of a reverse engineering process or a redesign initiative since it needs the outcomes of the LCA (or any streamlined methodology) for the product under analysis to relate the impacts to the functions offered by that same product. The outcome is the identification of possible redesign opportunities from an environmental stand point. The FIM relates impacts to functions through the structure of the product (Devanathan et al., 2010) and the

high uncertainty involved in the process has been addressed in a later publication (Devanathan et al., 2010; Ramanujan, Bernstein, Zhao, & Ramani, 2011). The proposed methodology integrates easily into any reengineering process or tools such as a quality function deployment (QFD), or a Pugh chart can be fed with the outcomes of the FIM, helping the design process. However, the tool does not address functional unit definition even though it relies on the complete understanding of the functionality of the product under analysis. It can be said that each application of the proposed method is specific to each product under analysis and cannot be extended to other products within the same class.

Looking to address comparability and also feeding the design process, Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010a) developed the concept of product families for LCA comparison (LCP-families) which enable reference ranges to estimate the environmental impacts of a new product. The basic idea behind this work is the grouping of products with common LCA traits which serve as benchmarking to set targets for environmental impact values for new product developments. The products enclosed in a LCP-family not only should share common LCA traits, their life cycle also should be able to be represented by a limited set of parameters, and those parameters should be scalable. The formal definition for a LCP-family states "…(an LCP-family is) *a set of products whose life cycle assessment shares a common behavior, and can therefore be compared in a practical way*" (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010a). Considering that comparability in LCA is enabled through the functional unit, this is then the base to form the LCP-family.

In the reviewed work, the authors point out the lack of guidance when defining functional units and that in order to use functional units in LCP-families, its formulation needs to be systematized. The previously presented Fuon Theory is therefore developed by the same authors and it is aimed to address the systematization needed to generate these reference ranges (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010b).

Throughout the work done in reference ranges, the authors illustrate a detailed process in order to obtain comparability among different LCA studies, and also compare to a newly designed option. Comparison is done in a quantitative way and the new product can be assessed as better or worse than the products it is being compared to. Considering both the proposed systematization of functional units through the Fuon approach and the reference ranges for product comparison, Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010a, 2010b) have successfully incorporated LCA in the design phase of products. However, the lack of connections between their approach and functional analysis can be identified. In addition, no formal guidance is given in order to identify similar products for LCP-families. The authors address the pressing issue of functional unit definition and

LCA comparison, yet the opportunity to advance these concepts with the inclusion of functional analysis is an open opportunity.

Addressing the need within the print industry, Ebner et al. (2009) developed a scorecard to identify research projects for eco-efficient print engines. This tool is not designed as a replacement for LCA but as a complement to identify potential green projects in the early phases. Guidelines to assess eco-efficiency of research concepts are given and also to choose between different opportunities. The inputs needed for the developed tool are quantitative, however are not as extensive as the data needed for a formal LCA. The scores obtained are a measure of effectiveness and, in order to calculate this, a functional unit was previously defined for every calculation the tool does. The tool was successfully implemented and the Xerox Innovation group uses it internally. This development shows the need of a fairly easy to use tool to assess environmental impacts in the print industry. As mentioned before, LCA is resource and time intensive and presents several areas that need improvement. The opportunity, in this case, lies again in a method for functional unit and reference flows definition. If a formal procedure is determined, the tool developed by Ebner et al. (2009) could be potentially expanded and more robust.

2.4 Summary

The review of literature for this thesis reveals how the application of LCA is done in industry and some of the areas of improvement that the method presents. In addition, the potential incorporation of some functional analysis concepts in the reference flow definition is discovered. Research developed around incorporating LCA in the product design stage is analyzed, and the potential of having a structured approach for functional unit and reference flow definition is exposed as an important research area that needs further advance.

3.0 Research Methodology

In this chapter the details for conducting this Master's thesis are described. As mentioned earlier, concepts from systems engineering and functional analysis will be of key importance for the development of the proposed framework. Considering that a theoretical approach will be recommended to be implemented in the goal and scope of LCA, an iterative process is expected for the development of the propositions that constitute the framework. In order to organize the work to be done, three phases are proposed and described below.

3.1 Phase One – Characterization of the Problem

After conducting the first round of literature research, the need for a more thorough and comprehensive problem characterization covering the issues with functional unit definition and comparability of studies within LCA has been identified. This comprehensive characterization into these problems is necessary in order to better understand the issues, but more importantly, with a comprehensive characterization of the issues insights into the ultimate goal of this Master's thesis, a proposed process to help enable LCA comparability, may become more readily apparent.

The different ideas and concerns expressed by several authors reviewed in the aforementioned literature review will be consolidated and a further examination of the available literature will be performed.

For this phase of the present Master's thesis, a systematic classification scheme for the issues that have been identified for defining functional units is needed. In order to arrive at that scheme, the literature research will be reviewed, expanded if needed, and a categorization and grouping of the problems in LCA and errors when defining functional unit will be developed. The exploration will cover general methodological issues, regardless of a specific industry.

As a starting point, the issues in functional unit mentioned by Reap et al. (2008b) will be further explored. In their review, the authors identify functional unit definition as one of the most critical problems to be solved in LCA. Several sources of error when defining a functional unit are recognized and shown in Figure 3. The errors can be generated from the different steps involved with functional unit.

In identifying and prioritizing the functions of a product system, it is important to properly state all of the functions that the product (or service) provides. Most products tend to have one primary function; however there are products that have multiple functions such as a multi-function printing device that prints, copies, scans and faxes. In these cases, sub-functions must be considered

since not accounting for these will result in a functional unit that does not reflect reality (Reap et al., 2008b).

When assigning functional units to multiple functions, it is possible that potential functional units may not represent all the functions. In this case, the practitioner needs to analyze the case and this is where the opportunity arises to apply concepts from functional analysis. It is also important that the function that is being analyzed is quantifiable. If the case arises where the function is difficult to quantify, the use of a functional unit that serves as a proxy may lead to less comparability (Reap et al., 2008b).

There are also potential errors from the allocations of the reference flows associated with the selected functional unit. The uncertainties arising from product use scenarios are important since they may affect the assumed lifetime and performance of the product. In addition, system dependency issues refer to changes that may affect the product system and therefore its whole performance (Reap et al., 2008b).

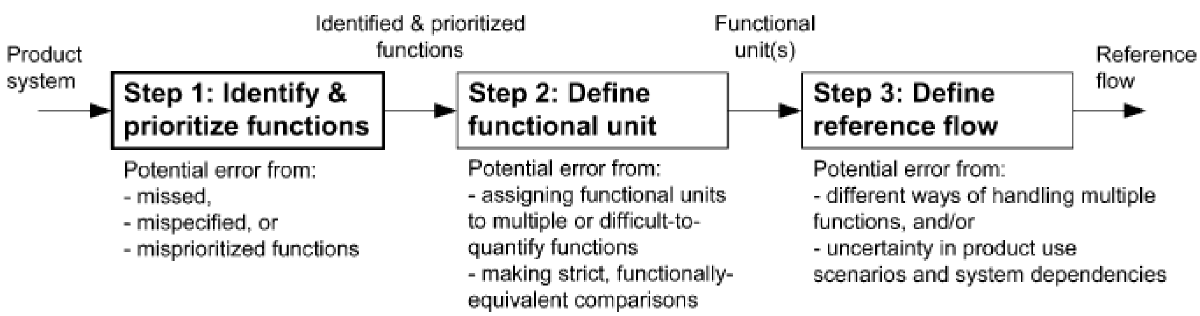


Figure 3 - Sources of error related to functional unit (Reap et al., 2008b)

A further look into these potential errors and the concerns that LCA practitioners have in this area will help guide the process of proposing guidelines for functional unit definition.

3.2 Phase Two – Recommend a Framework

Once the problem is appropriately characterized, a list of propositions and a process to implement these will be recommended to improve the definition of reference flows in the goal and scope of LCA. Based on functional analysis practices, the analysis of the system under study at the black box level is expected to be of key importance for the proposition.

Functional modeling is a powerful tool used to decompose the functionality of a product in order to understand it in a more abstract way, without the need of its structure. The modeling begins with the formulation of the overall product function and then breaking this into smaller sub-functions (Stone & Wood, 2000). Good practices in functional modeling state that functions should be expressed as a verb-object pair. The verb represents the function while the object is the flow involved in that function. The flow is the representation of the quantities that are input and output by functions (Stone & Wood, 2000). Three basic flows are considered in any design problem application: energy, material and information. The natural link to LCA comes with the identification of flows since the ISO 14040 standard (2006b) indicates the importance of determining the (reference) flow in each product system in order to fulfill the intended function, and therefore ensure comparability of LCA results. Bohm et al. (2010) highlighted one of the benefits of functional modeling remarking that it "…is an easy way to see what type of function is performed without being distracted by any particular form the artifact may take". Considering that identification of reference flows is part of the goal and scope of an LCA and that it is a key enabler for comparability, there should be a way to define these that is unrelated to the technology or the structure that the product under study has.

Black box modeling focuses on the primary function of the product and identifies the flows that enter and leave the product (Telenko & Seepersad, 2010). These diagrams are helpful to distinguish the necessary flows for the selected function. An example of a black box model is developed by Telenko and Seepersad (2010) and shown in Figure 4.

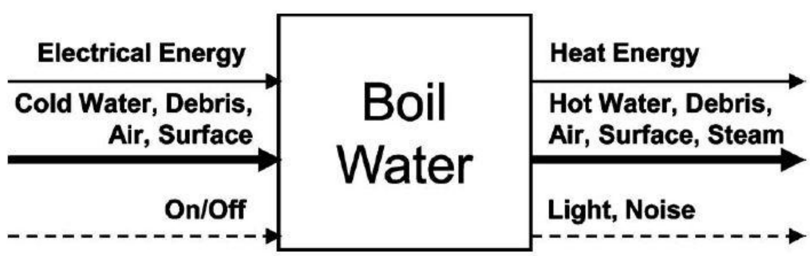


Figure 4 - Black box model of an electric kettle (Telenko & Seepersad, 2010)

By abstracting the functionality of a product and adequately identifying the flows involved, the process of identifying the relevant reference flows should be easier to align between different practitioners. The needed functional unit and flows identification in LCA is strictly related to the use phase of the product under analysis, and when defining these through abstraction consumer

behavior is external to the system. The use of a black box model will also help practitioners in the boundaries definition, an important step in the goal and scope of every study.

Some initial trials were performed in order to understand how insightful the application of black box modeling can be for the definition of functional unit. The intent of this second phase is to further these examples and finalize a recommendation for aligning practices.

3.3 Phase Three – Case Study Application

The final stage proposed for this Master's thesis is the application of the recommended framework on a specific case study. Several LCA studies are available to be analyzed from the Industrial and Systems Engineering department, and the exercise of applying the proposed approach will be done.

The main idea is to relate this approach to the LCA of mechanical products, focusing on the function performed by the product and regardless of the technology used. If the framework is successfully applied in a practical setting, then comparability will be a feasible objective. A functional analysis will be done at the black box level, identifying all the flows, and system engineering concepts will be applied to the specific case. The application of this model will be tested and the implications on applying the framework through the SimaPro® software will be analyzed. As mentioned earlier, this exercise will help us understand the utility, strengths, and weaknesses of the proposed method.

3.4 Summary

The aforementioned methodology, consisting in three specific phases, is expected to successfully result in a promising framework that will help better LCA studies' comparability. The first proposed phase will consist of identifying concrete issues in the LCA methodology. The idea behind this characterization is to clearly identify and classify the problems in LCA in order to later evaluate if the proposed framework helps to address some of these important problems. The second phase will cover the framework development and will detail the propositions recommended to be used in the goal and scope of LCA. The final and third phase will detail the application of the proposed framework in a case study developed using the SimaPro® software. The main objective of this final phase is to understand the implications of applying the framework in a real case study, defining the feasibility, utility, strengths, and areas for further improvement of the framework.

4.0 Characterization of Problems in LCA

The practical application of LCA has pinpointed several issue areas that this tool presents. The fact that the methodology was designed and initially used to analyze simpler products such as soda bottles or packaging, and the fact that today its use has been extended to more complex products with moving parts and several functions, has led to the increased complexity of the methodology. Considering the many problem areas present in the methodology, a comprehensive survey was done in order to categorize them. The main objective of this characterization is to properly identify these problem areas, categorize them, and after developing the framework reveal if it helps address some of these, improving the practical use of the tool.

4.1 Identifying the issues in LCA

The issues found in LCA have been mentioned by several authors, and in order to help the understanding and classification of these problem areas, an affinity diagram was developed.

In order to be comprehensive, the KJ method for affinity diagrams was followed. This method was developed by Professor Jiro Kawakita from the University of Tokyo, and provides the basis to perform a structured brainstorming and analysis (Esterman, 2010a). There are three basic steps by which this method is executed. Initially, the narrative data is collected and compiled into separated cards or post-its. In this step, redundancy is allowed in order to generate as much data as possible. Then, the cards are sorted in logical groups and labeled. This process helps the clustering and grouping of the cards within similar subjects. Finally, a KJ diagram is developed and analyzed. This diagram groups the subjects by their commonality, and also enables the possibility of overlapping different subjects under one common area.

For the analysis of the problems found in LCA, the first and second steps of the method were followed. The KJ diagram was initially developed, but later not continued since the grouping of the issues was found to be better done by LCA stage. The idea behind using the KJ method and developing an affinity diagram for the LCA issues was to look for common linkages between the different statements and problems found by different authors in the literature.

After collecting the data, over 60 cards with LCA issues stated by different authors were identified. The initially identified problems groups were defined as following:

1. LCA general constraints
2. Functional equivalency
3. Functional unit difficulties
4. Selecting boundaries

5. Lack of guidelines
6. Impact categories
7. LCA results/interpretation
8. Data availability and modeling

Since affinity diagrams allow for issues to overlap in different categories, the grouping and categorization of the issues was re-worked in order to have a cleaner list of identified problem areas. In addition, the group names were revised, and finally different group levels were defined.

It was found better to first classify the issues depending on which is the main LCA stage in which these happen, and later, within each LCA stage, a further classification was attempted.

While LCA presents several issues, the classification done for this Master's thesis resulted in a higher number of issues identified in the goal and scope of LCA. Considering that the main objective of this work is to help better comparability among studies, and that the assumptions, system boundaries, and functional unit and reference flows are selected in this first stage of LCA, the classification was very focused on the issues in this stage.

The full classification of identified problems in LCA can be found in the following tables. The general issues found are detailed in Table 1. The issues found in the goal and scope of LCA were sub-divided in three categories shown in Table 2. Finally, some of the problems identified in the Inventory, Impact Assessment, and Interpretation phases are detailed in Table 3.

As mentioned earlier, while many issues come up in the later stages (inventory, impact assessment, and interpretation), several important problems are present in the goal and scope which defines the study. A list of LCA general constraints, shown in Table 1, was identified as issues that apply to the tool itself and do not impact a stage in particular. Limitations such as the environmental focus of the tool, the static analysis that it provides, and the high level of resources needed to perform studies are mentioned in this category. These issues mostly impact the reach that this tool can have. For instance, for resource constrained projects, the tool is not applicable. In addition, since the data does not take spatial and temporal considerations into account the analyses become obsolete with time and geographies. Another important issue to mention is the lack of connection with product design. Even though the tool is intended to contribute to product designers (ISO, 2006b), when applying the methodology practitioners find it to be a very complex task.

Table 1 - Identified general LCA issues

Problem Category	Problem
LCA General Constraints	LCA excludes social and economic considerations
	LCA does not take into account spatial and temporal considerations
	LCA studies present methodological inconsistencies, making them hard to compare
	LCA is resource and time consuming
	LCA is data intensive
	Expertise is needed to conduct LCA
	LCA is not suitable for product design

The issues identified in the goal and scope of LCA, shown in Table 2, were sub-divided in three smaller groups since different areas are covered in this stage.

The first sub-category groups the difficulties with the functional unit. The simplicity of the tool which was initially developed for simple products is mentioned as a drawback since, for more complex products, the product utility is hard to define and the norms do not recommend guidelines for this. In line with this, some practitioners miss product functions that are not considered for the functional unit definition. The difficulty in comparing different products and defining equivalent workflows between them is also mentioned in this group. The presence of non-quantifiable attributes and how these are related to the functional unit is another area of concern. The fact that practitioners define functional unit based on their own experience results in the use of words and language that is not necessarily the same even when the same product is under analysis. In addition, the fact that practitioners define the reference flows based on consumer habits or use scenarios is a problem since then the quantification of the inventory and the system boundaries is different depending on each case.

The second sub-category, shown in Table 2, groups the issues regarding the system's boundaries selection and assumptions. Issues such as the subjectivity when defining cutoff criteria in the boundary selection and non-clear guidelines on how to define both assumptions and system boundaries are mentioned in this sub-category.

Finally, the third sub-category, also shown in Table 2, encompasses the issues regarding data availability and modeling. Problems such as data gaps and imperfect modeling are a big part of some of the inaccuracies present in LCA. The cost of maintaining updated databases and libraries, and some quality issues in the data are part of this sub-category.

The number of issues found in the goal and scope of LCA is not negligible. Considering that this phase is the one that defines the tone and focus of the study itself, focusing on proposing some solutions for these issues is a good way to start improving the methodology.

Table 2 - Identified Issues in the Goal and Scope of LCA

Problem Category	Problem
Goal & Scope - Functional unit difficulties	Product utility is hard to define, limited to simple products
	Functions are hard to identify and prioritize
	Product alternatives offer functions/features in addition to the function of interest
	Not clear on how to consider sub (or extra) functions
	LCA is not clear on how to handle non-quantifiable attributes
	FU is defined using different language/words
	Definition of FU and reference flows are difficult due to consumer habits, product lifetime, and system dependencies
	Confusion defining FU for MFD
	Requirements for specifying FU and reference flows haven't been developed
	Different FU lead to different results (variability)
	Functional equivalency leads to inaccurate reflection of product reality

Problem Category	Problem
Goal & Scope - Selecting boundaries and assumptions	In practice, boundaries selected are sometimes not clear
	Cut-off criteria for boundary selection is not properly defined by ISO
	Lack of tools to support boundary selection in LCA practice
	No guidelines on how to approach assumptions

Problem Category	Problem
Goal & Scope - Data availability and modeling	Some impact categories suffer from data gaps (information is hard to obtain because it doesn't exist)
	LCA modeling is imperfect and life cycles are generally over simplified
	Data quality issues when data used does not represent local conditions (Local Technical Uniqueness)
	Uncertainty in modeling and databases
	Data is incorrectly extrapolated
	Problems with data availability and homogeneity
	Data collection can be very costly
	Data becomes out dated
	Badly measured data

The issues found in the Inventory, Impact Assessment, and Interpretation phases are detailed in Table 3. One of the main issues identified in the inventory phase is the one called allocation. Allocation called in the sense of how to appropriately allocate the environmental burdens of multi-functional processes such as incinerators, landfills, sawmills, etc. The issue is then the determination of how much of the environmental burdens caused by the multi-functional process should be assigned to each product (Reap et al., 2008a). The fact that no guideline for this issue exists, opens the possibility of arbitrary allocation that eventually leads to different or incorrect LCA results.

Some of the problems found in the impact assessment phase are related with how to choose an appropriate impact category method, and confusion regarding midpoint and endpoint categories. The spatial variation issue comes up again in this phase, related to how factors such as geographies or even meteorological conditions are not considered in some methods.

Finally, in the interpretation phase, the potential of double counting environmental burdens comes up as an important issue. In addition, the fact that LCA results are just an indication of potential impacts and not necessarily real impacts is something discussed by practitioners. The way a practitioner performs sensitivity and uncertainty analysis impacts directly on the interpretation phase and the conclusions of the study, and no formal guidelines are given for this hindering potential comparability among studies.

Table 3 - Identified Issues in the Inventory, Impact Assessment, and Interpretation phases

Problem Category	Problem
Inventory	Not clear on how to allocate environmental burdens to multi-functional processes
Impact assessment	No guidelines on how to select an impact category indicator and model
	No clear path on how/why to choose midpoint or endpoint categories
	Impact categories are not standardized
	LCA does not consider spatial variation (geology, topology, meteorological conditions) for some impact categories
	LCA does not consider local environmental uniqueness which is different depending on the place
Interpretation	There's potential for double counting environmental burdens because they can impact multiple categories
	LCA results are only an assessment of 'potential' impacts
	Choosing different scenarios influences decisions in the interpretation phase
	LCA impacts estimations are relative to a reference unit
	Weighting methods when interpreting results can be challenged, and results between studies vary greatly
	Lack of robust conclusions about lifecycle environmental impacts of different technologies
	ISO does not recommend when or how to use uncertainty or sensitivity analysis

Looking at the problems identified, it can be said that a lot of them impact the robustness of the LCA studies and that better guidelines could improve the comparability among studies. Considering that the goal and scope of LCA is the phase that determines the tone of the study, working on the issues present in this phase is a good starting point to improve and optimize the methodology and further work needs to be done to cover many issues not addressed by the present framework.

4.2 Functional Unit and Current Practices

A further look into functional unit definition was done in order to understand the ways practitioners currently face this difficult task.

Even though the ISO 14040 (ISO, 2006b) and ISO 14044 (ISO, 2006c) standards cover the definition of functional unit and its use when conducting an LCA study, they lack guidelines on how practitioners should perform this task. This gap in the standards enables open interpretation, and therefore practitioners define the functional unit for each specific study as best as they can. This

results in lack of comparability between different studies, a matter that has been mentioned by Bousquin et al. (2011). In addition, the use of different functional units for the same product systems can lead to different results (Hischier & Reichart, 2003).

The problems encountered by practitioners when facing the challenge of functional unit definition are mentioned by different authors. Rebitzer et al. (2004) indicate that to enable product comparisons the functional unit needs to be translated through the reference flows, which are specific to the product being analyzed. Functional unit is then defined by the authors as "a quantitative description of the service performance of the investigated product system(s)". The definition of precise functional units is then highlighted as one of LCA's methodological challenges. In addition, the limitations when trying to transfer conclusions between studies are also mentioned as an important challenge. The inclusion of useful lifetime of the product system and parameters that represent user/consumer behavior contribute to the fuzziness of the process for defining functional unit. Bousquin et al. (2011) highlight the complexity involved when defining the functional unit of multi-functional devices. The lack of clear best practices contributes to the confusion presented when multi-functional devices are under analysis.

