The use of Life Cycle Assessment through an Objective Framework Constructed by Simulation

by

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ABSTRACT

Mounting social pressure in the form of media and political attention are encouraging industry to focus more on environmental responsibility and resource management. This has promoted many methodologies to achieve a more responsible utilization of materials and energy. The optimization of production processes is a complex task that is only made more difficult by unclear and sometimes contradictory metrics of success. To optimize a production process, a complete understanding of the life cycle of the product in question must be attained. A thorough understanding of a process' environmental impacts may be obtained through life cycle assessment (LCA), a tool that can assist in the optimization of processes and the creation and support of environmental laws. When life cycle assessment is combined with the power and speed of simulation technology, a realistic representation of the entire life cycle of a product can be created from cradle to grave. To prove that this combination of tools is feasible, a computer simulation for a product's life cycle was created. This model was used to prove that a simulation was a viable method to model a product's life cycle, and that computer simulation could assist in the rapid comparison of altered models. This combination of simulation and life cycle assessment was proven successful through the use of an example scenario constructed from a 2005 study on diapers that was performed by the Environmental Agency of the U.K.

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CHAPTER 1

INTRODUCTION

The application of life cycle assessment (LCA) to large, complex systems faces several practical limitations. First, the scope of the analysis is limited by the level of detail and quantity of factors that can reasonably be studied. Second, the various aspects of the analysis that require subjective judgment must be accounted for. In both cases, the greater the level of detail applied to the analysis, the narrower the scope must be to ensure that the validity of the life cycle assessment is defensible.

The problem of conducting a large-scale life cycle assessment has much in common with optimization problems commonly addressed in Industrial Engineering – specifically, Operations Research. The tools that have been developed to address complex multivariate optimization problems in those disciplines may offer a valuable framework within which to apply life cycle assessment with enhancements in terms of both scope and transparency.

In the context of Industrial Engineering and Operations Research, stochastic simulations are a widely used tool for understanding and optimizing complex systems. As computers have gained the power to handle large, complicated simulated systems, the popularity of simulation methods has grown [1]. Simulation is not only a valuable tool for evaluating complex systems in the business world, but is also applicable as a scientific tool. The scientific value of simulation is substantiated by its prevalence in both literature and application [1, 2, 3]. Simulation has been demonstrated to be effective in many fields of study including biology and geology [4, 5]. An emerging application of simulation extends its use to environmental studies as well. This paper explores how simulation may provide a valuable framework for evaluating the environmental impact of processes and systems using life cycle assessment.

The ability of simulation to organize, characterize, and optimize complex, multivariate problems is well suited to the process of life cycle assessment. Portions of the life cycle assessment process require subjective comparisons to be made by the evaluator. By presenting these subjective assumptions within the context of a structured simulation, objective comparisons may be drawn between differing approaches to the life cycle assessment process. The simulation environment, through its efficiency of processing, can quickly compare differing assumptions and metrics. Through sensitivity analysis, insignificant differences may be discarded and significant differences may be further reviewed. The capabilities of simulation may lead to a means of resolving some problems associated with life cycle assessment, including developing a consensus or framework for testing differing methodologies.

Improvements to the methodology, tools, and techniques all increase the overall performance of life cycle assessment. Increases in the performance of life cycle assessment can lead to a proliferation of the tool, thus supplying more data for future uses. In essence, by building a reserve of data from past assessments, future assessments benefit from the wealth of data available. In addition to this, the use of life cycle assessment forces communities to center their focus on specific environmental issues [6].

To create an objective framework to assist in the performance of life cycle assessment, several objectives must be proven feasible. First, it must be proved that current simulation methods and software is capable of constructing a model that simulates the life cycle of a product or process. Following this, it must be proven that these life cycle models can be quickly modified to provide the ability to compare several versions of a single model.

CHAPTER 2

LIFE CYCLE ASSESSMENT

Life cycle assessment is a holistic method that looks at the relationship and efficiency of each process element and how they interact with one another. Life cycle assessment is designed to objectively evaluate the environmental impact of energy and materials consumption throughout the anticipated life of a product, process, or system [7]. Life cycle assessments are generally conducted in a four-step process: [8]

1. Definition of goals and scope
2. Inventory assessment
3. Impact assessment
4. Improvement assessment

Within life cycle assessment, the analytical portions of inventory assessment and impact assessment are the most data intensive [9]. They are also useful when trying to understand the flow and creation of waste and products.

2.1 History of Life Cycle Assessment

Some consider the first applications of life cycle assessment to be a series of studies on “net energy analysis”. After the initial conception of the method by the Coca-Cola® Company in 1969, which was used to compare their packing materials, the advance of the life cycle assessment methodology was slow. Through the mid 1970's, landmark studies in life cycle assessment were performed by Arthur D. Little, and the Midwest Research Institute. The key players behind these studies then left their positions and formed the Franklin Institute, which would play a part in popularizing and standardizing life cycle assessment and its methodology. [10] It wasn't until the mid 1980's, when the "green movement" hit Europe, where it was primarily applied to packaging and beverage containers, that the methodology enjoyed renewed enthusiasm, use and improvement. The newfound importance of waste streams and their environmental and economic impacts became a very important topic which led to the use of life cycle assessment in industry. Within industry, life cycle assessment was initially used as a means to prove product superiority, a marketing technique that gave one company a means to prove that their product was more environmentally friendly than an opposing company's. This was due in part to consumer interest groups, who could influence the purchasing preferences of consumer groups [11]. In the 1990's the Society of Environmental Toxicology and Chemistry (SETAC) started to host workshops to develop a standardized method of life cycle assessment. These workshops were international, and had participants from many countries and corporations including the Coca-Cola Company, and the Franklin Institute [11].