In addition to the issues mentioned above, different sources of error which diminish the confidence in the definition of a functional unit are revealed by Reap et. al (2008b). Overall, it can be said that errors can be generated from the inaccurate reflection of the product system. When identifying and prioritizing functions, it is important to consider and analyze all of the sub-functions of the product since it is important to represent the reality as best as possible. If the defined functional unit does not address all of the functions of the product under analysis, then the quantification of impacts which is based on this functional unit will be weak. When functional units are defined with the objective of representing equivalent functionality, there is a risk that the reality is not truly represented (Hischier & Reichart, 2003). Another possible source of error can be the quantification of the selected functional unit and the appropriate allocation of the reference flows.

When no holistic view of the product system is considered, the risk of weak functional units and reference flows that diminishes the study comparability arises. Currently, the ISO norms are the go-to sources for LCA practice; however the lack of guidance in the definition of functional unit has resulted in high variability among studies. After analyzing the challenges and possible sources of errors, the incorporation of systems engineering and functional analysis concepts is identified as an opportunity. In addition, the opportunity of decoupling the use behavior scenarios is identified as a clear path towards a structured approach in reference flow identification.

4.2.1 Some Examples of Functional Unit Definition

In order to exemplify how the definition of functional unit and reference flow is done in industry and the variability present in different studies, several cases are detailed below.

In their review about LCA as a tool, Rebitzer et. al (2004) set “cubic meter years of cooling to 15 °C below room temperature” as an example for functional unit for a refrigerator. Even though the metric of cubic meter years is not clear and the example is not clearly applied to a case, this functional unit can be argued as too detailed.

Lesage and Schoonenberg (2010) conducted a Comparative LCA and defined the functional unit to compare a Hewlett-Packard Indigo 700 and a Specific Competitive Sheetfed Offset Press as one non-targeted 8-page brochure with 4 process colors, 60% coverage, double-sided, printed on 100# text, glossy paper, meeting GRACoL specifications for optical density set points and printed as part of a 993 brochure job, which is estimated to be the economic break-even point between the two products being compared. The reference flow is defined in this report as “the amount of printed brochures required to meet the functional unit” and is then set to be 1 printed brochure/FU.

Veith and Barr (2008) performed a LCA study to compare two different printing technologies: flexographic and rotogravure. For this the functional unit was defined as the area of imaged plate or of printed substrate. Considering that these two technologies are completely different, the definition of functional unit was based on the functionally equivalency between these processes: the area of printed product.

Bozeman et al. (2010) developed an LCA study to compare a Solid Ink Printer to a Color Laser printed and defined the functional unit as 7,500 prints per month over a four year lifetime, which translates to a total of 360,000 prints. This case shows how the functional unit and the reference flows are closely interconnected for some authors.

In the case of a lifecycle inventory of an Inkjet printer developed by Ord and DiCorca (2005),the functional unit used was 100 pages of printed output, which represents 1/75th of the printer’s lifetime according to their estimations.

Ebner et al. (2009) developed a Green Scorecard to Identify Research Projects for Eco-Efficient Print Engines and the functional unit is defined as 10 million information units. The authors then define a unit of information as “the amount of information that is enclosed on a single A4 impression (side of a page) of average area coverage (as defined by the product, typically 5-6% area coverage per color)”. Again, the connection between functional unit and reference flows can be seen and not easily differentiated.

As mentioned earlier, the interconnection between the defined functional units and use scenarios is present in most cases. It is then proposed that this inherent relationship is hindering the comparability among studies, and a proper approach to analyze the system under study, identify reference flows, and decouple use behavior might be the way to go to structure an approach to define the goal and scope of LCA.

4.3 Summary

A comprehensive review on the problems present in the LCA methodology was done and issues were categorized depending on the LCA phase in which they are present. The problems found in the goal and scope phase were further categorized in sub-groups. Many of the identified problems come up because of the lack of proper guidelines in the ISO norms. Since practitioners apply the methodology with their best knowledge, some arbitrary considerations such as boundary selection, functional unit definition, allocation, and impact category method selection among others are done, ultimately hindering the possible comparison among different LCA studies.

Even though, several issues were found as general constraints and in every life LCA phase, the present work will focus in the issues present in the goal and scope of LCA considering that this phase sets the base for any LCA study. It is understood that the work done in this thesis serves as a good starting point for improving the methodology and optimize its use.

5.0 Framework Development and Proposition

Considering that it is in the Goal and Scope of any LCA when the premises for conducting the study are detailed, proposing solutions to the issues identified in this stage will enable clearer grounds for LCA practice, and ultimately contribute to better comparability amongst studies.

The process of developing this framework was mostly iterative. Considering that most of the work proposed in this Master's thesis is in the theoretical and abstract space, a big part of the development of the approach was fed by continuous feedback from the Thesis Committee.

Once the first theoretical propositions were defined, the application of these to some first initial examples was central since the translation of the theoretical grounds to the practical application is of key importance to the validity of the framework. These first initial trials are detailed in section 5.2 of the present chapter.

As an example of this iterative process, when moving from the abstract space to the implementation of the proposed framework to a life cycle inventory in these initial examples, several questions arose. Specifically, the procedure for allocating the relevant reference flows in the inventory of the system being analyzed which later enables the impact assessment phase. At this point, the concept of Cumulative Damage Function, explained in the following sections, came up. This function, which represents the usage profile and wear of the system under study and depends on different use variables, was critical to enable the application of the theoretical concepts in a real LCA. It was proposed then, that the bill of materials would be quantified considering both the use scenario that is being studied and the limit of that specific system under study. In the sections below, further details on these concepts will be done.

The complete application of the propositions to a case study was determined to be essential, since proving that it is feasible to apply the approach in practical LCA will give these new ideas better grounds for practitioners to both understand and apply the framework.

In the following section 5.1, the framework is presented through several steps, enabling a systematic method that practitioners can use.

5.1 Framework Recommendation

The basic premise of the present work is that through rigorous application of functional analysis and system engineering principles, some of the shortcomings that were identified can be addressed. More specifically, the following propositions are presented:

Proposition 1: Rigorously defining the enclosing system, the system inputs and system outputs will lead to the systematic identification of reference flows and scaling parameters that are relevant to all systems that fulfill a particular function.

Proposition 2: By decoupling consumer behavior from the reference flows and scaling parameters, scenarios can be constructed that will allow comparisons of LCA which leverage existing results.

Proposition 3: The use of the proposition 1 and 2 when coupled with a functionally decomposed model of a system, allows for a framework that is:

(a) dynamic

(b) easy to update as data quality improves

STEP I – SYSTEM DEFINITION

It is a well-established principle in LCA that the system boundaries need to be defined and explained. However, within LCA analysis the definition of the system and its boundaries is typically grounded in specific physical systems, manufacturing processes and life cycle stages. ISO 14040 states:

"LCA is conducted by defining product systems as models that describe the key elements of ***physical systems****. The system boundary defines the* ***unit processes*** *to be included in the system."* (ISO, 2006b) – emphasis added)

Similarly in Systems Engineering, establishing the system boundaries is also a well-established principle. In this case, though, establishing these boundaries is done in a more abstract manner. For the purposes of this work, a model proposed by Hull et al. (2005) is adapted and shown in Figure 5. There are three key elements of this figure: (1) The representation of systems by their functionality; (2) the fact that a system is embedded in other systems, or an enclosing system; (3) the fact that the system of interest interfaces with other systems.

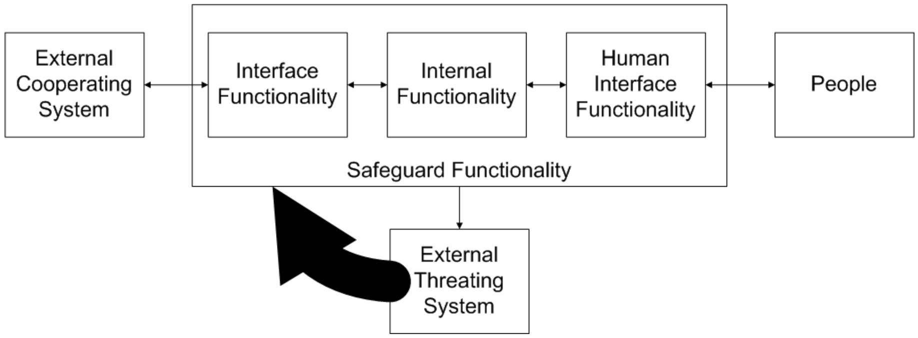
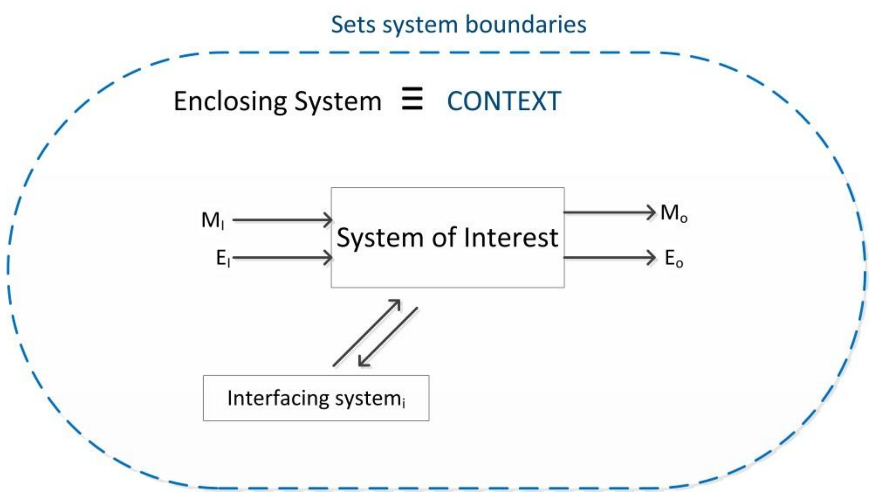


Figure 5 - An abstract system boundary model (adapted from (Hull et al., 2005))

With these observations in mind, the model shown in Figure 6 is proposed to establish the system boundaries based on system functionality and not on the physical system solution or actual manufacturing processes.



Where,

M_I = material in

E_I = energy in

M_O = material out

E_O = energy out

Figure 6 - Generic LCA Systems Framework

It should be noted that the boundaries defined by the proposed system engineering analysis are not the same as the system boundaries defined by LCA. However, the two are interrelated. The system boundaries that result from Figure 6 represent the use phase boundaries and its relation to

the system boundaries defined by LCA is illustrated in Figure 7. This last Figure 7 is the representation of the life cycle phases to be considered by an LCA study. As it can be seen in this figure, the system analysis proposed in Figure 6 represents the system use analysis. The effect of defining the use phase boundaries and the corresponding reference flows and scalable parameters (discussed below), is that it will constrain the LCA to be created in such manner that it can be scaled by use behavior, which will enable comparability and updating of the analysis without the need to re-create the LCI.

By looking at the system boundaries in this manner, it is argued that comparability of LCA studies can be established a priori, provided that the consumer is treated separately, which will be discussed in the next section.

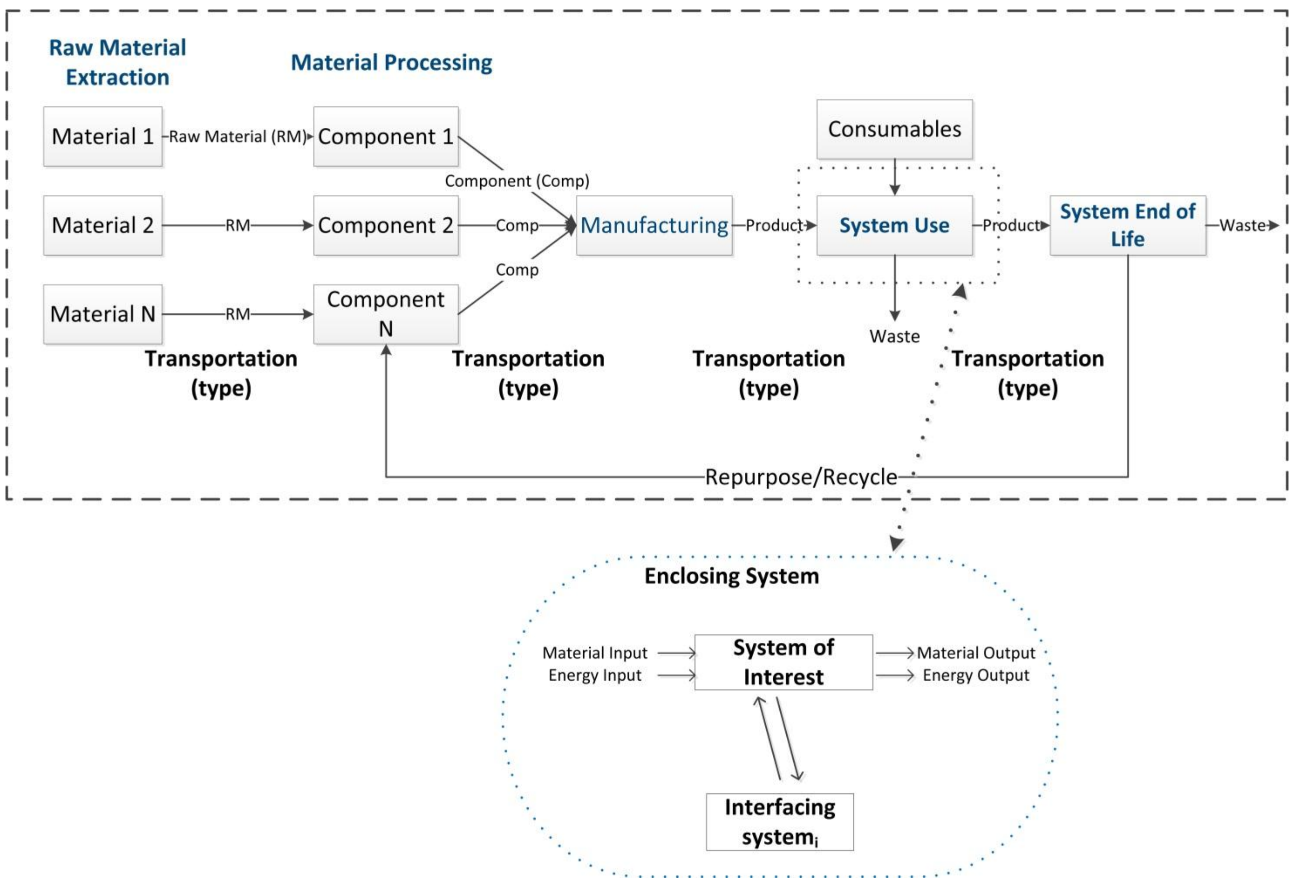


Figure 7 - Proposition 1 within LCA boundaries

It is important that the system of interest is described as an active verb-noun pair, which is standard in any functional analysis. The verb represents the function while the object is the flow involved in that function. The flow is the representation of the quantities that are input and output

by functions (Stone & Wood, 2000). Three basic flows are considered in any design problem application: energy, material and information, however for impact assessment the impacts are embedded in the material and energy flows. In addition, it is also critical that the functional description that is chosen be abstract enough that a wide range of possible solutions can be considered. It should be noted that there is no specific way to define the system inputs and outputs. These propositions are just guidelines on how to approach the system analysis and it is in the practitioner's judgment the proper analysis of the input and output flows of the system.

The second issue to address is the definition of the key material and energy transformations performed by the system of interest. This is an extremely important step as it will establish the class of systems that will be comparable in subsequent LCA studies. It is postulated that these material and energy transformations are what define the reference flows and scaling parameters to be used when conducting an LCA for these classes of systems. It should be noted that it is not necessary to be exhaustive in defining these transformations, but to establish the transformations that will be common among all systems of interest. For example, in order to 'Print Document', clearly energy is a needed input. If that energy is supplied by an electrical source or by human source is a detail that is left to the specific solution that is ultimately defined. Marking media and marking materials however are inputs that are common to all printing processes and need to be explicitly defined.

A third feature of Figure 6 is the definition of the enclosing system. The enclosing system will set the context of the system. An example from Hull et al. (2005) is that of 'Contain Liquid' (they actually referred to the system as a cup, but to be consistent with this framework it has been described in functional terms). The enclosing system is Earth's gravitational field. Clearly, our system solutions would be different if they were being developed for an environment without gravity.

As opposed to the work by Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b), which attempted to define every possible scaling parameter based on all possible applications, this is not necessary here as the context has been defined as part of the system boundary definition, which will give specific meaning to the reference flows and scaling parameters. Furthermore, what their work calls out as functional constraints would emerge during the functional decomposition described below, thus there is not a need to define these secondary parameters beforehand.

The fourth feature is that of interfacing systems. This helps to further refine the context within which the system of interest operates. As was the case with the transformed flows, it is not necessary to be exhaustive, but only to establish the interfacing systems that will be common to all

systems of interest. This will help avoid an issue that was encountered by Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b) in which they realized that materials were sometimes contained for the purpose of transportation. This is why they developed their logistics-intensive Fuon. If transportation systems are defined as an interfacing system, this would be accounted for.

Step II – Identification of Reference Flows and Scaling Parameters

Once the system and its boundaries have been defined, the relevant reference flows and scaling parameters need to be identified. These need to be in terms of either input or output flows, and they must correlate with the ultimate impacts that are generated by the system. Even though the definition of these flows and parameters is directly related to the use phase of the system under study, as shown in Figure 7, the careful selection of these will guide the assumptions and boundary selection in the overall goal and scope phase of the assessment. It is important to remark that the relevant reference flows need to be abstract enough in order to be independent from a specific technology. They also must be scalable by consumer use patterns. It is proposed that there will be characteristics inherent to the system, and the system definition and boundary diagrams that are generated that will help to guide the appropriate selection of flows and scaling parameters. In the following sections, preliminary examples of some test cases will be shown to help illustrate these ideas.

Step III – Use Behavior

As noted above, the integration of use behavior into the definition of a functional unit is one of the reasons that comparability of LCA studies has been limited. By decoupling use patterns from the functional unit definition, a more structured inventory and impact analysis can be conducted in terms of the reference flows and scaling parameters defined above. In order to determine the impacts associated with certain use patterns, different scenarios can be constructed and compared.

A key element of the framework proposed in this work is that the reference flows and scalable parameters can be modified based on the defined use scenarios. This scaling can be direct or indirect. In the direct case, the LCI can be directly scaled as a function of the use scenario parameters. This case mostly relates to the energy consumed by any system which is basically a function of use scenario parameters.

In the indirect case, the flows need to be allocated in proportion to the 'life' of the unit in question as a function of the use scenario parameters. As an example of this latter situation, consider the impacts associated with a print device that fulfills the print document function. The

consumed life of that device (and its impacts) will be a function the quantity and type of marking media that are printed by the system. As such, the impacts associated with those materials will need to be accounted for in a corresponding proportion.

In order to deal with the situation described above we define a "Cumulative Damage Function". The idea behind the Cumulative Damage Function is that, as a function of usage parameters, a certain portion of the 'life' of a particular unit of interest will be consumed. These cumulative damage functions are inherent to the technologies employed within the system that is implemented to fulfill the function. In other words, each of the relevant flows associated with each technology that has a cumulative damage function, describes the consumption of useable life through use. This function can be developed through the traditional battery of tests that exist within product development such as life-tests, reliability tests, and accelerated stress tests. It is worth reiterating that the input variables for these damage functions will be use parameters and will be the same regardless of technology.

The implication is that a specific allocation procedure, shown in equation (1), can be determined by which the bill of materials can be quantified in the life cycle inventory. It should be noted that the life limit shown in equation (1) can be governed by factors that include the functional limit of the system, the market obsolesce of the class of systems, the actual point in time when the system is disposed at the end of life, etc.

$$Allocation\ (\%) = \frac{consumed\ life}{\text{limit}\ \ (L_F, L_{OBS}, L_{NEED})} \quad (1)$$

Where,

Allocation %	= gives the total % of the bill of materials to be quantified in the LCI
Consumed life	= represents the use scenario under analysis
L_F	= represents the limit due to failure
L_{OBS}	= represents the limit due to obsolescence
L_{NEED}	= represents the limit due to the lack of need of the product under analysis

It is important to mention that the allocation procedure being referenced here is different from the allocation issues present in LCA. While in this example we are referring to the allocation procedure described in equation (1) which establishes how much of the defined bill of materials will be quantified for the environmental impact assessment, the allocation issues in LCA mentioned by different authors such as Reap et al. (2008a, 2008b) refer to how to appropriately allocate the environmental burdens of multi-functional processes such as incinerators, landfills, sawmills, etc.

The allocation issue in LCA is then the determination of how much of the environmental burdens caused by the multi-functional process should be assigned to each product.

The representation of different use scenarios through the reference flows and the scalable parameters will enable the construction of different workflows for the same system. When comparing different technologies that perform the same function, it is worth noting that the scenarios that are constructed do not have to be identical. Instead they can be constructed to be 'equivalent'. What is meant by this is that the consumer use pattern may, in fact, be a function of the solution developed and the workflows that are enabled by that solution. These alternative workflows should be accounted for, not obscured. It is then a task of the practitioner to define which the comparable scenarios of different technologies are that provide the equivalent function to the user.

Furthermore, different technologies may have vastly different operating regimes from one another. Sometimes this leads to the definition of a functional unit where the operating conditions for alternative solutions are defined to be in regions where neither technology would realistically operate in the guise of functional equivalency. What is of interest is not the equivalency of the operating regimes, but that the workflows that are associated with completing equivalent tasks using the alternative technologies are properly accounted for. This can easily be accommodated by this approach.

Step IV – Possible Extension to Functional Decomposition

One of the interesting opportunities that implementing the approach proposed above introduces is that same framework can be applied to the decomposed problem. That is, the high-level function of the system of interest can be decomposed to sub-functions, and the same abstractions that were discussed above can be applied at a lower level. It is easy to envision that this work can leverage the efforts to develop a functional basis and the use of design repositories (Bohm et al., 2010; Hirtz et al., 2002) to form the foundational blocks of the impact assessment. These foundational elements would then be integrated in manner dictated by the functionally decomposed model. This would enable LCA to become more dynamic and to also reflect improvements in data quality.

Functional modeling is a powerful tool used to decompose the functionality of a product in order to understand it in a more abstract way, without the need of its structure. The modeling begins with the formulation of the overall product function and then breaks this into smaller sub-functions (Stone & Wood, 2000).