In Europe life cycle assessment expanded rapidly and has become important partly thanks to government policy. In America, however, there has been no planned regulation of life cycle assessment other than a few executive orders that address the use of life cycle assessment in a nonregulatory sense [12]. An example is executive order 12873, signed in 1993 by President Clinton, which called for the use of life cycle assessment in federal purchases in order to safeguard natural resources through the use of recycling and waste prevention. While the United States government has been reluctant to pass legislation enforcing the use of life cycle assessment, many industries are beginning to use life cycle assessment of their own volition based upon the usefulness of the resulting information obtained [12].

Most of the life cycle assessments developed to date have been performed to determine the best method of packaging to use. Those assessments have successfully supported the reduction of waste through the reduction of packaging material. Other studies have been on consumer goods such as detergent or diapers. These life cycle assessments have found that the indirect impacts often far outweigh the direct impacts of production [11]. For example, the greatest impact of a blouse is not from its manufacture or the growth of the cotton used for the fabric, but during the use phase where it is repeatedly washed consuming water and electricity. Another such surprising finding is that the use of recycling or less toxic materials is not always the best method to reduce environmental impact; many cases have shown that greater quantities of energy and resources are consumed through trying to use green methods when the use of virgin or toxic materials could be far less harmful in the long run [12].

2.2 Goals and Scope of Life Cycle Assessment

In the early 90's SETAC hosted a number of workshops to help define the form of life cycle assessment. In the first meetings the setting of goals and scope was not given its own step in the life cycle assessment process. Instead, it was considered something that should take place in each of the other three steps. As work continued on the standardization of life cycle assessment it was eventually considered an individual step in its own right after the European workshops were held [11].

It is possible that the most important part of the life cycle assessment is clearly defining the goals and scope of the project. Life cycle assessment is a complex undertaking that could be far too complicated a project to be considered feasible without a clearly defined scope [13]. By limiting the breadth of focus with which a life cycle assessment will be concerned, the amount of work is decreased and the project made simpler. A small, focused project that is completed in a timely manner will provide more benefit than a massive project never brought to fruition. A well planned life cycle assessment will lead to a good understanding of:

- How life cycle assessment will aid the system [6].
- The project's purpose [11].
- The expected final product [10].
- The boundaries of the system to be studied [13].
- The conditions under which the system will operate [13].
- The assumptions that have been made about the system and its environment. [13].
- Possible alternative processes to be studied [13].
- Possible alternative resources to be studied [13].
- The roles that uncertainty and variability play in the system [10].

This also becomes a checklist to gauge the success of the life cycle assessment as it progresses, it allows the conductor of the study to compare what is being done to what is desired. This allows the conductor to decide if the work is keeping on track, and staying within the specified scope of his study.

2.3 Inventory Assessment

The second step required to perform an accurate life cycle assessment is the inventory assessment. Inventory assessment is an objective process of quantifying the flow of raw materials, energy, wastes, and any other emission produced by the life cycle in question. When laying the groundwork for the inventory assessment, it is helpful to consider the goals and scope laid out in the first step. A well planned inventory assessment should consider five separate points [14]:

- The products, and process to be studied
- Reasons for conducting the study
- Need of the end users, and possible applications of the study
- Elements of the inventory assessment addressed
- Elements not addressed in the inventory assessment

An inventory assessment may be thought of as a mass balance on a large scale, it aims to account for all the materials that go into each process and all the materials that come from each process [14]. Because an inventory assessment is so highly quantitative, it has remained relatively unchanged since the 1970's [11]. A life cycle is generally considered to consist of the following processes [15]:

- Raw material acquisition
- Manufacturing, processing, formulation
- Distribution, transportation
- Use, re-use, maintenance
- Recycling
- Waste management

The first objective is to catalog all of the raw materials that go into the creation of the product or the ability to render a service. From here it is possible to observe the individual resource inflows. These inflows arise from the satisfying of process demands. They are raw materials and energy required to perform the processes that make up the life cycle of the product in question. Examples of these inflows include:

- Kilowatt hours of electricity to power machinery
- Gallons of fuel required to run heavy equipment or ship materials
- Tons of steel required as a base material to manufacture the finished product
- Gallons of water required to cool or clean machinery and the product as it is being finished

Ancillary materials such as grease and cleaning products used to maintain equipment may not be required to assess the life cycle; this should be taken into consideration when the scope of the project is initially decided [14]. Often the weight of a product can be used to determine if a specific resource can be safely left out of the study. When an individual material is less than 5% of the total weight of an end product it can often be left out of the study, unless that material can have a severe environmental impact such as is the case with a car battery [13]. When considering recycled products, there are essentially two types to differentiate between: those recycled by the end consumer, and those recycled downstream in the production process as a recycled coproduct.

The second objective is to compile all of the emissions and any finished products produced; anything that is created intentionally or as a byproduct of the process should be accounted for. The final finished product, CO_2, NO_x and other air emissions, waste water, industrial sludge composed of toxic materials or carrying heavy metals and any other streams of waste or emissions created by the process should all be accounted for and included in the inventory assessment [11].

2.3.1 Inventory Assessment in the Public and Private Sectors

Life cycle inventory assessment has seen use in both the public and private sectors, even as a stand alone tool [14]. The uses in the private sector can be divided into two groups: those used for internal evaluation and external evaluation. Likewise, the uses of inventory assessment in the private sector can be separated into two groups which consist of policy making and public education.

The private sector benefits from life cycle inventory assessment when making internal evaluations and decisions. A privately owned company could use inventory assessment to compare alternative options. Using inventory assessment to compare alternative materials, products, processes or activities is a good way to consider the possible outcomes of each option available to a company. A second possible function that inventory assessment can perform is assisting green marketing strategies. A company can use inventory assessment to compare the resource consumption and residue release totals resulting from their product's life cycle. These results can then be compared to a competing manufacturer. A third possible use for life cycle inventory assessment is to aid in the training of personnel responsible for reducing environmental burdens associated with the life cycle or production of the product in question. Obtaining information about how a system works is important to understanding how it would react to changes and how it can be manipulated to better suit current needs. By obtaining new information on the residue flows produced through the life cycle of a product, it is possible to give personnel a better understanding of the system, which gives an increased ability to manipulate the system to foster improvement in both efficiency (manufacturing cost) and environmental impact [14].

Externally, the same private sector company could use life cycle inventory assessment to provide information to many outside entities. Information about the product's life cycle could be given directly to the public as part of a marketing strategy, or it could be distributed to non government organizations [14]. Non government organizations fall into many areas, including consumer interest groups and professional organizations. These organizations could potentially bring new employees to the work force or increased market share for the product in question. Information could also be shared with governmental bodies to document regulatory compliance [10]. This not only benefits the company during environmental audits, but also frees government dispensed pollution credits. This allows the company to sell excess credits to outside industries that have a difficult time meeting environmental regulations. This trading, often referred to as emissions trading, is an activity that was permitted in 1990 when the Clean Air Act was amended [16].

Within the public sector, life cycle inventory assessment has found a home as an evaluation and policy assistance tool. The ability to take the information gathered in the assessment, and use it to evaluate existing and prospective policies that relate to resource consumption and residue releases is valuable in its own right. When inventory assessment is supplemented with some impact assessment, the step can be used to develop such consumption and release policies. In addition to creating and evaluating government and public policy, inventory assessment can be used to highlight fields of information where little is known. Identifying gaps in knowledge can be a difficult task that becomes easier when an inventory assessment is stalled by such a gap in databases or general knowledge. Inventory assessment can also be used to evaluate statements of quantifiable reductions in materials and energy consumption, or residue releases into the environment. By developing curricular materials, inventory assessment can even be used to train engineers and other members of the product and process design team. Furthering this idea, materials can be designed from inventory assessment data to educate the general public. This could increase the general understanding of the impact a product or service has on the environment. This would tend to have a positive impact on the environment, if not the sales of the product or service in question [10].

2.3.2 Deterministic Methods in Inventory Assessment

Because inventory assessment is essentially a mass balance, the easiest way to express the system is through deterministic means. So that what could be a constantly changing variable based around a statistical range (stochastic) is instead a static unchanging value (deterministic). Using deterministic information as input data for each step in the life cycle makes the inventory assessment much easier to design and check against available information. Because of the deterministic nature of the data, each step in the life cycle would result in a single number for each residue flow resulting from the process. These flows could then be consolidated or evaluated individually to determine the areas where the greatest wastes are produced, and thus the areas with the greatest possibilities to save resources.

2.3.3 Stochastic Methods in Inventory Assessment

The use of stochastic data in inventory assessment requires the acquisition of ranged data for each and every process in the life cycle being studied. Assuming these data are available, they would result in a numerical range of possible residue flow outcomes. This method would still allow for the consolidation of these residue streams into a total for the life cycle in question, or individual residue streams allowing the assessment of the system to determine areas with a probability of producing high amounts of waste.

2.3.4 Limitations of Inventory Assessment

While life cycle inventory assessment is a useful tool in its own right, and an integral part of life cycle assessment, it should be understood that there are limitations and complications to its use. These can be broken into two categories; general limitations of life cycle inventory assessment, and problems presenting the information obtained through inventory assessment [14].

The general limitations to inventory assessment are all products of misunderstanding the data presented. For example, project outsiders are often prone to misinterpreting the information presented by an inventory assessment. This could not only lead to a general misinterpretation of how a process should be modified, but also the inference of a higher or lower degree of accuracy than is implied by the inventory assessment [14]. This combination could lead to either the doing the wrong thing for the right reasons, or the right thing for the wrong reasons. There would simply be no real merit in methods produced by misinterpreted conclusions. Another type of misinterpretation would be to allow readers to focus on a factor that is of little importance. To clarify, an undue focus on unimportant resource consumption could overshadow more important consumptions when incorrectly interpreted. Along these lines, information can be incorrectly interpreted when aggregated data is used. Aggregated data has the possibility of masking not only site specific variations in energy and material consumptions, but also the residue streams produced [14].

An inventory assessment also can cause failures in communicating results when the findings are not well presented. For example, an inadequate system definition can cause readers to consider a larger or smaller system than what is actually being studied. Inadequate explanation of assumptions made can also lead to confusion and a general decrease in the transparency of the inventory assessment. The level of accuracy in each individual stream in the inventory assessment is important. Confusion and misinterpretation is natural when the accuracy of inventory assessment is poorly presented. Even the manner of presentation is important for inventory assessment, as ill conceived groupings of data can cause confusion and misinterpretation of data. In addition, inventory assessment can cause confusion by presenting its findings when the scope of the system in question is not well conceived and described. Finally, general ambiguity is to be avoided as it tarnishes the transparency of the study. Ambiguous interpretations of presented data can be caused by insufficiane effect characterization and assessment of the considered resource and residue flows [14].