5.2 Initial Applications Examples

As mentioned above, the development of the proposed framework has been done as an iterative process. By developing different initial examples, the methodology has been refined and improved. Considering the development of any archetype, it is expected that with the use of these steps in new cases and product systems the proposition will be better and improved.

In order to better illustrate the concepts discussed above, some initial trials were performed on four example systems. These will be presented to illustrate a variety of issues. It is encouraging that these initial examples indicate that there is utility in approaching the development of the reference flows in this manner. These examples are 'Contain Material', 'Dry Hands', 'Print Document', and 'Transmit News'.

Step I – System Definition

The first example of 'Contain Matter' is shown in Figure 8. This example is chosen for its relative simplicity and because it helps to illustrate the need to introduce the appropriate contextual elements in the form of interfacing functions. The flow simply consists of accepting a material and containing that material. As was discussed above, the enclosing system consists of the Earth's gravitational field and as was illustrated in Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010b), additional context can be provided by the interfacing systems, transportation systems and the environment. These introduce the potential needs to transport the container and to isolate the container from the environment.

The second example, 'Dry Hands' has been chosen since it is an example that has been widely used in the literature (De Schryver & Vieira, 2008; ISO, 2006b; Montalbo, Gregory, & Kirchain, 2011) and is shown in Figure 9. It is a useful example because it demonstrates that even though the existing solutions for this function can widely vary, they can still be represented abstractly in a similar form. The main flows in this system are the drying medium and the wet hands, represented as hand and liquid. The end result of the function is that the liquid has been transferred from the hands to the drying medium. In this case the enclosing system is of minor consequence, but it does help set the context of a public restroom which was the constraint used in a recent LCA study (Montalbo et al., 2011). In addition, the interfacing system defined as water supply also constrains the system under analysis since it might be a possibility that the type of water used influences the function of drying hands.

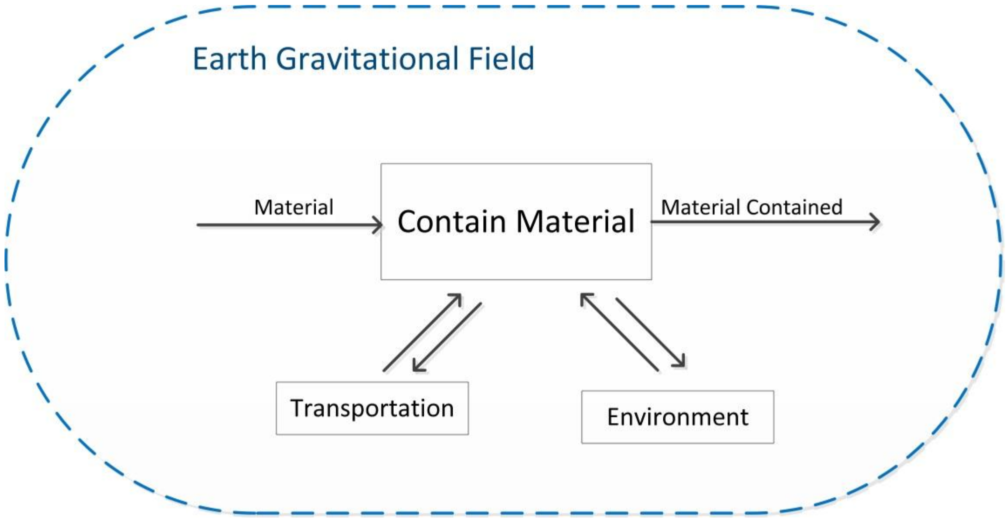


Figure 8 - System Definition for Contain Matter

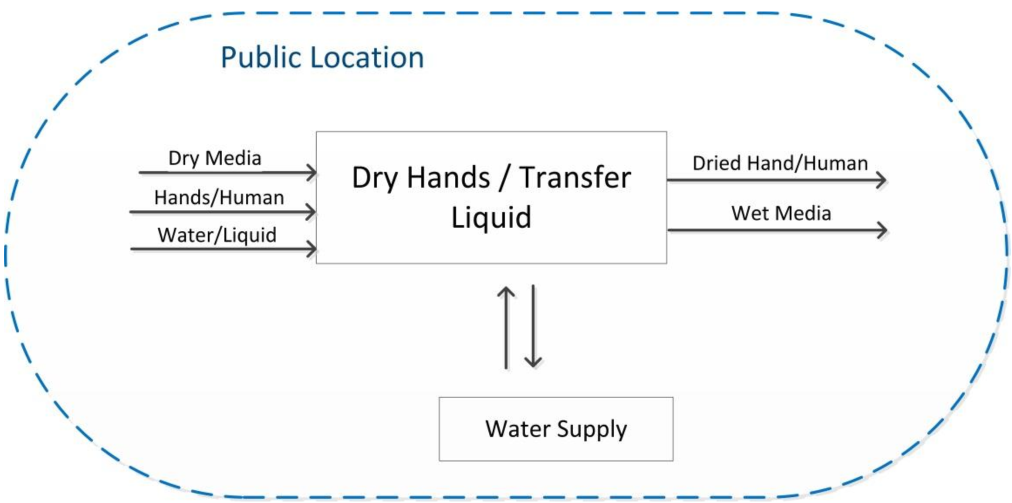


Figure 9 - System Definition for Dry Hand

The third example is a more complex system, that of a printer. This system is represented in Figure 10 as a 'Print Document' function. The 'Print Document' function introduces a variety of interesting situations to consider. The first is that many printers are multi-function products. However, if this is examined more closely, the multi-functionality results from how the sub-functions of scan image, process image data, transmit image data, and mark media are used in a particular workflow. Thus the representation is sufficient, except for the case of simply scanning a document. However, this situation can be rectified by the appropriate selection of the reference flows, which will be discussed below.

The other reason for selecting this example is that the impacts associated with print are especially influenced by consumer behavior (Bousquin et al., 2011). The main function in this case is 'Print Document'. The associated input flows are the marking media, the marking materials and the desired content and the output flow is the printed document.

The fourth example shown in Figure 11 illustrates a case where the very form of the fulfillment of the function, 'Transmit News' impacts the associated workflows and use patterns of the consumer. However, as in the case above, the situation can be represented in an abstract representation that is similar in form. The 'Transmit News' functions takes the input flows of content from informed people and transmits it to uniformed people. The interfacing systems in this case are the political system or entertainment industry that indirectly affects the consumer decisions on how to perform this function. These systems will inevitably impact the form in which this function is fulfilled, and are therefore related to assumptions that influence the analysis.

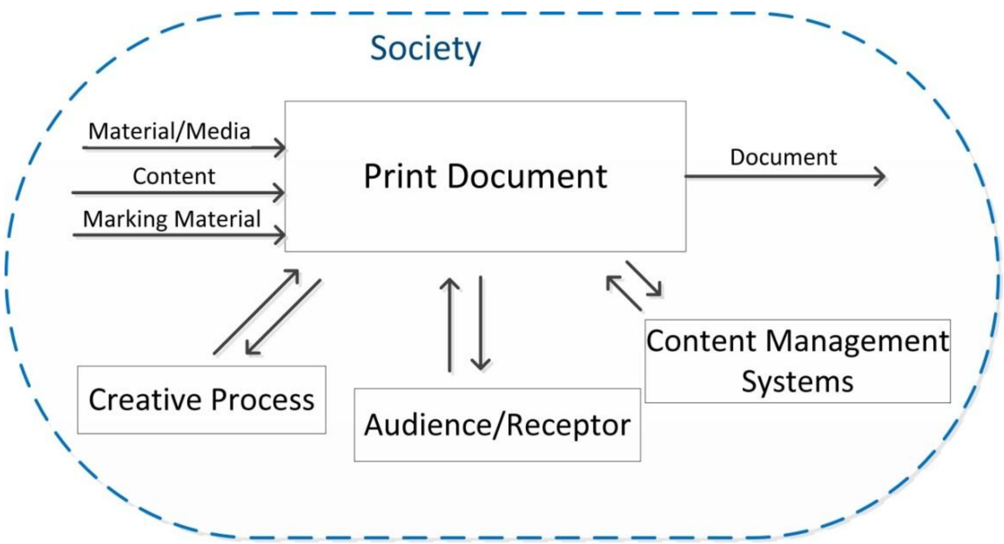


Figure 10 - System Definition for Print Document

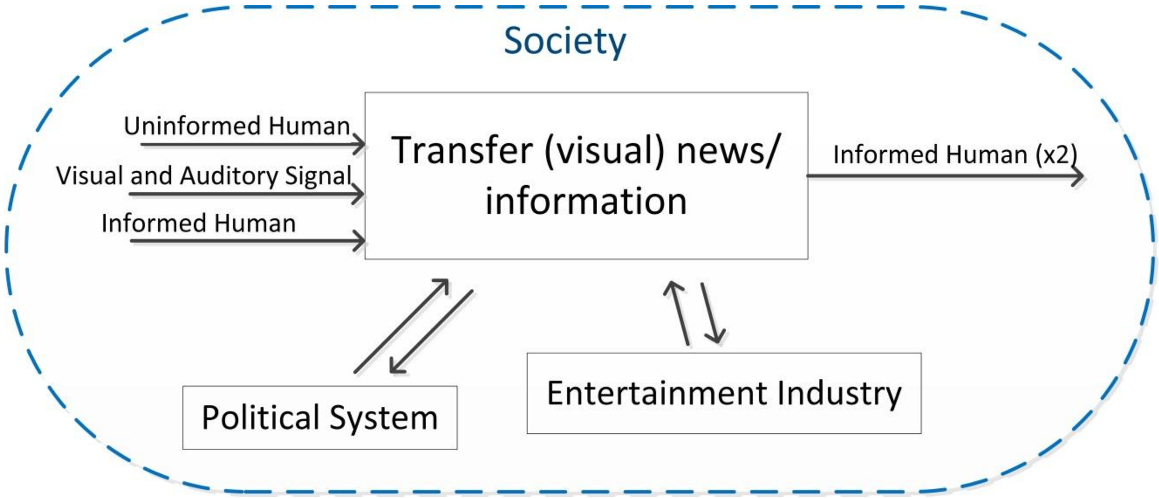


Figure 11 - System Definition for Transmit News

It should be noted that in the examples that were described above, where possible the functional basis developed by Hirtz et al. (2002) was used. However, because the level of abstraction was not always at a low-level, the functional basis did not always make sense. The rationale behind this is that the use of a consolidated vocabulary enables consistency and a systematic way to define the functions and flows under analysis. This idea will probably be more useful in the functional decomposition stage when the lower-level functions are derived.

Step II – Identification of Reference Flows and Scaling Parameters

As discussed above, reference flows that enable quantification of the bill of activities of the system need to be defined. The definition of the relevant reference flows needs to be linked to the flows identified in the system diagrams developed above and they need to be quantifiable through the Cumulative Damage Function. The premise given to properly define the relevant reference flows for system quantification is that these will be the flows which the user physically interacts with. In all the cases developed by the authors this premise holds suitable and thus it makes sense to continue moving forward with the reference flow identification, the further development of Cumulative Damage Function, and the proposed framework. When identifying the specific scaling parameters it will be important that the user behavior is considered, which highlights the importance the construction of the use scenarios.

In order to illustrate some of these issues, the reference flows for the four examples discussed above will be identified in the following paragraphs.

For the "Contain Material' example, the logical reference flow would be the material contained. This is consistent with the functional parameters defined by Collado-Ruiz & Ostad-Ahmad-Ghorabi (2010b). Note that details of what would actually be included in the LCI would depend on the details of the specific solution as well as the nature of the interactions with the interfacing systems.

In the case of the function 'Dry Hands', drying medium can be chosen as the relevant flow. To illustrate the interaction with the user behavior, the corresponding cumulative damage function will transform user behavior in different ways to quantify the LCI. For example, if paper towels are used it would be possible to characterize the average use of towels per hand washing, the distribution of behaviors could be characterized, these averages and distributions could be further segmented by user type, etc. In the case of an air dryer, these same characteristics could be assessed, but the relevant factor of interest is the time the user spends drying their hands that can be called the duration of each cycle. In addition, the stand-by mode can be modeled in this same function.

For the function 'Print Document', it is now necessary to have more than one relevant reference flow. In this case we would be interested in quantifying as a function of the mass of marking materials consumed and the amount of media consumed. Again, in order to illustrate the interaction with the use behavior of consumers the cumulative damage function needs to be developed. For example, the content being printed needs to be detailed as well as the specific documents. That might look like a 20-page technical report distributed to 100 people. From this information it would be possible to determine the amount media consumed (number of pages) and the amount of marking materials consumed (this would be a more complex model that relates page coverage to marking materials consumed).

Finally, for the 'Transmit News' function, the content transmitted is the proposed reference flow. This case is particularly interesting because, as was pointed out in Hischier and Reichart's work (2003), the way in which the consumer interacts with the news medium changes with the technology being used. The proposed approach enables the comparison of different workflows that are defined to be comparable. A possible approach can be normalizing by content; then different scenarios to acquire equivalent content can be compared. For instance, while in the case of a newspaper the stories may be read from 'cover-to-cover', on the Internet the user would be much more targeted when reading stories. This situation can be easily accommodated by the presented framework. It is important the role of the practitioner that defines which the equivalent workflows are that enable the comparison between different technologies that fulfill the same function.

Step III – Use Behavior

Due to the iterative nature of defining reference flows and parameters that scale with user behavior, many of the relevant issues regarding the use behavior have been discussed above. The following summarizes these observations from above:

- It is important that the reference flows and scaling parameters get scaled by the actual use patterns of the consumer. The scaling function that enables the allocating procedure for the inventory, the Cumulative Damage Function, need not be a simple relationship and could entail a sophisticated model to express the consumer use in a manner consistent with the relevant reference flows identified.
- The use scenario need not be the same between different LCI developed. The important consideration is to determine if the use scenarios are equivalent and to scale appropriately, ultimately helping to set base for comparability between different technologies.

In order to analyze how these propositions could have been used looking at an already developed LCA, a comparative LCA study that was developed by the Materials System Laboratory at the Massachusetts Institute of Technology (MIT) was used. The objective of this study was to compare different technologies of hand drying systems (Montalbo et al., 2011). Considering that the goal and scope phase of the study was very comprehensive and the functional unit definition of the study was done in a very organized manner, this example was developed in order to quickly assess how the proposed use of the Cumulative Damage Function and allocation procedure will fit versus the original way proposed by the authors.

In their work, Montalbo et al. (2011) define the functional unit as a single pair of dry hands. The corresponding reference flows are the ones that include "the allocated fraction of a hand dryer or the number of cotton or paper towels associated with drying that pair of hands". This allocation is obtained by defining the lifetime of a hand dryer set by its warranty which is a 5 year period. Using some internal information from the manufacturers, the authors estimate that 350,000 pairs of hands are dried in a hand dryer's lifetime. Therefore, the allocated fraction of a hand dryer defined for estimating environmental impacts for the hand dryers under study is 1/350,000.

Going to the proposed framework and specifically using the recommended allocation procedure to define the fraction of a hand dryer to be assessed in the inventory phase, the development of the Cumulative Damage Function profile needs to be done. The Cumulative Damage Function profile is strictly dependent on the wear of the technology being characterized, and the inputs are use patterns that stress or wear the system under study. For instance, reliability and stress testing

would be tools used to define how the Cumulative Damage Function is for the technology under study. In the case of a hand dryer, one can preview that the use variables that will input the function would be the number of pair of hands dried, the duration of the cycle, the stand-by time, etc. and the output of the Cumulative Damage Function can be in hours. In addition, the limit for the system would be some total of hours that determines its maximum lifetime. Having this information, it is now possible to set up different use behaviors or scenarios and allocate the fraction of hand dryer to be quantified by combining the Cumulative Damage Function and its limit.

$$Allocation\ (\%) = \frac{CumDmgFctn(\#pairs\ of\ hands, duration\ of\ cycle, standby\ time)[hrs]}{Total\ hours\ to\ fail\ or\ to\ be\ obsolete\ [hrs]}$$

By being able to quickly go over how this specific case would respond to the proposed allocation procedure shows that a structured framework could be developed to guide practitioners in quantifying the inventory phase and represent different use scenarios.

Step IV – Extension to Functional Decomposition

Figure 12 shows the functional decomposition for the function 'Print Document'. While this is not an exhaustive decomposition, it does illustrate a couple of points.

- The first level of decomposition is still fairly abstract and solution independent, as is the second level of decomposition.
- By the third-layer of decomposition, a technology had to be assumed and in this case that is electro-photography.

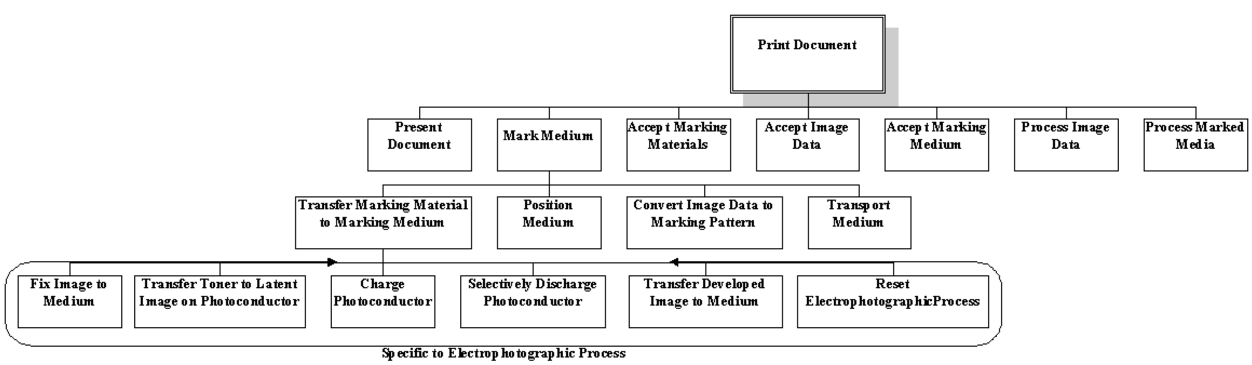


Figure 12 - Functional Decomposition of 'Print Document'

What is interesting to note is that any of the functions in this functional decomposition could be modeled within the framework identified above. The implication of this observation is that the object oriented paradigm can be applied to LCA. It is easy to envision that an early stage application of the approach proposed in this paper is at the high-system level and is empirical, as is the case today. The value in this scenario is that the analysis would not have to be redone if the use conditions change.

A later stage of application can develop these functional LCI as lower-levels of detail and they would be integrated by the relationships that would be implied by the functional decomposition. As the level of sophistication increases so would the ability to integrate these functional LCI in a more automated fashion. In the long-term, it is not difficult to envision that these LCIs are characterized at very low-levels, based on a functional basis, and the way in which these low-level LCIs are integrated, would be dictated by the functional decomposition of the system.

5.3 Summary

This chapter presented the recommended framework that integrates both system engineering and functional analysis techniques to the goal and scope of LCA. Three main propositions summarize the contents of the framework, and the details of the approach are explained in four separate steps: System Definition, Identification of Reference Flows and Scaling Parameters, Use Behavior, and Possible Extension to Functional Decomposition.

The approach was initially applied to four examples, and the successful application of the proposition proves necessary the full application of the framework to a complete case study using SimaPro® which will be developed in the following chapter 6.

6.0 CASE STUDY APPLICATION

Understanding the implementation potential of the proposed framework will be done through the application of a case study. The objective of this is to demonstrate the feasibility of the use of the framework and to identify possible areas that could be further improved to better enable this implementation.

The framework was planned to be applied to a case study in which technical information (such as product model, make, bill of materials, and SimaPro® modeling among others) is available. By having access to a SimaPro® project of the selected case study, the timing for the implementation of the framework would more predictable.

SimaPro® is a software tool developed by PRé Consultants from the Netherlands, and is currently the leading LCA software chosen in more than 80 countries (PRé-Consultants). The software allows for the modeling of products and systems using a lifecycle perspective. The databases built in it have a broad international scope and the software also enables the calculation of different impact assessment methods.

6.1 CASE STUDY SELECTION

The case study was selected from projects that were completed within courses in the Department of Industrial and Systems Engineering at the Rochester Institute of Technology. Considering that two courses from the department are based on the complete analysis of mechanical products, a list of possible and available cases was obtained.

The course called Lifecycle Costing and Assessment (0303-791) covers different techniques for quantifying environmental and social externalities through the application of different tools in a project based on a mechanical product. The three techniques covered in this class are Streamlined Lifecycle Assessment, Economic Input/Output LCA, and Process-Based LCA using SimaPro® as the main tool for this analysis (Thorn, 2011). The course Product and Process Design and Development (0303-760) covers the principles of product, manufacturing process, and supply chain development through the application of several reverse engineering tools in a project (Esterman, 2010b). The main objective of the class is to propose several redesign opportunities for the product under analysis based on the application of the several reverse engineering tools.

The gathering of available information regarding projects and mechanical products started with a list of available SimaPro® projects based on the 0303-791 course provided by Dr. Thorn. The list shown in

Table 4 details the different products that had a SimaPro® project already developed. The table also provides the academic year in which each project was created.

Table 4 - List of Products developed in 0303-791

	Project	**0303-791 Academic Year**
1	Heater	2009 & 2010
2	Hair Straightener	2010
3	Hair Dryer	2010
4	Humidifier	2010
5	Electric Can Opener	2010 & 2011
6	Paper Shredder	2010
7	Alternator	2010
8	Steam Vaporizer	2011
9	Rice Cooker	2011
10	Vacuum Cleaner	2011
11	Ice Cream Maker	2009
12	Electric Grill	2009
13	Coffee Maker	2009
14	Jig Saw	2009
15	Cellphone	2010/2011
16	Kindle	2011
17	Book	2011

As a starting point, the list provided a good base to move forward with the selection process. In order to set some structure, a set of criteria were developed by which each project would be assessed. Several conditions were defined and a target for each condition was defined. For instance, the performance of the teams that developed the SimaPro® model was evaluated using a 5-point scale, being 1 the lowest and 5 the highest score. The defined target was to select teams that obtained a 3 or more in this evaluation. The list of criteria considered and the corresponding targets is shown in Table 5.