2.4 Impact Assessment

The third stage of life cycle assessment is impact assessment, which is the most contentious portion of life cycle assessment due to the subjective nature of valuations required by the step. Impact assessment is a technical process that is both quantitative and qualitative by nature. It combines the data obtained from the inventory assessment stage with characterization and assessment methods. It should address ecological and human health factors, as well as other possible impact areas, such as habitat modification and biodiversity loss. Impact assessment has recently been expanded to consist of bottom up impact assessment, which is the more traditional approach, and the newer top down impact assessment. The difference between these two is explored in greater detail further in this chapter. Bottom up impact assessment consists of two steps defined by the International Organization for Standardization (ISO) as classification and characterization. International Organization for Standardization additionally offers three additional steps that are not necessary: grouping, normalization and weighting [17].

2.4.1 Classification

Classification consists of assigning information obtained in the inventory assessment stage to impact categories such as human toxicity, air pollution, and resource depletion. Every item of information obtained from the inventory assessment stage is used in this step; they are each allocated to one or more of the impact categories where they will count for, or against the plan as a whole. For example, the emission of SO_2 into the atmosphere can not only cause an increase in respiratory problems and other human health problems, but also cause acid rain and soil acidification. Because of this the emission of SO_2 would be shown as a contributing factor within multiple impact categories [12].

There are many possible areas where environmental stressors can be classified. In 1990, the United States Environmental Protection Agency's Science Advisory Committee used four parameters to rank environmental problems. They considered the spatial scale of the impact, the severity of the hazard, the degree of exposure, and the penalty of being wrong about the previous three parameters. The committee used these parameters to develop the following list of problems, ranked by risk level [7].

High risk problems

- Habitat alteration and destruction
- Species extinction/biodiversity loss
- Ozone depletion
- Global climate change

Medium risk problems

- Herbicides and pesticides
- Toxics, BOD, turbidity
- Acid deposition
- Airborne toxins, such as smog

Low risk problems

- Oil spills

- Ground water pollution
- Radio nuclides
- Acid runoff
- Thermal pollution

2.4.2 Characterization

Following classification is characterization, which is the calculation of characterization indicators based on factors that are often obtained through environmental modeling [18]. Predictably, the conversion of a measurable by-product into a predicted impact requires a degree of personal discretion. Accordingly, this step is where many differences between assessments originate. Characterization can represent the characteristic effects of impacts in five ways [10].

The first of these is based on loading, which is a direct quantitative comparison of the data from inventory assessment. The amount of material put into the environment is of key importance in this method, as they are compared directly [10].

The second method of representation is the equivalency model. This model is based on equivalency factors that are obtained through outside environmental models. These equivalency factors convert various emissions into one set of units. For example, there is an equivalency factor to convert emissions of methane into carbon dioxide. By converting all the emissions produced by a process to a few types, it makes a direct comparison quite simple [10].

The third method to represent the data is through their inherent chemical properties. This method relies upon data that has been pooled by industry, public sources, and government agencies. The data typically are focused on chemical toxicity, persistence, and bioaccumulation in an attempt to use the collective data to normalize the emissions produced by the life cycle being studied [10].

The fourth method of representation is based on generic exposure effects. This method considers the most common environmental and human effects that are possible from exposure to specific emission chemicals and wastes produced by the product [10].

The fifth method of representation considers site-specific exposure effects. This method is similar to the fourth method in its use of estimated harm based on common exposure effects. Where it differs is the addition of site-specific data to the exposure [10]. For instance, there could be a specific and unanticipated reaction to certain emissions. One example of such an unanticipated result is Minamata disease, which was caused by elemental mercury being metabolized by ocean bacteria. This process allowed organic mercury to contaminate local marine life, which resulted in a major environmental accident. [12].

2.4.3 Grouping

Grouping is a recent introduction to impact assessment that was put into place by ISO 14042, and is considered an optional step. Grouping is a semi-qualitative method of organizing impacts into categories or a hierarchy. The organization of the individual environmental impacts into categories is often based on similarities, either in what they affect, or what their causes are [19].

2.4.4 **Normalization**

Normalization is an optional step that attempts to use reference information to calculate the relative magnitude of the category indicator. Normalization converts various results from the characterization stage into similar units. This is similar to the equivalency model.

Normalization can be performed in many ways that result in different choices being revealed. Normalization can be split into external and case-specific normalization. External normalization uses an external database to perform the actual normalization of the category indicators, and some actually consider it to be a form of weighting. It has a tendency to force case-specific normalizations to a more open and far reaching view. Case-specific normalization, or internal normalization, is referred to as such because there is no requirement of outside data. Case-specific normalization uses two separate options within the life cycle assessment study to reference them against each other. Case-specific normalization is primarily seen as a precursor to the weighting step because the main focus of this method of normalization is the unification of unit types [19].

2.4.5 **Weighting**

Weighting, or valuation, is the most subjective part of impact assessment. It attempts to assign relative values of importance to different impact categories. While many argue that weighting can be based on environmental economics to reduce the subjectivity, it is still considered to be a highly subjective area of work [20, 21, 22]. For example, consider an industry that has the choice of two chemicals that will be expelled into a river. The first chemical will likely cause a drop in the population of the river's fish, while the second chemical is likely to increase the incidence of cancer in people that come in contact with it. Because the person in charge of the impact assessment favors human health over that of marine life, he chooses the first chemical. Though the rationale is defensible, such alternatives are seldom explicitly presented in actual impact analyses. This may be partially attributable to anticipated contention around the weighting factors used in the valuation stage. This is because the weighting stage may rightly be influenced by factors that are emotional or political, not just rational. Even though the subjectivity of the weighting step has caused controversy and contention, it is still widely used [23]. There are five major weighting approaches that are typically used in life cycle assessment [24, 25].

The first of these is the proxy weighting method, which uses quantitative measures to indicate the environmental impact of environmental stressors. Measures such as energy requirements or total mass displacement are concrete quantitative values that can be used to weight stressors. This quantitative aspect of the proxy method circumvents the subjective nature of weighting to a degree; however it is difficult to gauge the extent that these indicators will be able to assess complex problems like ecotoxicity [25].

The second weighting approach is based on technological abatement. It considers the approaches that would be required to deal with the environmental impacts resulting from the environmental stressors, assuming methods to deal with the impacts are presently existing and feasible. This method is often used in conjunction with the cost of the methods considered for remediation. When the cost of these technological abatement methods is considered, the method can be considered a monetization method [19].

The third method is based on monetization, and the costs associated with the environmental stressors found in the inventory assessment stage. Monetization is usually based on a group’s “willingness to pay”, meaning that a group is polled and their average response is considered to be the amount they are willing to pay to prevent a specific environmental impact, or save a specific environmental resource. This method is typically used on either individuals or on general societal groupings. When individuals are polled there is a risk of their answers being compromised, which is why there is an additional method that can be used to obtain the individual’s revealed “willingness to pay”. The revealed “willingness to pay” for an individual is typically found by observing an individual’s market trends [26]. Monetization can also be based on methods that do not revolve around the “willingness to pay” methods. Instead they are often based on the cost to do something as determined by the market or base cost of the technology and materials. The use of these methods not based upon “willingness to pay” is only viable when the methods of remediation are possible [27].

The fourth approach is the panel weighting method, which uses a group of experts to give a rating or opinion. The panel method has a great deal of variation that cannot be easily avoided for several reasons. The make up and size of the panel of experts alone can account for some level of variation between groups. In addition to this, the opinions received from experts can vary depending on how they are elicited and the question’s format. The level of background information provided can also cause experts to give different opinions. All of these aspects of presenting the question to experts can cause differences of opinion based solely upon how the experts read and understand the system being presented to them as a whole. Going further, the panel of experts can give differing results depending on how they are able to answer questions, and how that information is collected and aggregated. Imagine the difference between experts that reach a consensus on an answer, and experts that send their answers to a remote facility where they are averaged [28]. It should be noted that a group consensus does not necessarily increase the quality or accuracy of the panel's response [29, 30]. The design of a panel varies in actual practice. It has been suggested that as few as ten people are sufficient to create a panel [31]; however it is often the case that far more panelists are used [32. 33]. The panelists should consist of experts in the field under consideration, facilitators, and stakeholders. The exact group composition with these three groups depends on the technical complexity of the study [34]. The exact criteria for the selection of panel members is left to those creating the study, however it would be wise to consider the criteria listed in Table 1.

Finally, there is the fifth method – the distance to target weighting methods. These methods differ from one another by the equation that is used and the choice of targets picked. The simplest of these equations is $V_i = 1/T_i$, where V is the resulting weighting factor, and T is the chosen target [25].

- Experience in two or more of the specialty areas considered in the assessment
- Current or previous leadership or management role in one or more of the specialty areas considered
- Experience in at least one of the valued system components affected
- Representation of a particular sector, interest, or geographic area
- Seven to ten years of combined education and professional experience in impact assessment and / or one of the key assessment areas (disciplines) involved
- Experience in similar types of assessments or decision-making processes
- A high level of professional productivity as evidenced by
    - Publications
    - Participation in professional meetings and symposia
    - Experience in project management
    - Current or previous membership on EA panels
- Based on self-identified interest or expertise (those who simply wish to be involved)

Table 1 Expert panel selection criteria emerging from recent practice impact assessments [(Noble, 2004), (Noble, 2002), (Gokhale, 2001), (Bonnell, 1997), (Huylenbroeck and Coppens , 1995), (Richey et al., 1985) and (Sobral et al., 1981)]

2.5 Top Down vs. Bottom up Impact Assessment

Impact assessment has been relatively unchanged for many years. The traditional method of impact assessment is now known as bottom up impact assessment. Recently this method has been challenged by an alternate way to view the problem, using a top down approach [19].

Bottom up impact assessment is the traditional means of performing impact assessment, and has even been acknowledged by the International Organization for Standardization with the release of ISO 14042 [17]. Bottom up impact assessment is process centered, and microeconomic in scale. As bottom up impact assessment is the traditional method used, and is accepted by ISO [18]. Supporters of bottom up impact assessment assert that there is a lack of reliable data, which precludes the use of top down impact assessment [35].

Top down impact assessment is a more recent alternative, only in use since the mid 1990's, that recognizes that life cycle assessment is driven by the perceived value of certain things [36]. The top down approach begins with valued items, or "areas of protection", and flows from there towards the stressors that can cause damage. Top down impact assessment is damage driven and mainly concerned with damage to the environment, and is based around political economics [18]. One methodology based on this top down idea is the Eco-indicator 99 approach; which consists of four steps: fate, exposure, effect and damage analysis. The first of these, fate, links the emissions from a life cycle and connects them to an increase in the environment's concentration. The second, exposure, links the concentration change to a dose. The third stage, effect, links the received dose to health effects caused by the exposure to the given concentration. The final stage, damage, links the health effects to disability adjusted life years (DALY's) using an estimate of the number of years that will be lived disabled [36].

2.6 Subjectivity of Impact Assessment

There is no single best method in use for the impact assessment step because it contains so much subjective data, and there are many methods that attempt to provide an objective method for this data to be used [37]. Because a part of impact assessment's nature is subjective, there have been many attempts to create a uniform method. In fact, the Environmental Protection Agency noted 36 separate methods of characterization and weighting, none of which is widely accepted. The subjectivity intrinsic in impact assessment is a long standing problem. In fact, the very first impact assessment was rejected in 1969 because of its subjective nature [11].

Since so many methods can lead to differing and contentious results depending upon the data used in their creation, a framework for open and objective comparison could be useful. This is a key area where simulation could be of benefit. Instead of allowing studies to hide their subjectivity behind complex mathematical equations [11], the subjective sections should be made transparent and malleable.