Table 5 - Defined Criteria and Targets to Evaluate Potential Case Studies

Criteria	Target
Team Performance in SimaPro® model	>= 3
Example developed in 0303-760 or 0303-786	At least in one class
Existence of moving parts	Yes, moving parts are preferred
Represents a whole system	Yes, whole systems will be preferred
Complete availability of data (BoM + SimaPro®)	Yes, both are preferred
Availability of more cases	At least two cases (BoM+SP) available for analysis
Availability of more technologies	At least two technologies covering the same function

Looking at the list in Table 5, it can be seen that the team performance when developing the SimaPro® project was not the only criteria considered. Among other criteria considered, it was sought that the case under consideration was developed in at least one of the 0303-791 or 0303-760 courses. The cases with moving parts were preferred in order to provide a minimum level of complexity for the inventory and LCA analyses. Cases that represented whole products were also preferable; for instance, an alternator which is only a part of a car motor would not be an ideal case to move forward with. Ideally, the presence of both a bill of materials and SimaPro® project was targeted. In addition, it was attempted to target the products where more cases of the same technology were developed in any of the 0303-791 and 0303-760 courses. For instance, the heater case was developed twice in the 0303-791 course, both in 2009 and 2010. The specific brand and model of the heater analyzed in both situations was different, but the product itself was a heater. Finally, cases whenever the function of product being evaluated was able to be fulfilled by at least two technologies were preferred. For example, the case of the paper shredder that destroys information was an excellent one, since one can destroy information using different "ways" or technologies (tearing the media, using scissors, or even fire). Each project was evaluated in each criterion using a 5-point scale, being:

1 – Worst: Target underachieved
3 – Standard – Target achieved
5 – Excellent – Target overachieved

After a score was selected for each criterion for each case under consideration, an average was obtained that represented the overall quality of the information available according to the previously set targets.

Even though it might seem that the evaluation method is subjective, the process was conducted by the same subject. Meaning that each evaluation was done by the same person, and therefore the rating is considered to be valid since the same point of view was used for each specific assessment.

The full detailed scoring is shown in Table 6. As it can be seen, both the Can Opener and the Paper Shredder obtained an average score equal or higher than 4 points.

The Electrical Can Opener is an interesting case since it was not only developed in 0303-791 but also in 0303-760. In addition, two different teams performed two different SimaPro® LCAs on the same product (but different brand and model). However, the performance of these teams in these models was not outstanding. The fact that the function that the Electric Can Opener provides can be fulfilled by different technologies available is of interest, and the moving parts of the system comply with the target set.

The case of the Paper Shredder obtained the highest score. This case has been developed in both 0303-791 and 0303-760 classes, resulting in an interesting and comprehensive view of the system. The SimaPro® LCA project was carefully developed by Clark, Li, and Bodden (2011), and the specific mechanical product has a good number of moving parts. The main drawback for this case is the lack of availability of more cases for this product; however, there are plenty of technologies that fulfill the function offered by the product.

After evaluating the possible options according to the proposed criteria, the Paper Shredder case was selected to be further developed using the proposed framework.

Table 6 - Project Selection for Case Study Development

Criteria	Target	Heater	Hair Straightener	Hair Dryer	Humidifier	Can Opener	Paper Schredder
Team Performance	>= 3	3	4	4	3	3	4
Example developed in other class	At least in 760 or 786	1	1	5	1	5	5
Existence of moving parts	Yes, moving parts are preferred	2	2	4	4	4	5
Represents a whole system	Yes, whole systems will be preferred	5	5	5	5	5	5
Availability of data (BOM + SimaPro)	Both BOM and SimaPro simulation are preferred	5	5	5	5	5	5
Availability of more cases	At least 2 cases (BOM+SP) available for analysis	3	1	1	1	3	1
Availability of more technologies	At least two technologies covering the same function	5	1	3	1	3	5
Average		3.43	2.71	3.86	2.86	4.00	4.29

Criteria	Target	Alternator	Steam Vaporizer	Rice Cooker	Vacuum Cleaner	Ice Cream Maker
Team Performance	>= 3	2	2	2	2.5	0
Example developed in other class	At least in 760 or 786	1	1	5	4	1
Existence of moving parts	Yes, moving parts are preferred	4	4	2	4	4
Represents a whole system	Yes, whole systems will be preferred	1	5	5	5	5
Availability of data (BOM + SimaPro)	Both BOM and SimaPro simulation are preferred	5	5	5	5	3
Availability of more cases	At least 2 cases (BOM+SP) available for analysis	1	1	1	3	1
Availability of more technologies	At least two technologies covering the same function	1	1	1	3	3
Average		2.14	2.71	3.00	3.79	2.43

Criteria	Target	Electric Grill	Coffee Maker	Jig Saw	Cellphone	Kindle	Book
Team Performance	>= 3	0	0	0	3.5	4	2
Example developed in other class	At least in 760 or 786	1	4	3	1	1	1
Existence of moving parts	Yes, moving parts are preferred	2	2	4	3	3	1
Represents a whole system	Yes, whole systems will be preferred	5	5	5	5	5	5
Availability of data (BOM + SimaPro)	Both BOM and SimaPro simulation are preferred	3	3	3	3	3	2
Availability of more cases	At least 2 cases (BOM+SP) available for analysis	1	1	1	5	1	1
Availability of more technologies	At least two technologies covering the same function	5	5	3	5	5	5
Average		2.43	2.86	2.71	3.64	3.14	2.43

As mentioned above, the idea behind the application of a case study is to prove the feasibility of the use of the proposed framework using existing LCA tools such as the SimaPro® software. It is important to note that in order to do this; some information used needs to be approximated or even estimated using the best available engineering judgment. This means that the numbers and scenarios presented in the following sections are not totally accurate.

6.2 Theory of Operation: Paper Shredder

A paper shredder is defined as a mechanical device used to cut media with the ultimate objective of maintaining confidentiality, protecting personal and financial information, and avoiding identity theft (KN, 2012). Paper shredders are available in three different types: for use at home (personal), departmental (for small businesses), and industrial (for corporations). According to KN (2012), paper shredders generally offer three different ways of cutting the media. The single cut slices the document into thin vertical strips. The crosscut model shreds the media into small squares by cutting lengthwise and crosswise. Finally, the ultra-security cut shreds the media into illegible cuts.

The main type of media that generally home office machines destroy is paper-based followed by credit cards and compact discs. With many different applications of paper shredders, there is a large offering of this type of product in both the lower and upper ends of the consumer market (Guo, Henshaw, Louie, & Zhu, 2010).

In order to perform its function, media is inserted into the machine and the user turns the paper shredder on. A sensor generally detects if there is media present and will activate a motor which turns shafts that translate the media along guides. These guides lead the media to cutting cylinders which slice the media through friction. Shredded media is then deposited into a bin until the user disposes it (Guo et al., 2010).

In the present case, the Paper Shredder used as a model and base for SimaPro® will be the Aurora Paper Shredder developed by Clark, Li, and Bodden (2011) for the Life Cycle Costing and Assessment (0303-791) class.

When abstracting the functionality of the product from the way this function is performed (by shredding paper in this case), it can be said that a paper shredder conveniently destroys personal or private documents for disposal. There are other several ways that an end user can achieve this functionality, the use of a paper shredder being just one of them. The simple manual tear of the media, the use of scissors, fire to burn it, or even the use of abrasive chemicals can be considered. This introduces the possibility of different workflows and ways of accessing each technology. In

order to be able to compare different technologies that perform this same function, a comparable workflow needs to be identified. The proposed framework sets defined steps to perform an abstract analysis that can later be translated into the LCA comparison of different technologies.

6.3 Framework Application

In this section, the framework will be applied in two phases. The first phase will cover the application of the detailed propositions recommended in section 5.1 of the present document to the Paper Shredder case presented in section 6.2. The main objective of this exercise is to demonstrate that the use of the propositions is compatible with the current application of LCA through SimaPro®. The quantification of different use behaviors will be shown using the same SimaPro® project, demonstrating the versatility of the use of the recommended propositions and the Cumulative Damage Function.

The second phase will demonstrate how the proposed approach fits the use of SimaPro® in comparing different technologies with equivalent use scenarios, again through the use of the framework and its propositions.

It is worth noting that the information used for the use scenarios, such as each Cumulative Damage Function, was created to illustrate the application of the framework and does not represent real data.

6.3.1 Proposed Approach Applied to a Paper Shredder

When conducting an LCA, the first task to be completed by any practitioner is to define the goal of the study. In addition, several assumptions need to be stated regarding the life cycle stages to be considered, and the system boundaries need to be defined in order to identify what will be considered in the study and what will not. While traditional practices perform all of the aforementioned tasks directly to the particular product under study, the proposed framework suggests an initial abstract analysis of the system that is solution independent. By defining the system in this abstract manner the analysis is more amenable to any type of technology that provides the same function. Once all considerations in this space are done, then specifics of the case under study need to be considered.

For the case of the paper shredder, the proposed goal of the study is to assess the life cycle environmental impacts of destroying information through the use of the Aurora Paper Shredder. Even though the specific analysis will be done to the Aurora Paper Shredder, it is important that the goal is stated using the abstract terminology (the function that the product fulfills).

A life cycle diagram, shown in Figure 13, will help identify the phases to be considered, and which processes are to be included and excluded from the analysis. In the case of the shredder, raw material extraction, material processing, manufacturing, use, and disposal of the product will be considered. In addition, transportation between all those phases will be included as well. The important consideration to be highlighted in this example is that the upstream processes of the media that is destroyed are left out of the analysis. Considering that the main function being analyzed is destroy information, the impacts associated with the raw material extraction and processing, and manufacturing of the media only are left out of the scope of the analysis of the Paper Shredder. It is important to note that the environmental impacts associated with material production (paper, cardboard, CDs, credit cards) are known to be substantial and if true impacts were of interest, leaving these out of scope would be a significant exclusion. However, in terms of comparing technologies and LCA, these should not have an effect. In addition, the present example was developed only as means to illustrate the application of the framework, and the consideration of leaving these processes out of the analysis should not have a major impact on the main objective of this example.

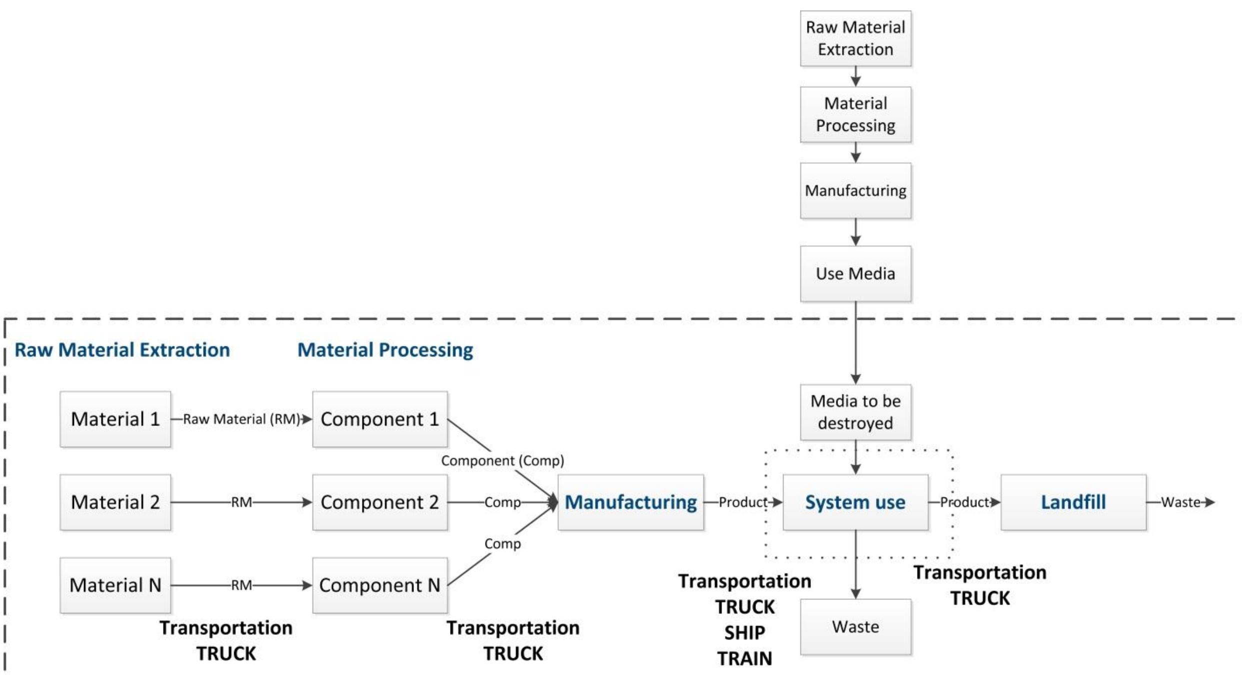


Figure 13 - Life Cycle Diagram for "Destroy Information" (Paper Shredder)

The next step is to take a closer look at the system use phase in order to identify assumptions related to the specific case. The ideas established in *Step I – System Definition* have been applied to the system under analysis in Figure 14.

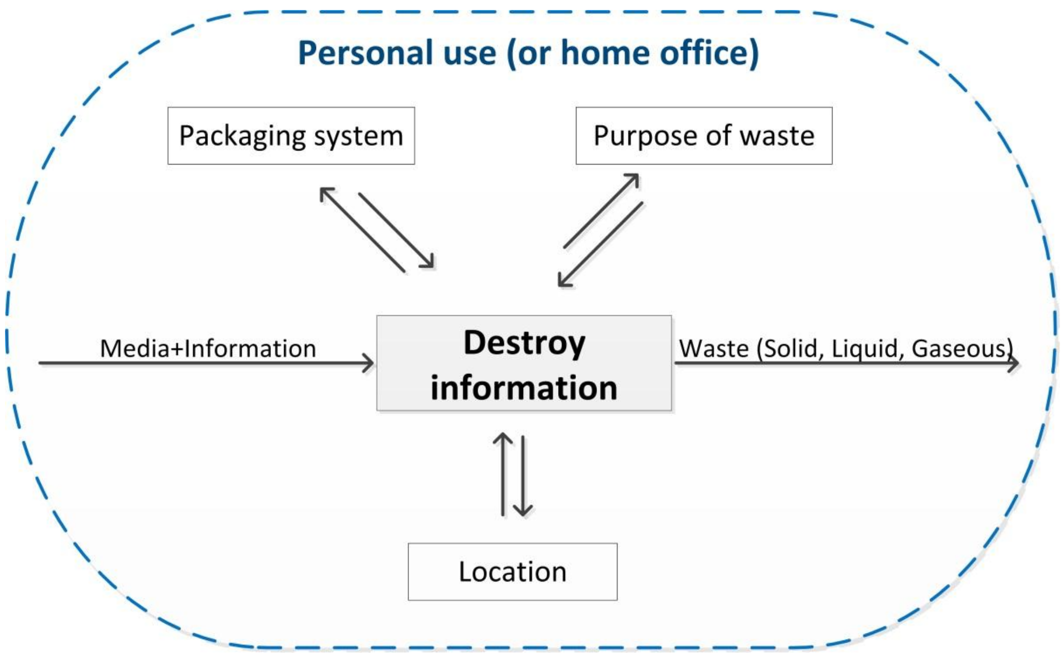


Figure 14 - Enclosing, Interfacing systems and main flows for 'Destroy Information'

As previously stated, the enclosing system sets the context for the analysis. For example in this case, by detailing that the function will be performed in a personal or home office situation, the setting in which the LCA will be done is defined. In addition, the definition of the enclosing system outlines the possible technologies that can enable this function, which can be related to destroying media or even erasing information. It also restrains different types of products that fulfill this function, for instance industrial shredders will be out of the scope of the analysis. It is important to mention that if this enclosing system is chosen differently, broader, then the inclusion of those types of products might be possible as well.

In this abstract space, the interfacing systems can also be defined and analyzed. The location helps determine which technologies can be used. For instance in the present example of "destroy information", the location where the function will take place influences the technology decision since an open space suggests the possibility of using a bonfire. The purpose of the waste will also help define the way this function is fulfilled. If there is need not to have any trace of the information being destroyed, then fire or even chemical compounds are options. If there are no issues with

having solid waste present, a shredder perfectly addresses the system need. Once the technology is selected, a packaging system associated to it will also impact the system analysis.

The analysis of these interfacing systems in this abstract space helps define some upstream and downstream considerations for the life cycle diagram such as the inclusion of the packaging impacts for this example. Once this abstract exercise is done, which apply to all technologies that perform the analyzed function, specific considerations and assumptions for the technologies to be studied such as a paper shredder or the use of fire should be taken into account when each specific analysis is performed.

Following the second step in the framework, detailed in section 5.1, the identification of the main flows of the system will provide the practitioner with the relevant flow (or flows) needed to quantify the life cycle inventory for any technology that performs this function.

Considering that the user mainly interacts with the media that needs to be destroyed, the proposed reference flow for this case is "media destroyed". Later on, the Cumulative Damage Function will be defined which will enable the quantification of the life cycle inventory based on this selected reference flow. In addition, it is expected that some type of energy will be required to perform this function. The type of energy used will be determined when the technology to be analyzed is defined. The needed energy will be defined by another function of the same use parameters that were used to determine the Cumulative Damage Function. As mentioned in section 5.1, the energy function is defined by the specific technology and product under analysis, and relates the energy used to the use scenario being represented in the LCA.

Moving on with the quantification of the bill of materials, one of the main points of the proposed framework establishes the idea of decoupling consumer behavior from the reference flow/s. This is the reason why the Cumulative Damage Function concept has been introduced as it relates the relevant reference flow previously identified (media destroyed in this case as it will be defined later) with different consumer patterns or scenarios.

Revisiting the meaning of this function, it can be said that the Cumulative Damage Function represents the degree to which each of the use variables contribute to using the total functional life of the product, and it enables the calculation of the quantification of the bill of materials that represents a specific use scenario. This quantification is done through the allocation function presented in equation (1) in section 5.1. The limit of the technology which is needed for this allocation can be governed by factors that include the functional limit of the system (time to failure, replacement cycle, etc.), the market obsolesce of the class of systems, the actual point in time when the system is disposed at the end of life, etc.

It is important to mention that the allocation procedure being referenced here is different from the allocation issues present in LCA. While in this example we are referring to the allocation procedure described in equation (1) which establishes how much of the defined bill of materials will be quantified for the environmental impact assessment, the allocation issues in LCA mentioned by different authors such as Reap et al. (2008a, 2008b) refer to how to appropriately allocate the environmental burdens of multi-functional processes such as incinerators, landfills, sawmills, etc. The allocation issue in LCA is then the determination of how much of the environmental burdens caused by the multi-functional process should be assigned to each product.

Going back to the example being developed, as defined earlier for the case of the function “destroy information”, the identified reference flow is “media destroyed” and the use parameters proposed to define the corresponding Cumulative Damage Function are listed in Table 7. These characteristics are applicable to the general Cumulative Damage Function for “Destroy Material” as shown in equation (2), and are not associated to any specific technology. This means that regardless of the way the material is destroyed, the different use scenarios should be represented by quantifying these characteristics or variables. The form the function takes will be technology dependent. For instance, the Cumulative Damage Function for a Paper Shredder can have a linear form but if fire is used then the function might take a more complex form with the same variables. As mentioned earlier, for the application of this case study, both the Cumulative Damage Function and the Energy Consumption function will be created in order to illustrate the cases under study.

$$(2) \qquad Cum\ Dmg\ Fcn\_Destroy\ Inf = f(use\ characteristics) = f(x1, x2 \ldots x11)$$

Table 7 - Use parameters that define the Cumulative Damage Function of "Destroy Material"

Reference flow	**media destroyed (letter sheet equivalents)**	
Descriptive characteristics (variables)	number of letter sized sheets destroyed	x1
	number of letter sized cardboard destroyed	x2
	number of CDs destroyed	x3
	number of credit cards destroyed	x4
	number of simultaneous letter sized sheets	x5
	number of simultaneous letter sized cardboard	x6
	number of simultaneous CDs	x7
	number of simultaneous credit cards	x8
	time between destroying media (seconds)	x9
	time in stand-by mode (seconds)	x10
	time destroying media (cycle) (secs)	x11

In Table 7 the proposed use variables to define both the Cumulative Damage Function and the Energy consumption Function can be seen. These use variables will enable the construction of different use scenarios. The proposed variables in this example are not only related to the quantity of media being destroyed, but also the way it is being done (i.e. simultaneously or not) and the time and cycles in which the function is being performed (or not) is also considered. In this specific example, these variables were created to represent the case study, but in a real case they should be specifically defined for the function being analyzed and by the knowledge each practitioner has in their system under study. The performance of stress, wear, and energy consumption tests will help refine these variables that define different use scenarios.

Once all the abstract analysis was performed, the specific considerations (manufacturing details, transportation details, bill of materials, etc.) for the product under analysis need to be done. In this case, the specific product under analysis is the Aurora Paper Shredder, and the transportation assumptions and bill of materials developed by Clark et al. (2011) are used since their SimaPro® project will be the basis for this framework application. The assumptions considered by the team and further considerations regarding the bill of materials are stated in Table 8.

Table 8 - Assumptions for the Aurora Paper Shredder

1	Plastic parts comprise 32.5% of the product (65 parts, 1630 gr): nylon, ABS, Polystyrene, and Polystyrene resins
2	ABS, Polystyrene, and Polystyrene resins are supplied from Tianjin, China (shipped by truck)
3	Nylon is supplied from Jiangsu, China
4	Plastic parts are manufactured in Dongguan, China
5	Polyethylene packing bags are supplied from Dongguan, China
6	Steel accounts for 38% of the product (1607 gr)
7	Iron is mined, processed into steel, and parts are manufactured in Hunan, China
8	Paper related materials comprise 12% of the product
9	Paper related parts are supplied from Guangdong, China
10	Copper for wires is supplied from Chile (12,000 miles shipped by freight)
11	Rubber for wires is supplied from Thailand (1,500 miles shipped by train)
12	Electronic components are supplied from Shenzhen, China
13	Paper Shredder is manufactured in Shenzhen, China
14	Once assembled, the product is shipped by freight to a Los Angeles port, then by train to a rail yard, then by truck to a distribution center, and finally by truck to the local store
15	Passed its lifetime, the paper shredder is disposed in the curb, going straight to a landfill

Once these assumptions have been made, the specific Cumulative Damage Function needs to be defined. As established in Step III of section 5.1, the function should be developed through the traditional battery of tests that exist within product development such as life-tests, reliability tests, and accelerated stress tests. In this specific example, the function was created arbitrarily with the purpose of illustrating the approach for this case and no actual testing or analysis was conducted. Looking at the product itself, the materials that it is made with, the energy source needed, etc., the function is created as linear and shown in equation (3).

$$(3) \qquad Cum\ Dmg\ Fcn_{\ shredder} = \sum_{\mathrm{i}=1}^{11} \mathrm{a_i} \, . \, x_i$$

The specific function is then defined in equation (4) and enables the quantification of different use scenarios for the Aurora Paper Shredder example. As it can be seen, the variables that characterize this function are the variables defined for the function “Destroy Material” detailed in Table 7.

(4) $$Cum\ Dmg\ Fcn_{\ shredder}(letter\ sheet\ equivalents) = x_1 + 5 \cdot x_2 + 12 \cdot x_3 + 10 \cdot x_4 + x_5 + 10 \cdot x_6 + 24 \cdot x_7 + 20 \cdot x_8 + 2 \cdot x_9 + x_{10} + 4 \cdot x_{11}$$

For this specific case study, the Cumulative Damage Function was defined to be in letter sheet equivalents as the unit for measurement. This unit was selected for this example due to the ease of picturing the wear of the systems under analysis. However, other variables could be used for measuring the wear of the system such as hours of operation, and rotation of the gears in the case of a paper shredder, among others.

In this example, the constants for the variables were generated to relate all the variables to the letter sheet equivalent; and even though these were created arbitrarily, some logic was applied to the selection of these constants. For instance, a piece of cardboard is thicker than a sheet of paper and that is why the weighting for the cardboard variable is 5. A CD not only is thicker but also more brittle suggesting more wear to the shredder, and that is why the constant assigned is 12.

Again, it is important to mention that this proposed Cumulative Damage Function is arbitrary and was created specifically to demonstrate the feasibility of using the framework in SimaPro®.

Moving forward, having now equation (4) it is possible to quantify different use scenario and an example of this can be seen in Table 9.

Table 9 – Use Scenario Example for Aurora Paper Shredder

			Constants	Use scenario 1
Descriptive characteristics (variables)	number of letter sized sheets destroyed	x1	1	1000
	number of letter sized cardboard destroyed	x2	5	100
	number of CDs destroyed	x3	12	3
	number of credit cards destroyed	x4	10	1
	number of simultaneous letter sized sheets	x5	1	6
	number of simultaneous letter sized cardboard	x6	10	2
	number of simultaneous CDs	x7	24	0
	number of simultaneous credit cards	x8	20	0
	time between destroying media (seconds)	x9	2	800
	time in stand-by mode (seconds)	x10	1	4000
	time destroying media (cycle) (secs)	x11	4	4500
Cum Dmg Fcn (letter sheet equivalents)				**25,172**

Following the proposed framework, the allocation of the bill of activities for this example is done through the equation (1) described in section 5.1. In this case, the limit needed to calculate the allocation of the bill of materials which can be governed by factors that include the functional limit

of the system, the market obsolescence of the class of systems, the actual point in time when the system is disposed at the end of life, etc., is also created with the only purpose of conducting this example. The limit in this case is chosen to be 100,000 letter sheets equivalents, twice as much as the examples of other technologies developed later in this chapter.

Once the limit for the specific product under analysis is defined, the allocation percentage by which the bill of materials will be quantified in the life cycle inventory is defined. For the example of the use scenario presented in Table 9, the result is shown in equation (5).

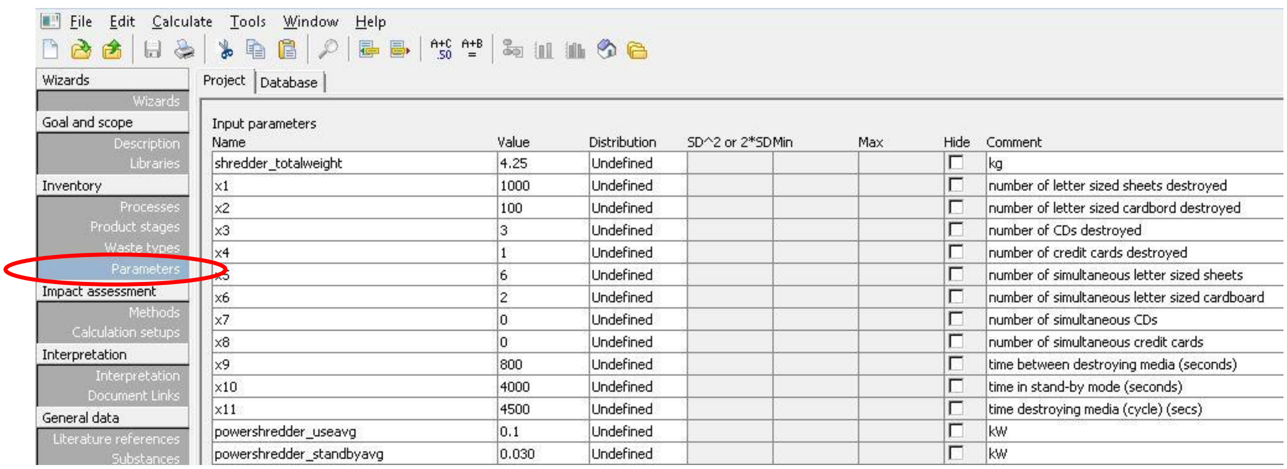
$$(5) \qquad Allocation\ (\%) = \frac{25{,}172\ ltr\ sht\ eq}{100{,}000\ ltr\ sht\ eq} = 25.2\%$$

When looking at the energy used, in the Aurora Paper Shredder example, the type of energy needed is electricity. The electricity used for the scenario being represented needs to be defined as well and the function that relates the use variables to the electricity used is proposed in equation (6). In order to facilitate calculations for this case study, equation (6) was defined based on average power ratings for the Aurora Paper Shredder. Both the energy consumed during the use of the shredder and the stand-by mode are considered in this equation. The important remark is that the energy consumption function is related to the same variables that define the use scenario. In this specific example, the seconds used in the use scenario are converted to hours. In the case of use scenario 1 defined in Table 9, the electricity consumed is 0.165 kWh.

$$(6) \qquad energyshredder_{Avg}(kWh) = powershredder_{useAvg} \cdot \frac{x_{11}}{3600} + powershredder_{standbyAvg} \cdot \frac{(x_9+x_{10})}{3600} = 0.1\ kW \cdot \frac{x_{11}}{3600} + 0.03\ kW \cdot \frac{(x_9+x_{10})}{3600}$$

The quantification of the trips to the store (to purchase the product) and to the end of life, landfill in this case, will be done with the integer number that represents the number of shredders needed for the specific use scenario. According to the example use scenario 1, from Table 9, the impacts that will be quantified are related to an allocation of 25.2% of the shedder's bill of materials. However, the number of trips to both the store and the end of life cannot be a fraction, and one shedder needs to be quantified for these trips. In the hypothetical case in which the allocation was 250%, then three trips to both the store and end of life should be quantified. A second use scenario will be presented later in this case study which will show the case in which the allocation and quantification of the bill of materials is higher than 100%.

The implementation of all of these functions and use scenarios is enabled in the SimaPro® software through the use of parameters. The parameters section can be found in the Inventory section of SimaPro®. In this tab, the input and calculated parameters can be set. The input parameters will be the independent variables that define the use scenarios, and the calculated parameters will be the functions defined, such as the Cumulative Damage Function, the Energy Consumption Function, etc. A representation of how input parameters can be defined is shown in Figure 15. Under the Name column the user outlines the name for the variable being defined. The Comment column can be used to describe what that parameter represents and each value is defined in the Value column.



Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
shredder_totalweight	4.25	Undefined					kg
x1	1000	Undefined					number of letter sized sheets destroyed
x2	100	Undefined					number of letter sized cardbord destroyed
x3	3	Undefined					number of CDs destroyed
x4	1	Undefined					number of credit cards destroyed
x5	6	Undefined					number of simultaneous letter sized sheets
x6	2	Undefined					number of simultaneous letter sized cardboard
x7	0	Undefined					number of simultaneous CDs
x8	0	Undefined					number of simultaneous credit cards
x9	800	Undefined					time between destroying media (seconds)
x10	4000	Undefined					time in stand-by mode (seconds)
x11	4500	Undefined					time destroying media (cycle) (secs)
powershredder_useavg	0.1	Undefined					kW
powershredder_standbyavg	0.030	Undefined					kW

Figure 15 - Input Parameters for the Aurora Paper Shredder representing Use Scenario 1

Characteristics such as shredder weight, shown in Figure 15, are recommended to be defined as input parameters since if a different weight needs to be analyzed, then the sensitivity analysis is made easier.

The Cumulative Damage Function, allocation procedure, energy used, and transportation multiplier are defined in the Calculated Parameters section, shown in Figure 16.

Calculated parameters

Name	Expression	Comment
cdfshredder	x1*1+x2*5+x3*12+x4*10+x5*1+x6*10+x7*24+x8*20+x9*2+x10*1+x11*4 = 2.52E4	letter sheet eqs
allocationshredder	cdfshredder/limitshredder = 0.252	
energyshredder_avg	powershredder_useavg*x11/3600+powershredder_standbyavg*(x9+x10)/3600 = 0.165	kWh
transportshredder	trunc (allocationshredder)+1 = 1	# of shredders

Figure 16 – Calculated parameters for the Aurora Paper Shredder

Once the scenario has been defined in the Parameters section, as detailed in Figure 15, the calculated allocation, energy used, and transportation multiplier can be called when defining the life cycle of the Shredder as shown in Figure 17.

The allocation procedure establishes how much of the defined bill of materials will be quantified for the environmental impact assessment. The energy used is defined through the energy function, detailed in equation (6), and the use scenario variables detailed in the input parameters. In addition, as mentioned above, both trips to the store and to the end of life are multiplied by the transportation multiplier which represents how many total shredders are being quantified. The use of all these features is shown in the life cycle construction of Figure 17. The Paper Shredder assembly was built based on the bill of materials for the Aurora Shredder developed by Clark, Li, and Bodden (2011) and as considered in the assumptions (detailed in Figure 13) the raw material extraction and processing, including the transportation of all these is considered in the construction of the assembly.

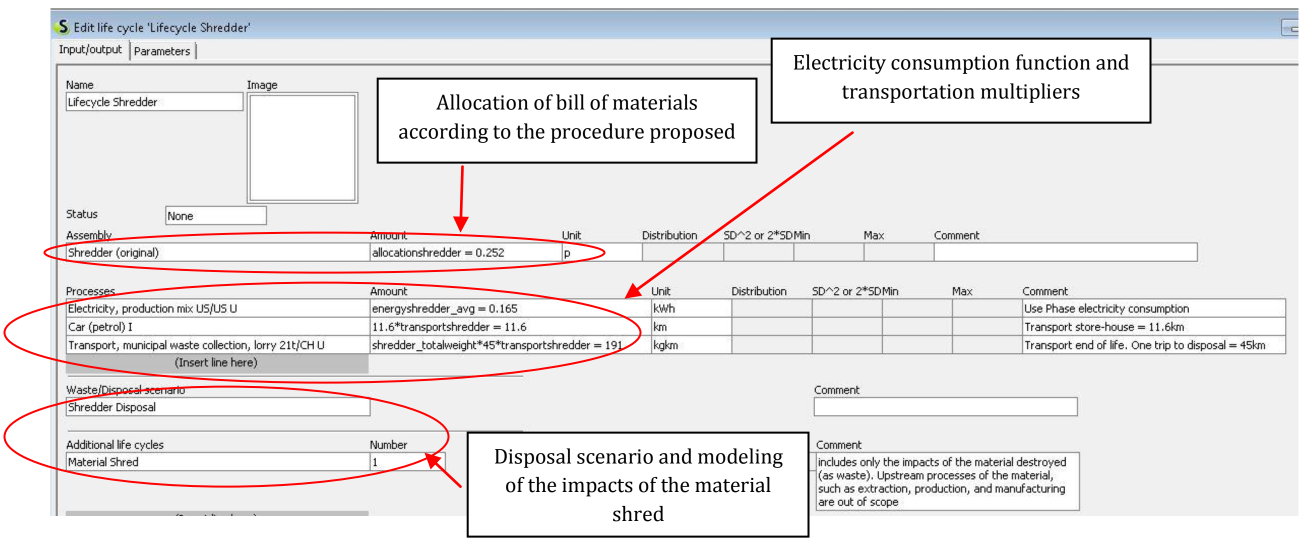


Figure 17 – Life Cycle of the Aurora Paper Shredder Case

The life cycle of the Shredder also needs to specify a waste or disposal scenario for the product. In this case, it was assumed (as shown in Figure 13) that the shredder was going to be disposed in a landfill. For this, a disposal scenario was created and is shown in Figure 18. As it can be seen, the allocation defined for the Paper Shredder is used in this disposal scenario, and the best representation for the end of life was found in the Ecoinvent library as the Durable goods waste scenario. This disposal scenario represents the waste from durable goods in the USA. The Ecoinvent library defines a durable good as a good which does not quickly wear out, or more specifically, it

yields services or utility over time rather than being completely used up when used once (PRé-Consultants, 2011).

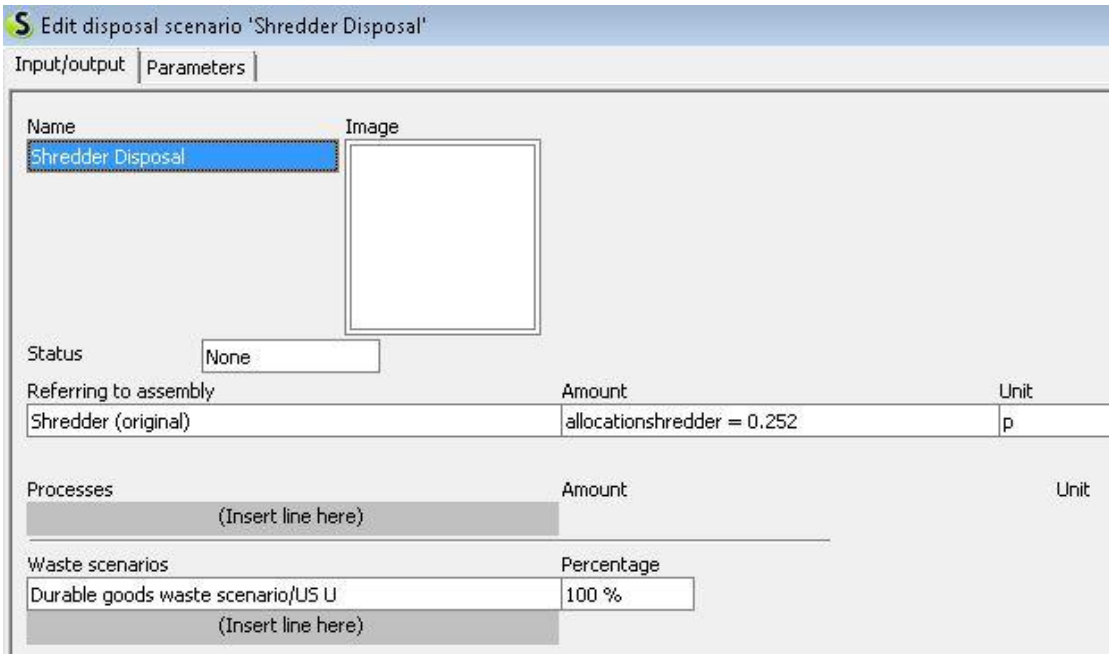


Figure 18 - Disposal Scenario for paper Shredder

The final point to account for in the life cycle of the Aurora Paper Shredder is the impact of the media being destroyed. In this case, the quantity and the details of the media being shred are defined by the use scenario being quantified. Different subassemblies that represent each of the media being shred were created. An example of the Paper shred subassembly and the CDs shred subassembly are shown in Figure 19 and Figure 20 respectively. In addition to the paper shred, the cardboard, credit cards, and CDs shred are defined. For the quantification of the media, the use variables from the input parameters are used. In this case, the average weight for each media is needed to quantify the total kg being shred by the Aurora Shredder.

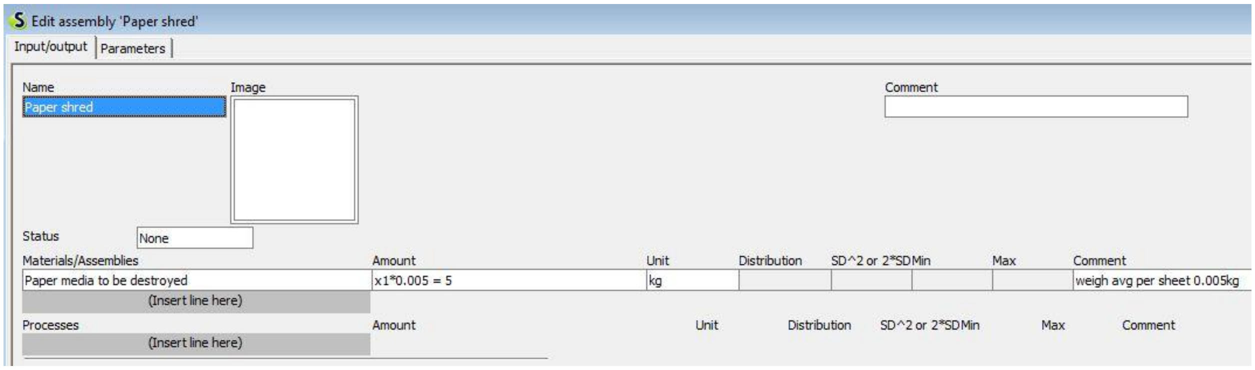


Figure 19 – Subassembly representing the paper being shred

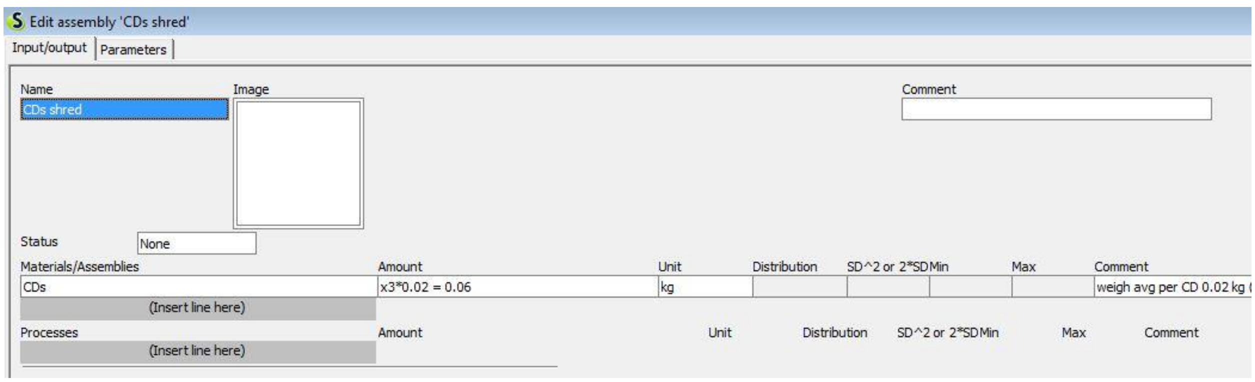


Figure 20 - Subassembly representing the CDs being shred

A total assembly accounting for all the media being shred is created and is detailed in Figure 21. The use scenario defined through the input parameters, as shown in Figure 15, is being called in every one of the subassemblies that define each of the media being shred.

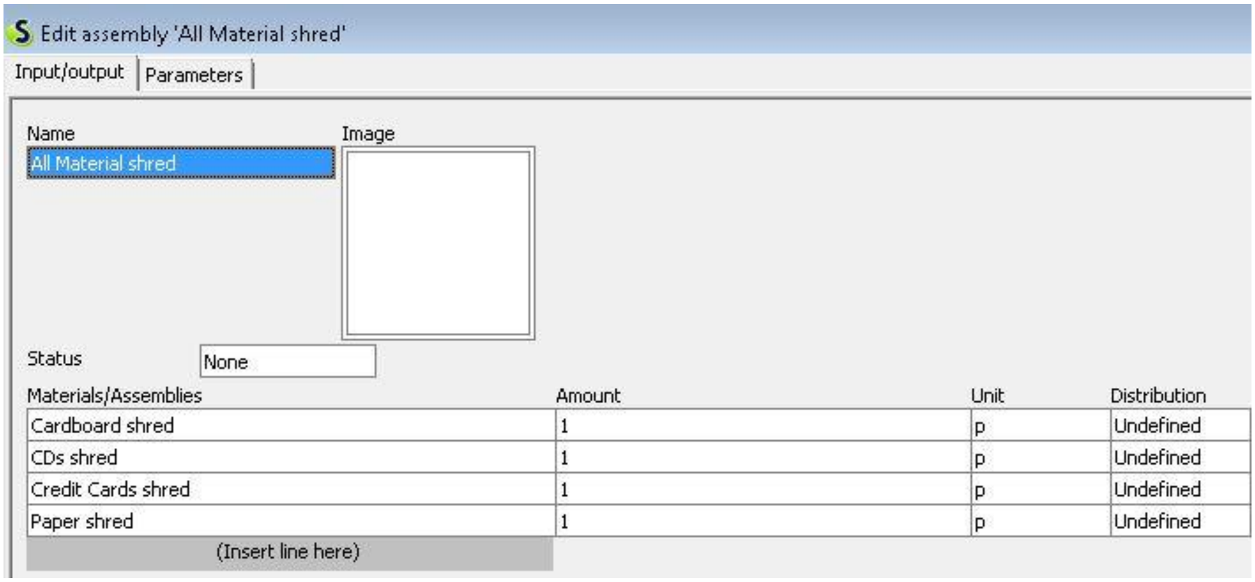


Figure 21 - Total assembly defining all the media being shred

Following the initial assumption that stated that the impacts associated with the raw material extraction, processing, and manufacturing of the media would be left out of the scope of the analysis, the above subassemblies only define the material of each media through the creation of “dummy” material bocks. These dummy blocks only represent the type of media being destroyed and their waste type has been defined accordingly in order to accurately estimate the impacts of disposing that media.

In order to represent the impacts of shredding the media, and the destination of the waste, a life cycle of the Material Shred is generated and shown in Figure 22. In this life cycle, a previously defined disposal scenario for the material shred is used. The defined disposal scenario is detailed in Figure 23 and the Waste Scenario from the Ecoinvent library was used as the most suitable. Considering that this scenario represents the total household waste stream of the USA including municipal waste and waste separation in advance (PRé-Consultants, 2011), it was considered that all the material shred (100%) follows this waste scenario.