2.7 Redeeming Impact Assessment

For all of its subjective roots and flaws, impact assessment is an important step that should not be discounted. Even the medical industry is beginning to see the benefit to impact assessment [38]. The advantage of explicitly tailoring life cycle assessment to include an individual's or society's value choices, is that the ethical values of one group can radically differ from another. By keeping the subjective portions of impact assessment visible, transparent, and modifiable; they can be tailored to the use of individual groups, or used to come to a generalized cooperative answer [19]. Transparency is key to all of life cycle assessment, and impact assessment is no exception [39].

Transparency is hindered by unclear assumptions and the use of proprietary data; while transparency is aided by detailed and complete assumptions and input data. The level of detail in impact assessment is referred to as the level of sophistication, and it controls the ability of impact assessment to present accurate, detailed information. A high level of sophistication should be a goal of every life cycle assessment. When considering how to improve the impact assessment's level of sophistication there are several points that should be considered [39]:

- Study the objective of the life cycle assessment.
- Value of an uncertainty or sensitivity analysis.
- The inventory assessment data and the specifications behind it.
- The depth of knowledge and understanding in the chosen impact categories.
- The availability of modeling data that support the objectives.
- Use of specialized software that can assist in the objectives.
- Availability of funding.

2.8 Improvement Assessment

The fourth and final stage of life cycle assessment is the improvement assessment stage, where the information gained from the previous steps is put to use in planning. Improvement assessment is considered to be an evaluation of the opportunities present in the life cycle of a product or process. These opportunities are chances to decrease the consumption of raw materials and energy, and to decrease the emission of wastes produced throughout the life cycle [14]. Improvement assessment should use the information gained from the inventory and impact analyses to create strategies to optimize the system the life cycle assessment was based upon [12] and may be quantitative or qualitative in the nature of the improvement's measurements [14].

While marketing is a viable use of life cycle assessment, a growing use is the improvement of products and processes through their life cycles [11]. As industry focuses increasingly on using life cycle assessment for systems improvement, research has recently focused on the methodology of improvement assessment [10]. This increased scrutiny on improvement assessment is important because without the use of improvement assessment the only aspect of life cycle assessment that can be used to discern improvements is the second step, life cycle inventory assessment. This method is not wholly desirable since inventory assessment would fail to take into account health and environmental impacts and would instead infer decisions based on the emissions produced and everything consumed in the process [11].

The importance of improving processes and products alone is not the only reason to perform improvement assessment. The use of improvement assessment also ensures that life cycle assessment isn't used solely to justify the current institution, perpetuating wasteful practices. The use of improvement assessment forces the evaluation of various available options, including the current method, to aid in the continuous improvement of the product or process in question. Improvement assessment also forces an emphasis on the use of life cycle assessment as a tool to reduce the environmental impacts caused by the system in question. To this end, impact assessment forces companies to realize that all systems have some environmental impact that can be altered. Though improvement is frequently an outcome, it is worth noting that redesign of systems and products is arguably not actually a part of life cycle assessment, rather, it is an application of what has been learned through the study. Meaning that while a life cycle assessment can lead to improvements, or compare results from conceived improvements; it does not necessarily have a step devoted to redesign. [10].

2.9 Benefits and Uses of Life Cycle Assessment

Life cycle assessment has many uses and benefits. In fact, the applications of life cycle assessment are a growing area of study and continuously being expanded. . While there are many benefits to be gained from life cycle assessment, only four shall be covered for the sake of brevity.

Keeping in mind that money is a primary motivator for industry; governments around the world have introduced environmental credit programs. These programs give companies incentives to improve their environmental standards by giving companies permission to pollute a certain amount. Companies that are able to reduce their pollution can have a surplus of these pollution credits, which they in turn can sell to more wasteful companies. This ability to turn a profit by reducing waste, and by selling excess environmental credits to other companies, allows aspiring companies to increase their revenue on two fronts [12].

The constant incentive to improve products in today's competitive market is staggering. Products have to constantly be made more efficiently, cheaper, and more environmentally friendly. Because of this modern drive towards environmental improvement, engineers have developed the idea of Design for Environment (DFE). This idea of designing a product specifically to minimize its environmental impact has a natural symbiosis with life cycle assessment. This can be seen in thousands of life cycle assessment studies that have been performed to determine the most environmentally friendly method of packaging, most noticeably by Coca-Cola. Life cycle assessment assists in "green" engineering design through the calculation of indicators that can act like an environmental report card, showing which indicators are best improved [40].

Designing a product specifically to decrease environmental impact leads very naturally to the next topic: the use of life cycle assessment to aid in the marketing of a product. Marketing a product has one purpose, securing market share. Life cycle assessment can provide a framework on which to design a marketing campaign [40]. This can be seen simply by turning on the television and observing the rush of advertisements that are based around the environmental impact of the products being sold. In some cases, life cycle assessment can be the base for all product assertions throughout the product's life cycle [41]. It must be noted, however, that unfounded environmental claims about the creation of a product can lead to a public backlash - a lesson learned by McDonalds when they claimed their packaging was made from recycled cardboard stock [42].

The ability of industry to monitor its own hazards in an objective manner is an important benefit that can be gained from the use of life cycle assessment. This is especially true when a new product, process, or material is being considered [40]. This ability to self monitor environmental conditions becomes even more valuable when it is used as a framework to prepare for environmental audits [41], which can result in an increased market share through detailed method analysis and the avoidance of steep environmental fines [40].