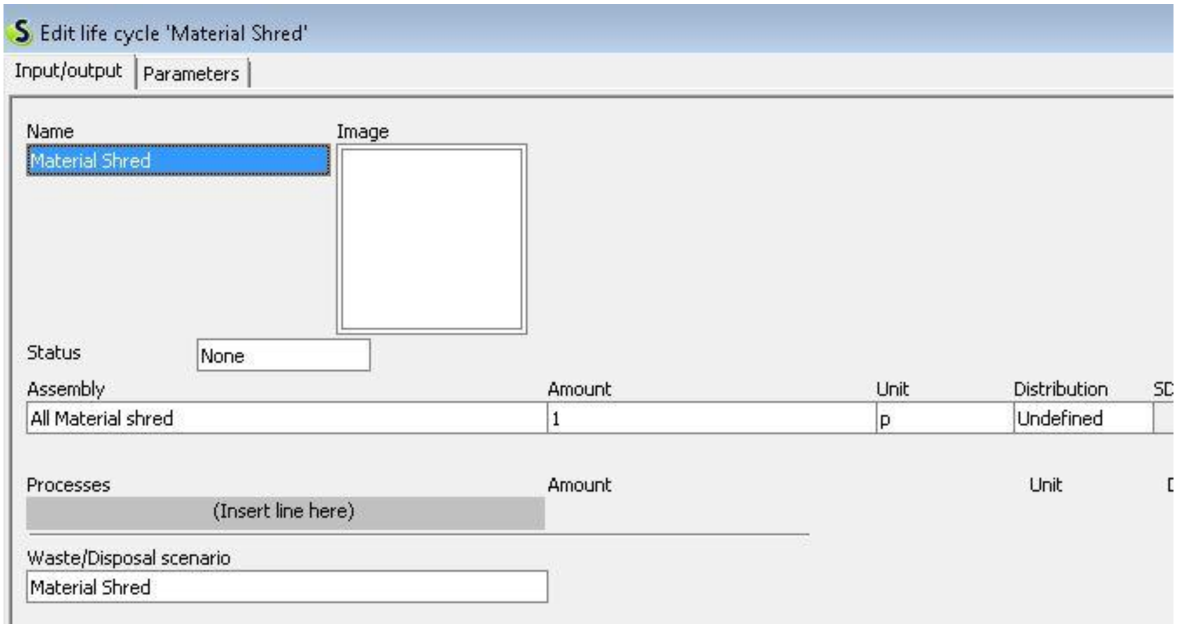


Figure 22 - Life Cycle of all the Material Shred

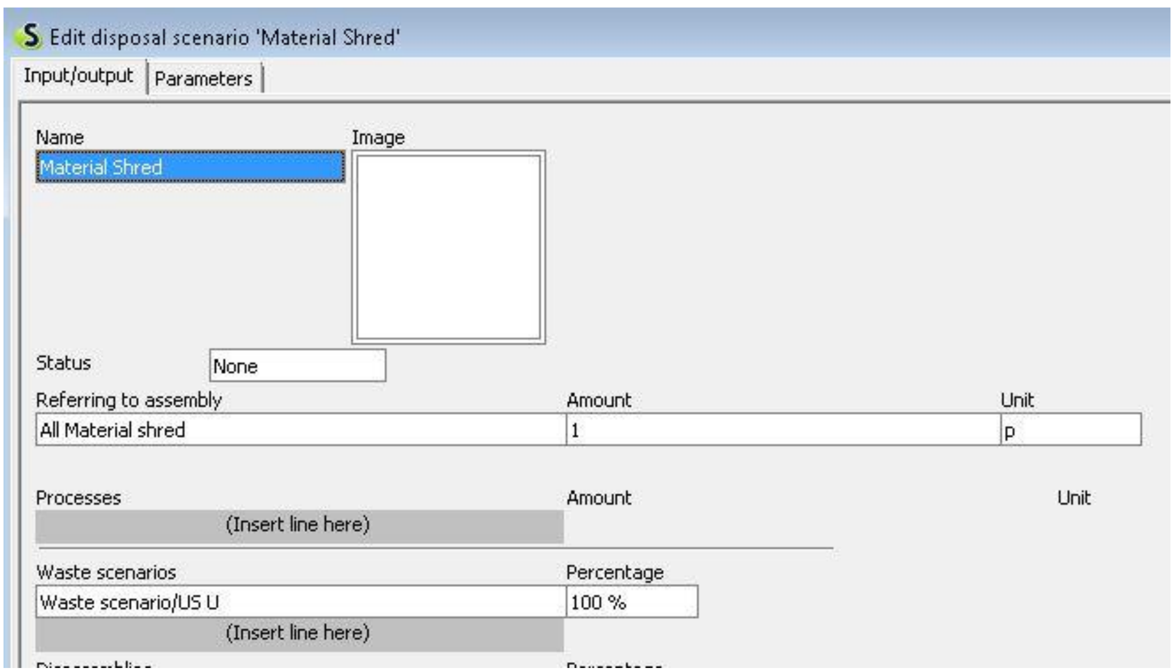


Figure 23 - Disposal Scenario for All Material Shred

Once the Aurora Paper Shredder life cycle is complete, as detailed in Figure 17, the environmental impact assessment can now be calculated in the Calculation Setups section of Impact Assessment.

In order to illustrate this example, the network representing the Greenhouse Gas (GHG) emissions of the Paper Shredder is shown in Figure 24.

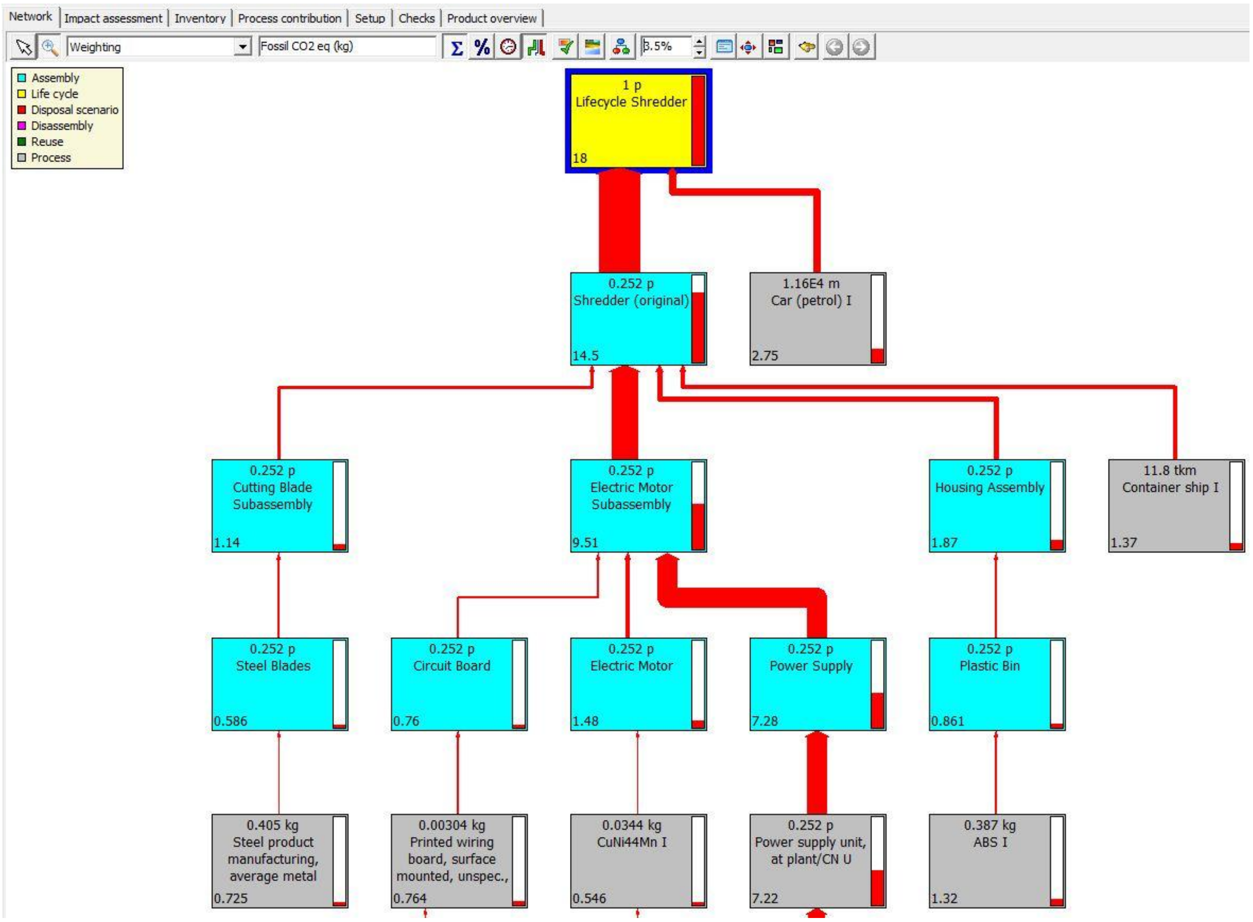


Figure 24 - GHG emissions in Fossil CO2 eq (kg CO2 eq) for the Paper Shredder in Use Scenario 1

The Cumulative Energy Demand (CED) can also be assessed using the same use scenario 1 as example. By choosing this calculation method, the network for the Shredder being quantified using use scenario 1 can be calculated and is shown in Figure 25.

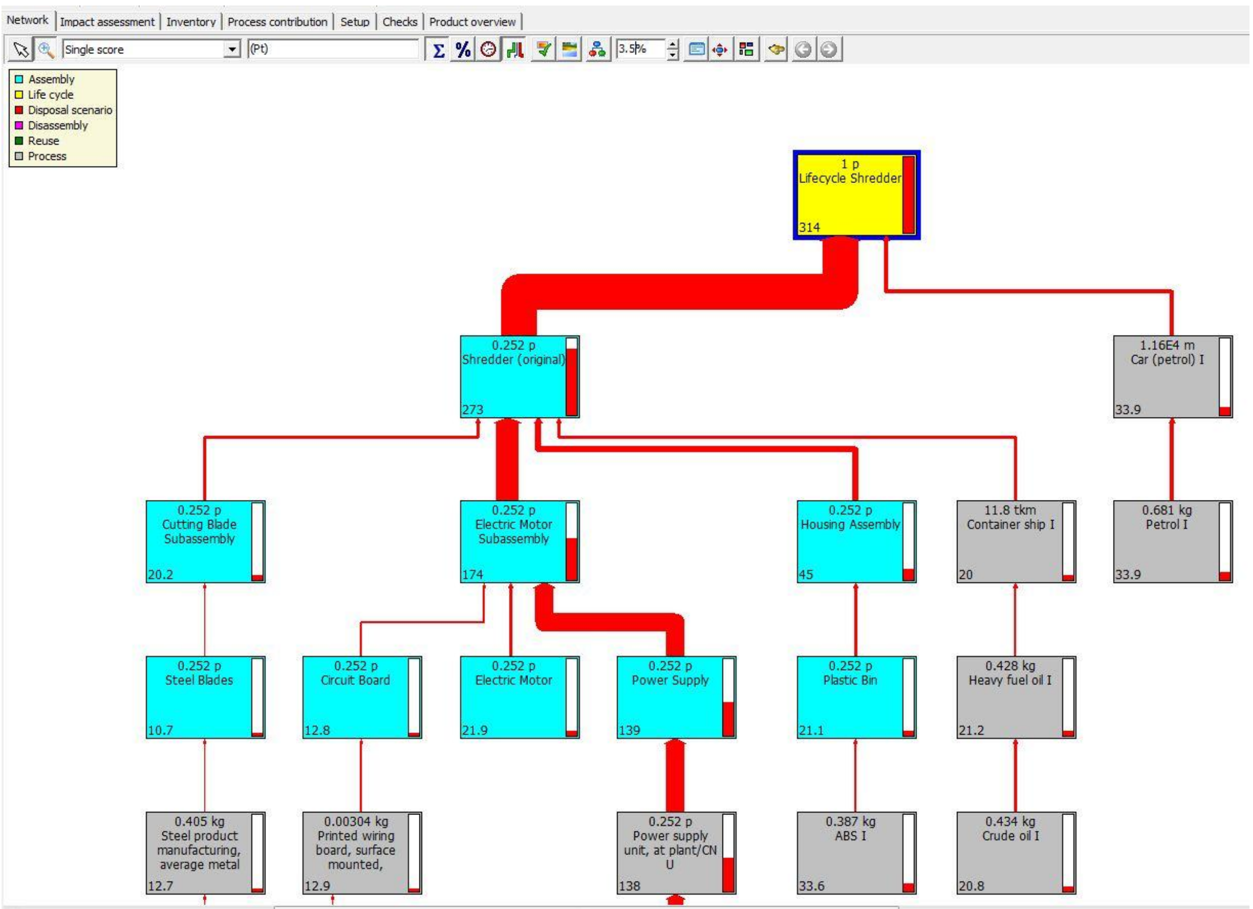


Figure 25 - CED for Aurora Paper Shredder in Use scenario 1

It is important to consider that the results obtained from this example are not of relevance since the whole example was created for the sole purpose of demonstrating the feasibility of implementing the framework in SimaPro®. The actual GHG and CED impacts obtained are not representative of the environmental impacts of a Paper Shredder and should not be considered as valid.

Because the use scenario has been decoupled from the quantification of the life cycle inventory and has been defined through the use of parameters, the representation of a new use scenario is now easier and faster to perform. A new use scenario 2 can be defined by changing the input parameters as shown in Figure 26.

The representation of this example aims to demonstrate the case of a use scenario that requires more than one paper shredder to fulfill the user needs. In the case shown in Figure 26, the allocation percentage obtained is of more than 100%, more exactly of 111%, meaning that the user is in need of two paper shredders to destroy that amount of information. In this case, as mentioned earlier, the transportation multipliers should be considered as 2 since the consumer needs to obtain two shredders from the store and, eventually, two shredders will be disposed.

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
shredder_totalweight	4.25	Undefined				☐	kg
x1	18000	Undefined				☐	number of letter sized sheets destroyed
x2	1400	Undefined				☐	number of letter sized cardbord destroyed
x3	20	Undefined				☐	number of CDs destroyed
x4	3	Undefined				☐	number of credit cards destroyed
x5	10	Undefined				☐	number of simultaneous letter sized sheets
x6	4	Undefined				☐	number of simultaneous letter sized cardboard
x7	2	Undefined				☐	number of simultaneous CDs
x8	0	Undefined				☐	number of simultaneous credit cards
x9	8000	Undefined				☐	time between destroying media (seconds)
x10	12000	Undefined				☐	time in stand-by mode (seconds)
x11	14500	Undefined				☐	time destroying media (cycle) (secs)
powershredder_useavg	0.1	Undefined				☐	kW
powershredder_standbyavg	0.030	Undefined				☐	kW
limitshredder	100000	Undefined				☐	letter sheet equivalents

Figure 26 - Input Parameters for the Aurora Paper Shredder representing Use Scenario 2

In order to perform the change in the use scenario, by just changing the input parameters with the new conditions, the calculated parameters are instantly updated as detailed in Figure 27. The fact that the use scenario is now updated influences all assemblies and life cycles accordingly, and the environmental impacts of this new scenario can be calculated. For this new use scenario 2, the GHG quantification is shown in Figure 28 and CED in Figure 29.

Calculated parameters

Name	Expression	Comment
cdfshredder	x1*1+x2*5+x3*12+x4*10+x5*1+x6*10+x7*24+x8*20+x9*2+x10*1+x11*4 = 1.11E5	letter sheet eqs
allocationshredder	cdfshredder/limitshredder = 1.11	%
energyshredder_avg	powershredder_useavg*x11/3600+powershredder_standbyavg*(x9+x10)/3600 = 0.569	kWh
transportshredder	trunc (allocationshredder)+1 = 2	# of shredders

Figure 27 - Calculated Parameters for the Aurora Paper Shredder representing Use Scenario 2

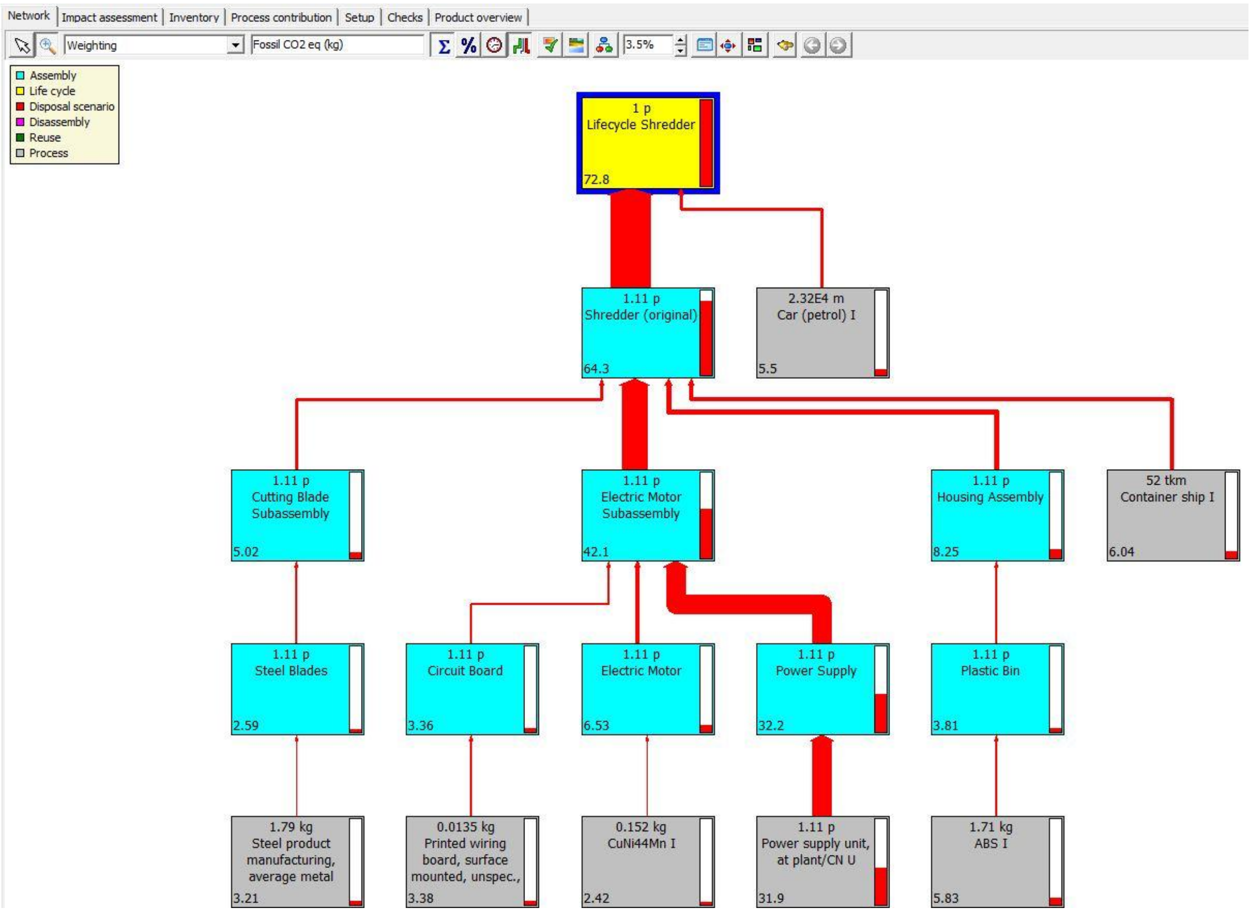


Figure 28 - GHG emissions in Fossil CO2 eq (kg CO2 eq) for the Paper Shredder in Use Scenario 2

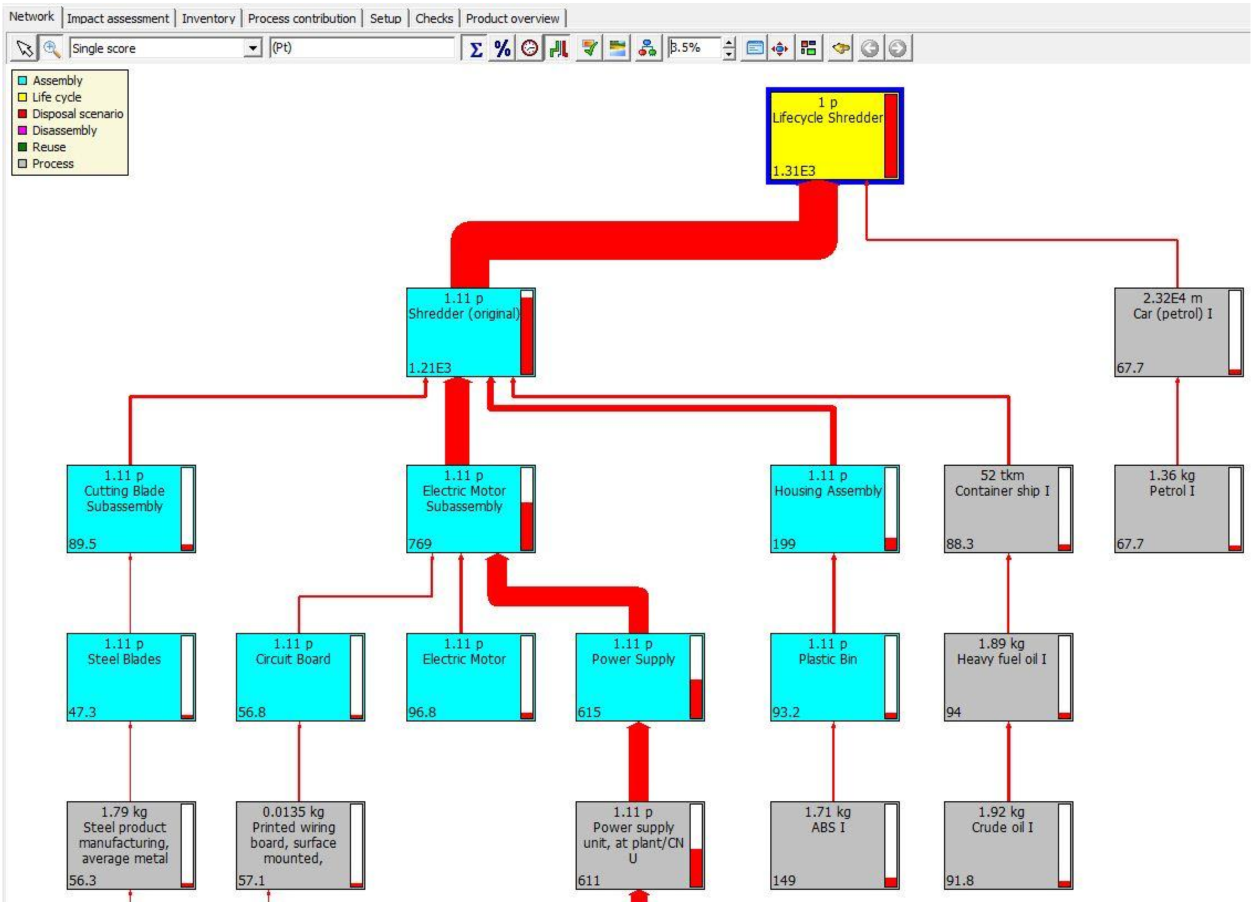


Figure 29 - CED for Aurora Paper Shredder in Use scenario 2

The new conditions set for this use scenario 2 can be seen in both networks above. For instance, the quantification of the Shedder assembly is 1.11p, the material shred is now more than in scenario 1, and the Car trip to the store is doubled vs scenario 1.