CHAPTER 3

LIMITATIONS OF LIFE CYCLE ASSESSMENT

While life cycle assessment is a powerful tool that has gained worldwide acceptance and increased use [43,44], there are some important limitations of the tool. Three major sources of error and inconsistency within life cycle assessment are identified below. These include problems with obtaining reliable data upon which to base the study, limitations related to the size and complexity of a system, and subjective judgments required for the impact assessment.

3.1 Problems with Data Collection

The problems of life cycle assessment begin with the goals and scope set at the beginning of the study. When goals and scope are poorly established, the entire study is jeopardized by the resultant delays created by rework required when insufficient data are collected [14]. These delays can be costly and may generally be avoided with correct planning and insight.

The next problem is the actual collection of information. The availability of data can vary depending on what product or process is under consideration. Data may be found from a number of sources including [10, 15]

- Government databases
- Engineering calculations

- Estimations based on similar processes
- Journals and other open literary sources
- Reference books
- Industry reports
- Specific data collected for a project

Ideally, the data should be both recent and relevant to the study. The amount of specific data to be used is determined by the needs of the study. In some cases, a generalized study may be all that is needed. However, when very specific data are required, problems associated with the use of proprietary information may be encountered. Very little can be done about the use of proprietary information; at times it is a necessary tool. Unless the full details of the underlying data can be disclosed, however, restrictions imposed by the use of proprietary information may damage the credibility of the study by decreasing the transparency of the model [14]. Despite increasing availability of relevant data to support life cycle assessment, there is always a need or desire for additional resources [45].

The results of a life cycle assessment should be set out clearly to reduce the likelihood of ambiguous interpretation [14]. Life cycle analyses that can be interpreted ambiguously are problematic for a variety of reasons. First, the results might be misused to support a course of action that is in contradiction to the findings of the study. Second, resulting negative perceptions associated with both the analysis and the methodology may lessen the overall effectiveness of life cycle assessment as a tool.

3.2 Problems with Consistency of Assessment

The inconsistency of life cycle assessment primarily stems from two areas: the quantitative data used through the inventory assessment and the qualitative information that impact assessment is based upon. The quantitative data collected from primary and secondary sources, meaning site specific information and data collected from available databases, can vary depending on the data collection method and the data source. The qualitative data also varies, but instead varies on the societal norms and political agendas that influence the subjective tendencies of the evaluator [13, 46].

During the collection of information, the data collected can be of varying quality. Information gathered should include not only averages, but also measures of the natural variance of the system in question, range, distribution, and the accuracy of the measurements themselves. In addition to data which lack these factors, the collection of information can be slowed or tainted by poor data gathering methods. The method of data collection is highly important and must not only be rigorous, but also transparent. In this way, when there is a problem with the collected data it may be identified and corrected with minimal effect on the rest of the study methodology. Transparency is vital to the reputation and understanding of life cycle assessment. Inadequately explained assumptions may lead to confusion and create mistrust in the final result [14].

The qualitative data used in impact assessment is based upon societal beliefs and political ideology as stated earlier. As such, it is subject to change from community to community and culture to culture. Because of the cultural variance and the inherent subjectivity of the value judgments required for parts of impact assessment there is no single best method in use [37]. Some methods, such as the Ecopoint method, rely on the law to determine the resiliency of an environment and thereby determine the limits for the impact categories [11].

3.3 Problems with Analyzing Large Scope

A life cycle assessment is a long and complicated process that grows in complexity in proportion to the item or process it is meant to study. For example, performing a life cycle assessment on something as complex as a car engine would be very difficult and highly involved. Each component part of the engine would need every step of its creation catalogued and information for each of these steps would have to be found or gathered [13]. Eventually, the complexity of the product or process would create such a complicated life cycle assessment that it would be totally impractical to achieve a meaningful result.

A method currently exists that attempts to shorten the amount of data and work required by complex life cycle assessments. Known as streamlined life cycle assessment, it attempts to remove aspects of a full life cycle assessment without damaging the accuracy of the study. Keith Weitz of North Carolina's Research Triangle Institute and his coworkers have identified nine separate approaches to streamlining life cycle assessment [14]:

- Screen product with inviolates list, treating some suggestions as automatically wrong
- Limit or eliminate components or processes of minor importance
- Limit or eliminate life cycle stages
- Include only selected environmental impacts
- Include only selected environmental parameters
- Limit consideration to components above threshold weight or volume values

- Limit or eliminate impact analysis
- Use qualitative rather than quantitative information
- Use surrogate data

CHAPTER 4

USING LIFE CYCLE ASSESSMENT IN CONJUNCTION WITH ENVIRONMENTAL IMPACT ASSESSMENT

Life cycle assessment and environmental impact assessment are two tools that have long been considered unique tools with separate foci. Environmental impact assessment and life cycle assessment were developed by separate scientific communities, and are often used by unique practitioners within specific legal contexts. Life cycle assessment has focused on specific projects and individual processes, while environmental impact assessment has focused more upon local and source evaluations of impacts. Environmental impact assessment has been tuned to take into account several other factors usually not considered in life cycle assessment; such as time release aspects of chemicals, geographic location, and current pressures on the environment [47]. This difference between life cycle assessment and environmental impact assessment has often been remarked upon [48, 49]. In fact, the focus of environmental impact assessment is often considered contradictory to that of life cycle assessment because it emphasizes an assessment that is independent of both time and location in relation to a production system. Simplifying the difference, life cycle assessment has, at times, been called a tool to make decisions; while environmental impact assessment is concerned with the process of decision making [47].

Recently, life cycle assessment has been proven to be a feasible tool that can assist in the performance of environmental impact assessment. This can be seen primarily by case studies outlining the use of life cycle assessment within environmental impact assessment

[47]. Furthering this is the work of experts detailing how life cycle assessment can be used to address parts A and B of Table 2 [50,51,52].