If wanted, the impact assessment method selected can be different. The use of SimaPro® facilitates this and the selection of the methods to calculate environmental impacts is easy. In this case, both GHG emissions and CED were selected. The first one is one of the environmental impacts most known by the general public, and the second one has proven to be a good surrogate since it tracks and relates very well with other impacts.

The application of the proposed approach demonstrated above has proven to be successful using SimaPro® and improving the re-use capability of already existing data. Further insights and discussion will be covered in section 6.4 of the present chapter.

6.3.2 Comparison of Different Technologies that "Destroy Material"

The proposed framework also opens up the possibility of selecting comparable scenarios between different technologies that perform the same function and, using the same use variables for the Cumulative Damage Function, compare these technologies through the software.

If the function "Destroy Material" was to be fulfilled by using fire through the use of a Bunsen burner, the descriptive variables were to be the same but the function takes a different form that relates to the product itself. Following the framework, the analysis of enclosing and interfacing systems were to be similar, and the analysis maintains its validity. Specific considerations to the Bunsen burner need to be done, however the overall enclosing ad interfacing systems are the same and the relevant reference flow is the same as well.

In the new example of a Bunsen burner, the specific assumptions regarding its materials, sourcing sites, bill of materials, etc. need to be done. Considering that a previous project was not available, general estimations were done and are shown in Table 10.

Table 10 – Assumptions for the Bunsen Burner

1	The total weight is 0.7 kg, mainly made of an aluminum alloy and rubber
2	The burner is sourced from Jiangsu (China)
3	From Jiansu to Shangai, the burner is shipped by truck
4	From Shangai, the burner is shipped by freight to San Francisco, CA
5	From San Francisco is shipped by truck to Rochester, NY
6	The natural gas is sources from the grid in Rochester NY
7	Passed its lifetime, the burner is disposed in the curb, going straight to a landfill

Next, the specific form of Cumulative Damage Function for this example needs to be defined. As mentioned in previous sections, a battery of stress and reliability testing would also determine the limit for the allocation procedure. In this case, both were created to facilitate the representation of this example.

The Cumulative Damage Function was assumed again to be linear, but the constants that relate the use of a burner were created different. In equation (7) the proposed Cumulative Damage Function for the example of the burner is shown. In this case, the limit for the Bunsen burner is set to be 50,000 letter sheet equivalents. The energy consumption function for the Bunsen burner was defined using the natural gas consumption of a general burner, and relating it to the use parameters that define the different use scenarios. The proposed energy consumption function is represented in equation (8).

$$(7) \qquad Cum\ Dmg\ Fcn_{bunsen}\ (letter\ sheet\ equivalents) = z_1 + 5 \cdot z_2 + 0 \cdot z_3 + 0 \cdot z_4 + z_5 + 3 \cdot z_6 + 0 \cdot z_7 + 0 \cdot z_8 + 4 \cdot z_9 + 4 \cdot z_{10} + 8 \cdot z_{11}$$

$$(8) \qquad energybunsen_{Avg}(MJ) = NGconsumption_{bunsen} \cdot \frac{(z_9+z_{10}+z_{11})}{3600} = 3.165\ \frac{MJ}{h} \cdot \frac{(z_9+z_{10}+z_{11})}{3600}$$

When comparing two different technologies, the important analysis of what equivalent workflows are needs to be done. For instance, in the case of comparing a shredder to fire, the equivalent workflows do not necessarily have to be exact use behaviors. It is possible that destroying credit cards or CDs with fire will not be done by the user and, in this case, the practitioner is responsible for defining what would the equivalent workflows be that enable the comparison of the two technologies.

For the new example under study of a burner, an equivalent use scenario 1 for comparing the burner with the paper shredder is defined. Using parameters in SimaPro® the use pattern 1 for the burner is proposed as shown in Figure 30.

bunsen_totalweight	0.7	Undefined				☐	kg
z1	1000	Undefined				☐	number of letter sized sheets destroyed
z2	100	Undefined				☐	number of letter sized cardbord destroyed
z3	0	Undefined				☐	number of CDs destroyed
z4	0	Undefined				☐	number of credit cards destroyed
z5	50	Undefined				☐	number of simultaneous letter sized sheets
z6	5	Undefined				☐	number of simultaneous letter sized cardboard
z7	0	Undefined				☐	number of simultaneous CDs
z8	0	Undefined				☐	number of simultaneous credit cards
z9	900	Undefined				☐	time between destroying media (seconds)
z10	900	Undefined				☐	time in stand-by mode (seconds)
z11	1800	Undefined				☐	time destroying media (cycle) (secs)
limitbunsen	50000	Undefined				☐	letter sheet equivalents
NGconsumption_burner	3.165	Undefined				☐	MJ/h

Figure 30 - Input Parameters for the Bunsen burner representing Use Scenario 1

The input parameters that represent the use scenario are combined in the calculated parameters to define the Cumulative Damage Function, allocation procedure, energy use, and transport multiplier for the burner. All these are shown in Figure 31. In the example for the burner, the energy used is natural gas from the grid and the calculation is based on the natural gas consumption of a burner.

cdfbunsen	z1*1+z2*5+z3*0+z4*0+z5*1+z6*3+z7*0+z8*0+z9*4+z10*4+z11*8 = 2.32E4	letter sheet eqs
allocationbunsen	cdfbunsen/limitbunsen = 0.463	
energybunsen_avg	NGconsumption_burner*(z9+z10+z11)/3600 = 3.17	MJ
transportbunsen	trunc (allocationbunsen)+1 = 1	# of bunsen

Figure 31 - Calculated parameters for the Bunsen Burner

As done with the Paper Shredder example, in the life cycle of the burner, shown in Figure 32, the practitioner will use the calculated allocation, energy used, and transportation multiplier which relate the use scenario being analyzed to all the life cycle stages of the product.

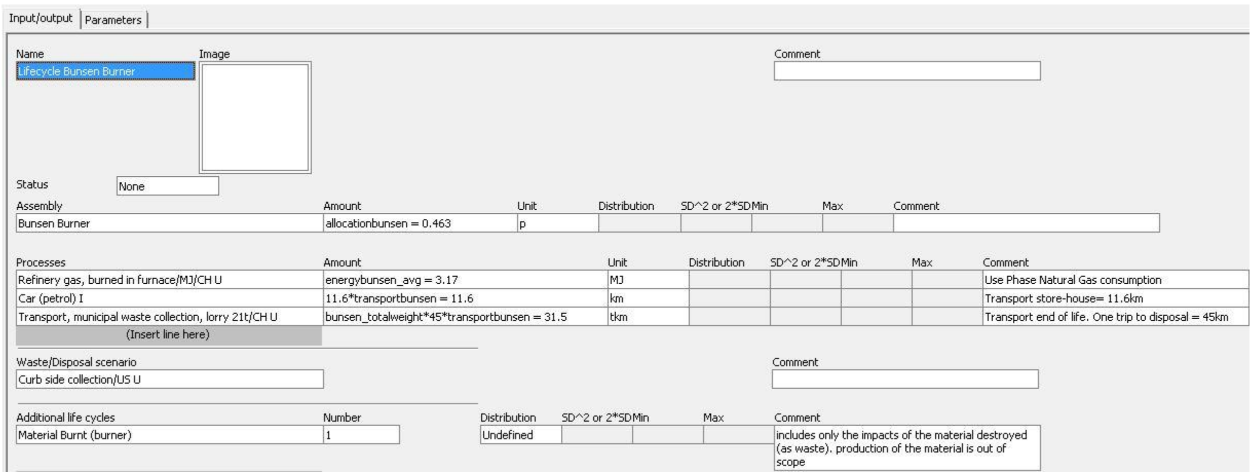


Figure 32 - Life Cycle of the Bunsen Burner

The waste scenario selected for the Burner is the Curb side collection, offered by the Ecoinvent library. In this case, the library details that this scenario is valid for the waste collected at the curb side (originally called municipal waste), considering that the waste separation already took place (PRé-Consultants, 2011).

The impacts of burning media, such as paper or cardboard, are accounted for in the additional life cycle called 'material burnt (burner)'. Following the same procedure as with the Paper Shredder example, subassemblies representing the material being burnt were built. These subassemblies used the use parameters defined for the use scenario to feed the model. An overall assembly accounting for all the media burnt was generated and the waste scenario defined for all media burnt was incineration to approximate the impacts of burning material. The details in Figure 33 show the waste scenario selected to act as proxy and represent the impacts of burning different type of media. This disposal scenario is the one called in the life cycle of the burner shown in Figure 32.

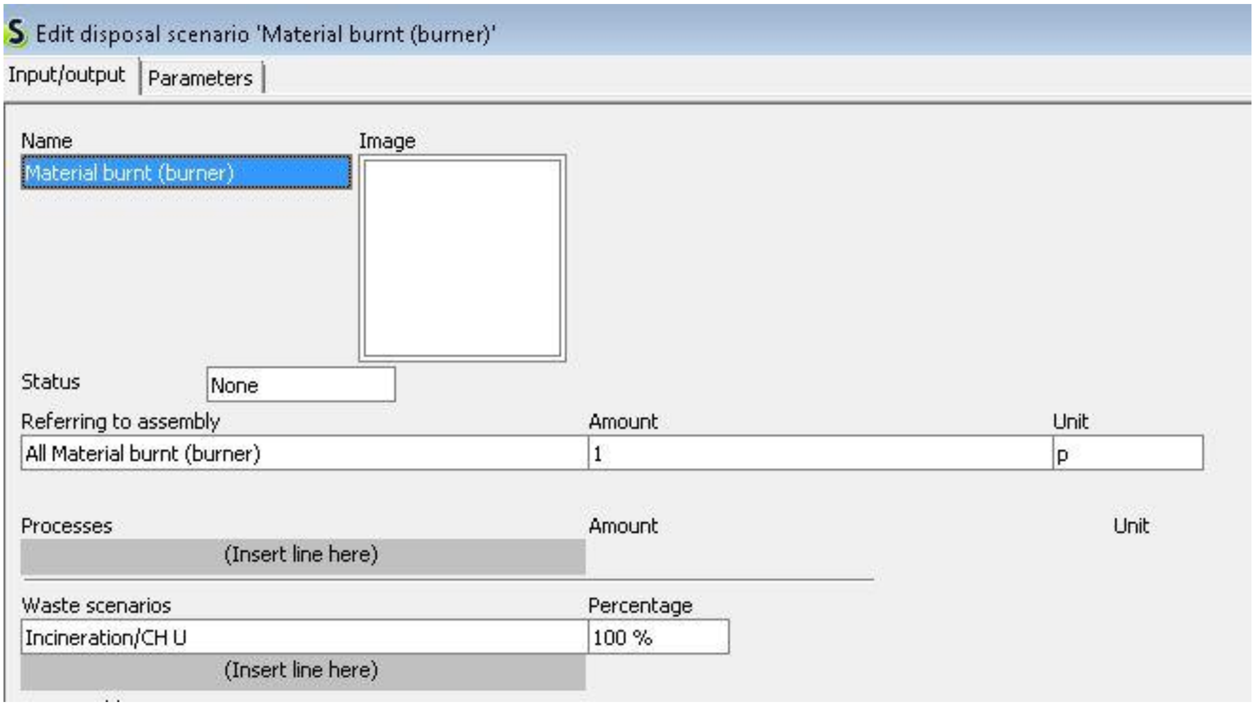


Figure 33 - Disposal Scenario for All Material burnt by the Bunsen Burner

Now that the life cycles for both the Paper Shredder and the Bunsen burner are complete using the defined equivalent workflows or use scenarios, the comparison of the environmental impacts is feasible through the Impact Assessment section of the software.

The comparison of the GHG emissions of both products in the equivalent use scenario 1 is shown in Figure 34, and the CED is represented in Figure 35.

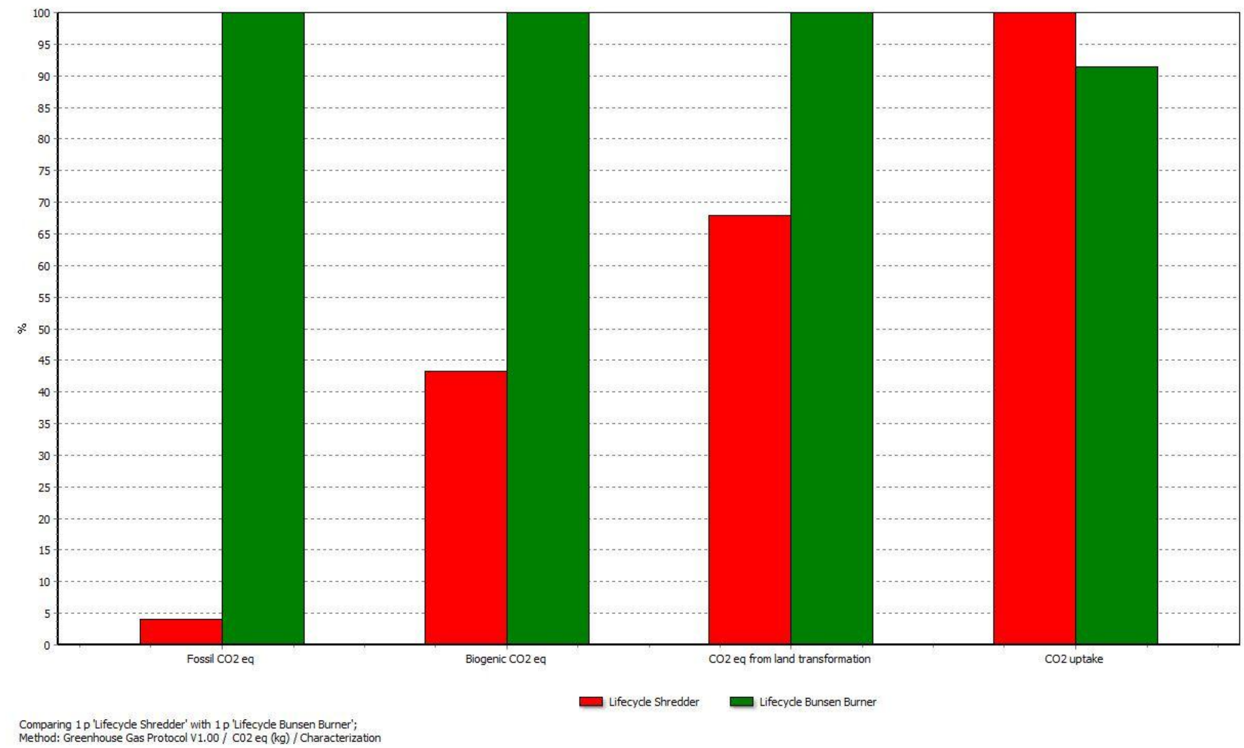


Figure 34 - GHG emissions comparison between the Paper Shredder and Bunsen Burner

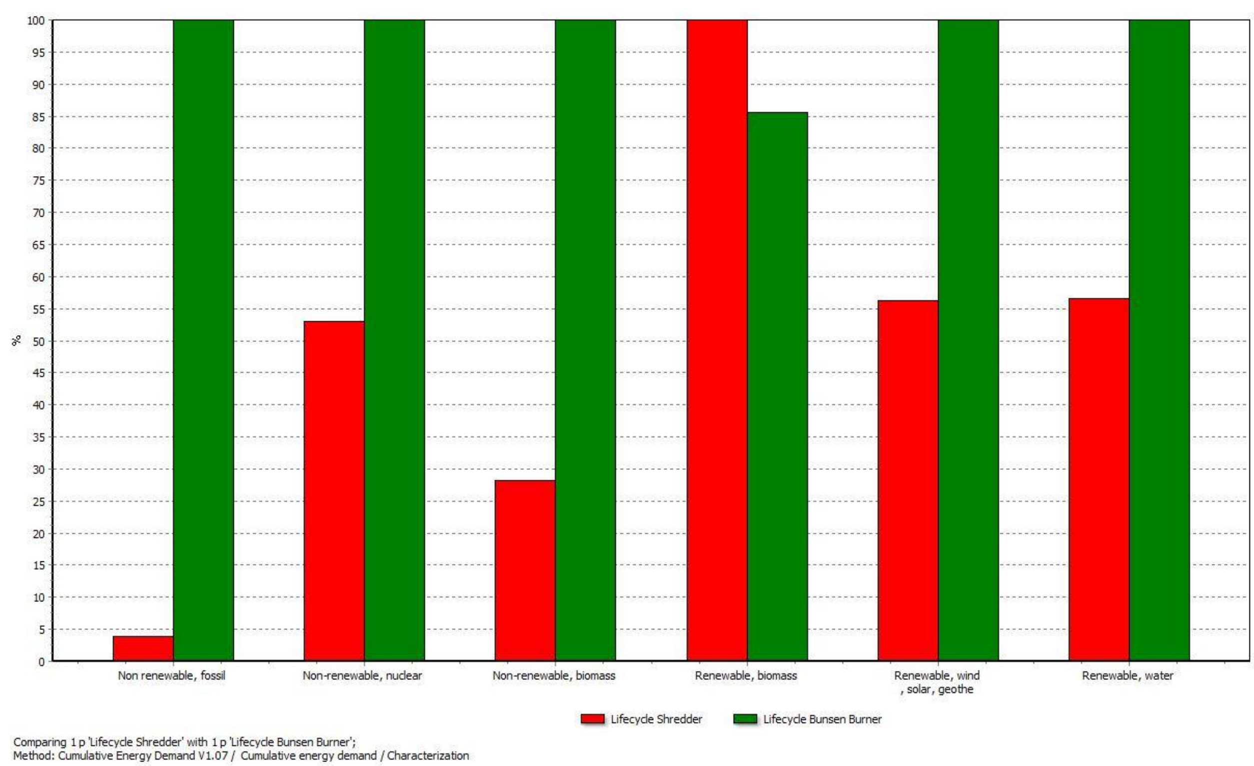


Figure 35 - CED comparison between the Paper Shredder and Bunsen Burner

To further detail the possibilities of comparing different technologies that "destroy information", the framework can also be applied to the case of destroying the material with a simple bin and matches. Again, since the function analyzed is still "Destroy Information", the descriptive variables for the Cumulative Damage function are the same and the function itself will take a different form related to the new technology under study. The enclosing and interfacing systems analysis still remain valid, and this analysis helps set the specific assumptions regarding the materials used for this case. The assumptions in this case, are again general estimations since a previous detailed project was not available for consultation. These estimations and assumptions are shown in Table 11.

Table 11 - Assumptions for the Tin and Matches

1	The total weight of the bin is estimated to be 2 kg, mainly made of stainless steel alloy
2	The bin is sourced from Guangdong (China)
3	From Guangdong to Shenzhen the burner is shipped by truck
4	From Shenzhen the burner is shipped by freight to San Francisco, CA
5	From San Francisco is shipped by train to Rochester, NY
6	The match is considered as a consumable, the amount used depends on the use scenario
7	The wood used for the matches are sourced from Uruguay by truck
8	Each match weighs approximately 0.002 kg and contains chemicals such as phosphates, paraffin, potassium among others
9	Passed its lifetime, the bin is disposed in the curb, going straight to a landfill

The Cumulative Damage Function for this case was also created as linear and is shown in equation (9). Furthermore, the limit for this specific example was set as 50,000 letter sheet equivalents. In this case, the energy to generate fire comes from the use of matches and that is why an extra life cycle is defined that accounts for the amount of matches that are used for each use scenario.

$$Cum\ Dmg\ Fcn_{\ bin}(letter\ sheet\ equivalents) = y_1 + 5 \cdot y_2 + 0 \cdot y_3 + 0 \cdot y_4 + y_5 + 1 \cdot y_6 + 0 \cdot y_7 + 0 \cdot y_8 + y_9 + 0 \cdot y_{10} + 8 \cdot y_{11} \tag{9}$$

As mentioned before, in this case, the practitioner again needs to define what would the equivalent workflow be that enables the comparison between the different technologies.

For the bin case, an equivalent use scenario was created by which the comparison between this and the other two examples presented earlier is valid. Again, the use of parameters in SimaPro® enables the representation of any use scenario and an equivalent use scenario 1 is shown in Figure

36. The calculated parameters for this case, shown in Figure 37, are the corresponding Cumulative Damage Function, allocation procedure, and transport multiplier for the end of life of the bin.

bin_totalweight	2	Undefined				☐	kg
y1	1000	Undefined				☐	number of letter sized sheets destroyed
y2	100	Undefined				☐	number of letter sized cardbord destroyed
y3	0	Undefined				☐	number of CDs destroyed
y4	0	Undefined				☐	number of credit cards destroyed
y5	50	Undefined				☐	number of simultaneous letter sized sheets
y6	30	Undefined				☐	number of simultaneous letter sized cardboard
y7	0	Undefined				☐	number of simultaneous CDs
y8	0	Undefined				☐	number of simultaneous credit cards
y9	0	Undefined				☐	time between destroying media (seconds)
y10	0	Undefined				☐	time in stand-by mode (seconds)
y11	1800	Undefined				☐	time destroying media (cycle) (secs)
limitbin	50000	Undefined				☐	letter sheet equivalents

Figure 36 - Input Parameters for the Bin Case representing Use Scenario 1

cdfbin	y1*1+y2*5+y3*0+y4*0+y5*1+y6*1+y7*0+y8*0+y9*1+y10*0+y11*8 = 1.6E4	letter sheet eqs
allocationbin	cdfbin/limitbin = 0.32	
transportbin	trunc (allocationbin)+1 = 1	# of bins

Figure 37 - Calculated parameters for the Bin Case

The allocation procedure and transportation multiplier was once more used in the life cycle of the bin case as shown in Figure 38. In this last figure, the number of matches used can be identified in the additional life cycles and can be easily changed. For this specific use scenario, it was assumed that three matches were used.

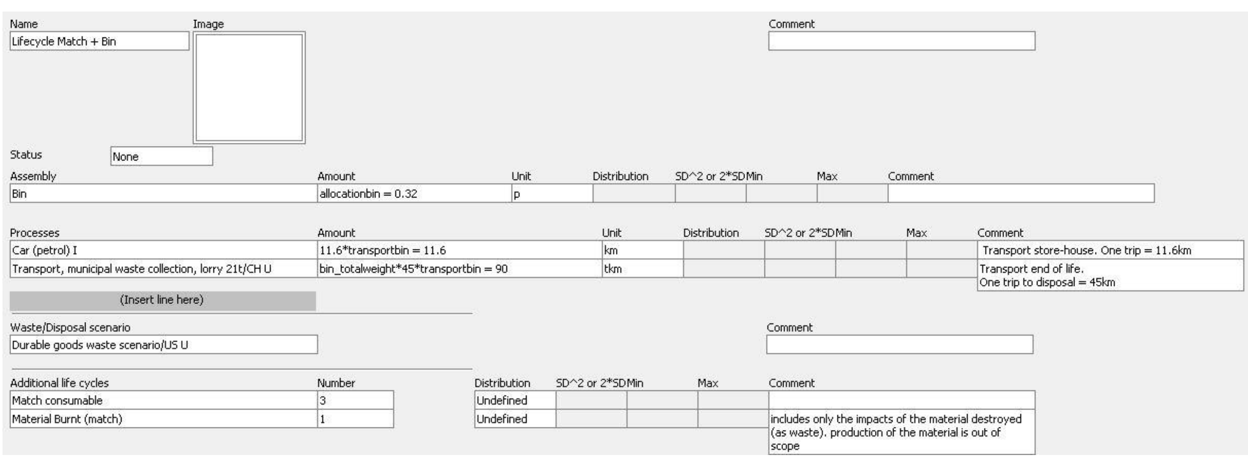


Figure 38 - Using the Allocation Procedure in the Bin case

The disposal scenario for the bin was selected to be the Durable goods waste scenario from the Ecoinvent library, also previously used for the Shredder.

Considering that in this case media is burned as in the Bunsen burner example, the representation of the impacts of burning media was done similarly as the Bunsen case. The impacts of burning media, such as paper or cardboard, are accounted in the additional life cycle called 'material burnt (match)'. Again, subassemblies representing the material being destroyed were built using dummy material block which maintain the earlier assumption that no upstream processes for the media destroyed were to be accounted for. These subassemblies used the use parameters defined for the use scenario to feed the model. An overall assembly accounting for all the media destroyed was generated and the waste scenario defined for all media burnt was incineration.

Finally, the three presented examples with their corresponding and equivalent use scenarios can be compared using the SimaPro® Calculation setups section. Following the framework, the life cycle inventory for each of the represented cases has been decoupled from their use behaviors, and the possibility of changing the use variables using the parameters in SimaPro® enables a dynamic model that can be modified as needed.

Having defined an equivalent use scenario 1 for the three technologies being described, the comparison of the GHG emissions between the three technologies is shown in Figure 39, and CED in Figure 40.

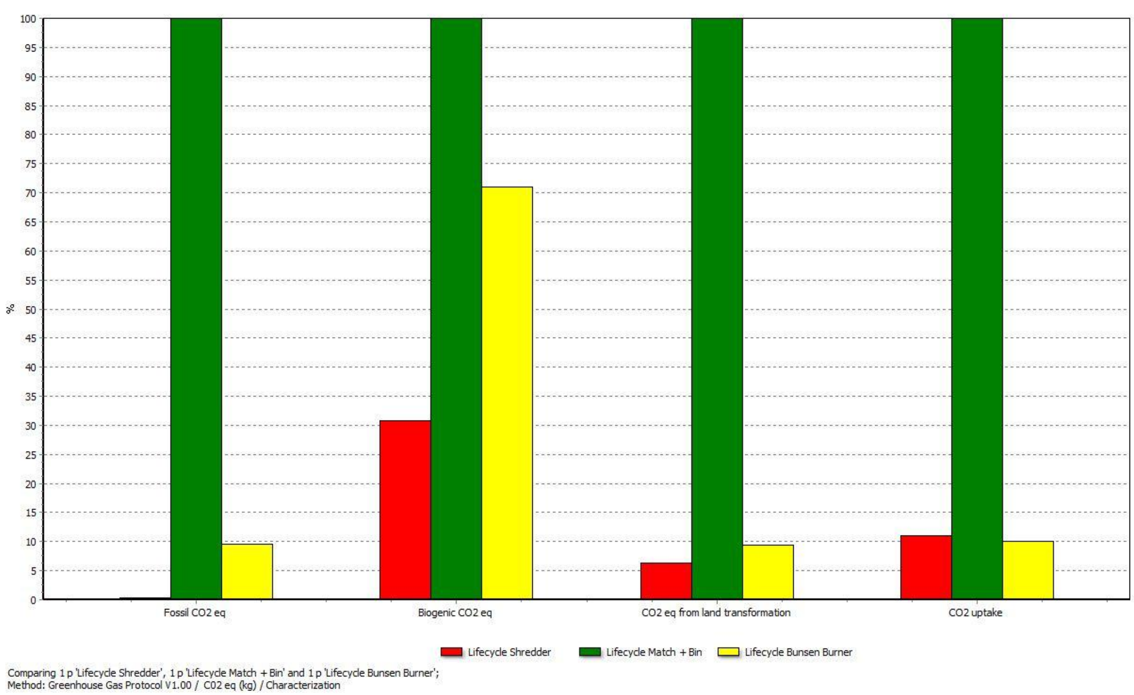


Figure 39 – GHG emissions comparison between the three presented cases: Paper Shredder, Bunsen burner, and Bin+Matches

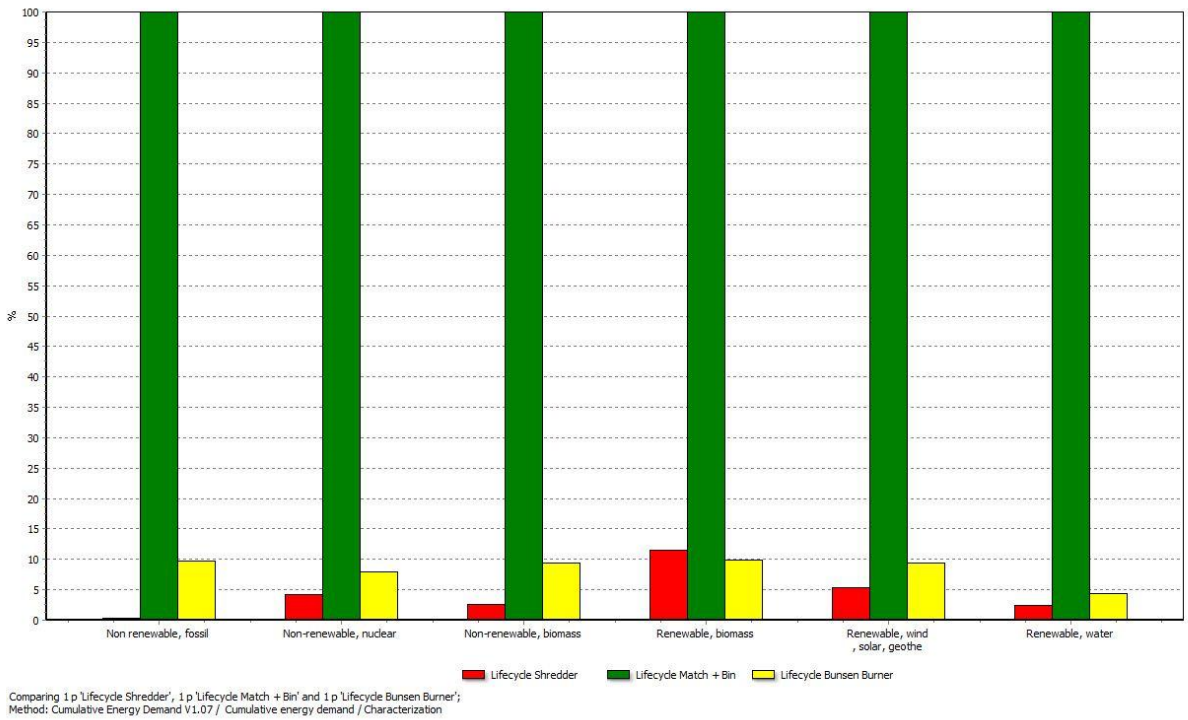


Figure 40 - CED comparison between the three presented cases: Paper Shredder, Bunsen burner, and Bin+Matches

6.4 Insights and Discussion

As mentioned in the previous section, the practical application of LCA using the proposed framework has proven to be successful for the case of "destroy information" and its implementation through three different technologies that fulfill this function. Throughout this exercise, several practical matters came up but all were successfully addressed with the use of parameters which facilitates the application of the framework.

One of the most important learnings from this case study is that the initial setup of the model is extremely important. It is essential that the practitioner understands what is linked to usage, and the case might be that it is most of the inventory phase. Having a complete understanding of the importance of the use scenarios and how these can be built, then everything that is impacted by usage has to be set up through parameters. By doing this, the posterior analysis of different use scenarios will be extremely dynamic and easy to conduct.

In addition, with the development of the case study some suggestions can be made to improve the versatility of the model. This is the fact that whenever possible, the use of parameters should be prioritized. For instance, defining a variable that sets the weight of the product might be of interest

when analyzing how the weight (or the size also) impact the LCA. In addition, transportation distances can also be defined as input parameters and later sensitivity analysis can be done by changing different distances.

Finally, the presence of co-products or ancillary benefits (or impacts) needs to be related to the use scenarios being quantified in the parameters. In the developed case study, these ancillary impacts were modeled through subassemblies that represented the media being destroyed, and the impacts were approximated with the use of waste scenarios. For instance, the impacts of burning media was represented by selecting incineration as the waste scenario for the Media Burnt assembly, which was added as an additional life cycle of the main product. The important outcome of this exercise is how to manage these co-products. Again, the importance of the use variables defined as input parameters is brought up again since these initially defined the quantification of the media being destroyed.

Overall, the utilization of the framework seems to be promising and the recommendation is to develop further cases in order to exercise the use of parameters and prove the possible re-use of already existing data, models, and projects.

7.0 CONCLUSIONS AND FUTURE WORK

This chapter summarizes the work developed and the main observations from this thesis. Furthermore, some future work opportunities are also detailed. The prospect of the proposed future work will enable the evolution of the LCA as a methodology that can address complex systems.

The initial motivation for the thesis was based on the known difficulties that practitioners face when defining the functional unit in the goal and scope of an LCA. A deeper study of these issues led to the broader focus of trying to define a structured framework by which comparability among LCA studies could be improved. The idea of a framework is consistent with the numerous initiatives in industry to standardize assumptions for the application of LCA, which were not always successful. In addition, the finding that functional analysis, a powerful tool among designers and engineers, had adequately incorporated in the goal and scope of LCA opened up the possibility for a structured approach that could be incorporated into the practical use of LCA.

A review of the literature revealed different areas for improvement opportunities within the LCA methodology. The use of LCA within product design was reviewed as well as some tools that have been developed to incorporate environmental assessment into product development. Moreover, several authors working on new proposals for improving LCA were analyzed and the need for a structured approach in defining functional unit and reference flows was identified as vital.

The research methodology was executed in three distinct phases. The first phase characterized the problems in LCA with the objective of grouping the issues for better assessing how the proposed framework addresses some of these issues. The second phase was the development of the framework itself, which leveraged system engineering and functional analysis principles. In this stage, initial examples were developed in order to test if the proposed approach was feasible for implementation. The development of these initial examples was of great importance to further refine the propositions. The third phase consisted of the selection and application of a practical case study using SimaPro®. This phase was also greatly influenced by the insights from the initial examples. The main objective of this last stage was to prove the feasibility of the implementation of the proposed framework, and to further analyze the strengths and areas for improvement of the proposal.

The characterization of the problems in LCA was done by grouping several problem areas mentioned by different practitioners in the literature. The categorization of the issues found in LCA resulted in four main groups: LCA general constraints, Goal and Scope phase, Inventory phase,

Impact Assessment, and Interpretation. The problems found in the goal and scope were further categorized in three sub-groups: functional unit difficulties, selecting boundaries and assumptions, and data availability and modeling. Considering that the work done in the goal and scope phase sets the tone of the LCA study, and that the pressing issues of functional unit and reference flows definition are found in this stage, the focus of this thesis was on these issues and the problems in this category were further explored.

The development of the framework was an iterative process. The present work was initially developed in an abstract manner and the development of initial examples to demonstrate the use of the propositions was of key importance for the refinement of the detailed implementation of the propositions. Eventually, the framework was defined to have three specific propositions that were further explained in four steps.

The first proposition defines the enclosing and interfacing systems in order to better understand the context and constraints of the system under study. In this step, the definition of the abstract function fulfilled by the product using functional analysis concepts is performed and the identification of relevant reference flows is performed.

The second proposition identifies the need of decoupling consumer behavior from the reference flows identified previously. In this stage, the development of a function that describes the system in terms of wear, and another function describing the energy consumption of the system are defined. These functions are the key enablers for quantifying and scaling the system inventory by user behavior.

Finally, the third proposition establishes the grounds for further work. The integration of functional decomposition is brought up as a promising area to enable better dynamicity of the tool.

It is important to mention that the continuous feedback received from the thesis committee and the development of examples, and later the case study were indispensable for the successful development of the present work.

The final phase of the present work consisted of the selection and implementation of the framework on a previously developed LCA (including a SimaPro®) project. By applying the propositions on a real case study, the framework was further refined, its application was proven successful and some implementation details were further developed. Overall, it can be said that the application of the abstract framework to a practical case study was helpful in developing the implementation details of the proposition.

The application of the framework in SimaPro® was enabled through the use of Parameters which made the implementation of both the Cumulative Damage Function and Energy Consumption

function easier. While developing the project, several points came up that had not come up before, such as the quantification of consumables, the modeling of their impacts (generally called ancillary impacts), and the quantification of transportation. All these topics were easily accommodated with the approach and the use of parameters.

Another great learning from the application of the case study in SimaPro® was the fact that the initial setup of the model is of extreme importance. Understanding what factors are related to use parameters is crucial to develop a model that is clear and organized. In addition, the use of parameters should be prioritized whenever possible since they enable a better base for the later use of sensitivity analysis, making the model very dynamic and easy to update.

Finally, the use of the Cumulative Damage function and Energy Consumption function in a practical setting reinforced the possibility of comparing different technologies that perform the same function when equivalent use scenarios are defined by the practitioner. The practical development of created cases such as the Bunsen burner and the use of matches demonstrated how the proposed framework can be used and how its implementation enables the comparison of these different systems.

In general, it can be established that the main contribution of this framework is the separation of the use behavior from the reference flow analysis and definition. As shown in earlier chapters, until now, practitioners relate functional unit and reference flows to specific use scenarios, hindering the further reuse of the information contained in the LCA study. Ultimately, the present proposed framework provides a structured approach for the analysis of different technologies that can enable a more robust ground for comparison making analyses more reusable.

This work has motivated the idea that by more formally applying system engineering principles and functional analysis to conduct an LCA and that by decoupling the use behavior from the reference flows; it becomes possible to scale assessments by user behavior.

A summary of some of the issues addressed by the proposed framework is shown in Table 12. This table revisits some of the issues identified in chapter 4 of the present thesis and discusses how this work aids to address them.

Table 12 - Summary of Issues Addressed by the Proposed Framework

Problem Category	Problem Description	How is the Problem Addressed by the Approach
LCA General Constraints	LCA studies present methodological inconsistencies, making them hard to compare	The proposal of a structured approach will help practitioners when applying the methodology
Goal & Scope - Functional unit difficulties	Product utility is hard to define, limited to simple products	The approach establishes a framework to systematically analyze the functionality of the system of interest
	Functions are hard to identify and prioritize	
	Not clear in how to consider sub (or extra) functions	
	Requirements for specifying FU and reference flows haven't been developed	
	Different FU lead to different results (variability)	
	Product alternatives offer functions/features in addition to the function of interest	The inclusion of a holistic and comprehensive view in terms of enclosing and interfacing systems provides a uniform framework to identify main function and other constraints
	LCA is not clear on how to handle non-quantifiable attributes	
	FU is defined using different language/words	The use of functional analysis provides a more robust language
	Definition of FU and reference flows are difficult due to consumer habits, product lifetime, and system dependencies	The decoupling of consumer behavior enables the easier quantification of the bill of activities making it easier to reuse analyses conducted
	Functional equivalency leads to inaccurate reflection of product reality	The use of abstract functional analysis and the decoupling of consumer behavior enables potential comparability of equivalent workflows
Goal & Scope - Selecting boundaries and assumptions	In practice, boundaries selected are sometimes not clear	The inclusion of a holistic and comprehensive view in terms of enclosing and interfacing systems provides a uniform framework to tackle boundary selection and to identify the relevant system flows which ultimately defines the broader LCA boundaries and assumptions
	Lack of tools to support boundary selection in LCA practice	
	No guidelines on how to approach assumptions	

Goal & Scope - Data availability and modeling	Data quality issues when data used does not represent local conditions (Local Technical uniqueness	The abstract view on functionality enables the possibility of analyzing a system regardless of local details, which can be detailed in the use behavior stage and modified depending on each specific case under analysis
	Problems with data availability and homogeneity	The possibility of incorporating the approach through functional decomposition enables a dynamic framework to include improvements in data availability and quality
	Data becomes out dated	
Interpretation	Choosing different scenarios influences decisions in the interpretation phase	The use of parameters makes the use of sensitivity analysis and different scenarios easier
	LCA impacts estimations are relative to a reference unit	The approach establishes a framework to systematically analyze the functionality of the system of interest and decouples the key elements in such a way that it becomes easier to reuse analyses conducted. It does not define a functional unit per se, but it does define standardized fundamental flows that are key to enable comparability. The impacts will still be relative to a reference unit, but the ability to evaluate different scenarios and references is easier and information can be reused.
	Lack of robust conclusions about lifecycle environmental impacts of different technologies	The use of abstract functional analysis and the decoupling of consumer behavior enables potential comparability of equivalent workflows of different technologies that perform the same function

Furthermore it is also useful to revisit the thesis objectives and research questions in order to assess this work. Below, the thesis objectives are transcribed in italics and some thoughts on how these objectives were achieved are developed.

- *Reconcile the literature on functional unit and LCA weaknesses in order to fully understand the present gap and set a path forward to propose a new process to help enable LCA comparability*. In this work, several authors were consulted to generate and affinity diagram and later a categorization of several issues present in LCA. The analysis of how some of these issues are addressed by the present proposal is shown in Table 12.
- *Looking at the functional unit definition by ISO, its implications with reference flows and functional analysis develop a recommendation to unify and guide the goal and scope definition of LCA*. A structured framework was developed in chapter 5 and refined through an iterative process. Three propositions are proposed that provide guidelines to include in the goal and scope of LCA.
- *Apply the proposed approach to a concrete case study*. The framework has been successfully applied to the function "destroy information" and more specifically to a paper shredder, a Bunsen burner, and the use of matches.

Some of the research questions that guided the process for developing the proposed framework were presented in chapter 3 and below a summary on how these were addressed is shown:

1. *What is a functional unit? How is it defined in practical LCA?* The analysis of functional unit and its practical implications was done in the categorization of the problems in LCA. More specifically in section 4.2
2. *What do the detractors of LCA say regarding weaknesses of the methodology and implications of functional unit?* The problems encountered in LCA and functional unit were covered in the categorization of problems done in chapter 4
3. *Are there any proposed solutions to unify functional unit definition? What are their strengths and weaknesses?* Some proposals were found in the literature and revised in the literature review developed in chapter 2
4. *How does LCA contribute to the product design process? (Most practitioners do not consider LCA as a tool for product development; however ISO mentions this as one application for the method).* The position of LCA within product development was reviewed in the literature research in chapter 2, more specifically in section 2.1

5. *Can functional analysis aid the process of examining the function and reference flows of a product in order to enable comparability among different product structures?* The use of functional analysis was of key importance when developing the proposed framework in chapter 5
6. *How can study boundaries and assumptions be approached in order to contribute to LCA comparability?* The use of system engineering principles was also of key importance for the system analysis and the first proposition of the recommended framework.
7. *ISO standards are open to future improvements in the state-of-the-art technique, is it an option to contribute to the development of the standard and LCA practice?* Ideally, the framework becomes common practice among LCA practitioners and the standard can be improved. However, for now, the recommendation is to keep developing examples and refining the method.
8. *Looking at a case study, analyze the implementation of the proposed method.* The case study application was developed in chapter 6 and the successful implementation of the approach was proved through the use of SimaPro®

A promising framework based on systems engineering and functional analysis principles has been proposed that can aid to enable LCA comparison, which has traditionally been a difficult task. A broad range of previously characterized LCA problems can be improved by the propositions involved in the proposed framework. The practical implementation of the approach in a case study was proven successful and the framework looks like a promising tool to be included in the practice of LCA.

7.1 Future Work

The third proposition of the present framework establishes the possibility of integrating functional decomposition to recursively apply the framework as the functions are systematically decomposed. This proposition then opens up the possibility of dynamic LCAs and the possibility of leveraging design repositories to aid in the process of developing actual LCIs.

This work, however, mainly focused on the detailed development of the first two propositions and further work on the last proposition is needed. The development of a detailed functional decomposition and the application of the framework to the lower levels of the decomposed model should be implemented. The application of LCA to each of the building blocks is recommended to be developed and to demonstrate if the possibility of building up the impact assessment by using those building blocks is feasible.

In addition, the development of more practical case studies is encouraged in order to keep refining the methodology. Although the approach was applied in detail to only one case study, the presented results are promising in terms of the potential of the proposed tool.

This study was initiated as a response to multiple concerns regarding LCA and comparability among different studies. The proposed framework evolved from the idea of standardizing functional units to a holistic view of goal and scope of LCA which integrates system engineering and functional analysis concepts which are generally familiar to designers and engineers. Ultimately, the tool sets the grounds for a structured framework to face the definition of functional unit and reference flows, a topic that has not been detailed by the ISO standards and is of high relevance to LCA practitioners.

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