Step a: Definition of evaluation criteria

- Identification of areas of protection, and the relevant categories of environmental impact end points related to those protection areas.
- Choice of impact category end points relevant to the comparison, and possible midpoints or target points used as a "proxy" for the true end point.
- Choice of criteria or approach to produce a score or a ranking for the impact category.

Steb b: System definition and inventory

- Choice of the system boundaries of the process system relevant to the comparison.
- Inventory of relevant environmental interventions caused by this system.

Step c: Selection of alternatives

- Selection of relevant alternatives.
- Integrated judgment of remaining alternatives.
- Sensitivity analysis.
- Final choice of the alternative.

Table 2 Main steps in the evaluation of environmental impacts of human activities. (Tukker, 2000)

Life cycle assessment and environmental impact assessment may be used in conjunction because there is no inherent contradiction between the impact assessments and choice of system to be studied. Life cycle assessment becomes, in essence, the base for environmental impact assessment's work. The focus of systems afforded by a life cycle assessment lends itself nicely to the process of comparing feasible alternatives presented in an environmental impact assessment. While environmental impact assessment in itself is far more interested in an individual facility, there is no reason why the data gathered through life cycle assessment cannot be used to benefit further studies with differing end goals [47].

4.1 Environmental Impact Assessment

Environmental impact assessment is a broad decision making tool that has seen far more government acceptance than life cycle assessment. Its use continues to spread across the world in a continuously expanding range of contexts [53]. While the tool has been shown to be effective in improving environmental considerations during the decision making phase of plans and programs [54,55,56,57], it still falls short of its ultimate goal of encouraging the proliferation of sustainable development [53]. The failure of environmental impact assessment to reach its desired effect is increasingly thought to be linked to its lack of basis in accepted theory [58,59,60]. To better understand environmental impact assessment, there should be a basic understanding of its method, current use, current research, the potential reasons to use the tool, and its regulatory origin.

Environmental impact assessment can be defined as a tool that assists in pinpointing potentially unacceptable outcomes, so they can be prevented during the planning stage [61]. A rough breakdown of the activities within environmental impact assessment can be seen in Table 2. Breaking environmental impact assessment down further results in a list of the principles and axioms that environmental impact assessment is based upon (shown in Table 3). Environmental impact assessment can further be broken down into three levels of environmental impact assessment: strategic environmental impact assessment, environmental impact assessment at a company or project level, and an environmental impact assessment on the location or logistics of a project [62]. Because environmental impact assessment is largely concerned with the process of decision making, it is worth noting that decision making itself can be broadly broken down into the three aspects of policy, plan, and project [62].

Since its inception, environmental impact assessment has usually been considered as a tool used to assist in the process of learning and negotiation between different parties – including evaluation of alternatives [63,64]. Canada has embraced this tool. In Canada, environmental impact assessment has been recognized as a primary decision making tool to enhance and maintain environmental quality while carrying out economic and industrial activity [65]. Since the acceptance of environmental impact assessment in Canada, all federal departments must consider the ecological impacts of their projects in three key ways. First, any potential environmental effects that could result from a Canadian federal project should be considered both spatially, and temporally. Second, the human impact must be taken into account. This means that the project must consider how it will not only change human health, but also how it will positively or negatively affect social and economic systems. Further, Canada mandates that the scope of their federal project assessments include the study of impacts that extend beyond their borders. Third, potential effects of the environment on the project itself should be considered. This last step is important for ensuring the lifespan of the project, in addition to planning for problems. This final step is considered to have a second part, addressing public concerns regarding the project and any environmental effects it could potentially inflict upon the area [65]. And in fact, much of this is the same in the United States of America.

Much modern research has focused on decision oriented practices for strategic levels of decision making, neglecting environmental impact assessment. It is thought that the fickle nature of funding and research interest is the cause of this, rather than satisfactorily operating environmental impact assessment. In addition to this, the capricious nature of research and funding towards environmental impact assessment propagates the theoretical impoverishment that already plagues the tool [66]. The fickle nature of research is further exacerbated by ineffective means of comparing decision oriented assessment practices. In fact, it is currently impossible to establish a comparative method to rank decision oriented environmental assessment practices because there is no experimental replication, or unequivocal standard for judging decisions [67,68]. Recent interest in the topic has included work by Cormier and Sutter, who have proposed the integration of separate assessment types to streamline the overall process. Their assessment processes consist of [69]:

- Chemical, physical, and biological impairment assessments.
- Causal pathway assessments to determine causes and identify sources.
- Predictive assessments to estimate environmental, economic and societal risks and benefits.
- Outcome assessments to evaluate the results of integrative assessment decisions.

Even though environmental impact assessment has largely failed to achieve its primary goals, it is still considered a useful tool to improve environmental considerations during project development and completion [65]. As our knowledge expands and improves our use of environmental impact assessment, more and more people will come to see the benefits and importance of the tool [65]. This idea of eventual acceptance and proliferation is based largely on the rationale behind environmental impact assessment. The tool is important to humanity as a whole because it protects the environment, which is the originator for all goods and services that are vital to today’s modern world. Because the actions of people inevitably alter their environment, a method of decision making must be used to consider and account for these changes. Unacceptable or irreparable changes to the environment should be ferreted out before being inflicted upon the populace at large. The subtle nature of the environment lends itself to slight alterations that are unrecognizable without formal analysis by a trained eye. All of these reasons support environmental impact assessment, or another scientific based means of decision assessment to provide the public a continuing stream of goods, services, and well being [69].

4.1.1 Using Environmental Impact Assessment

Environmental impact assessment, occasionally known as impact assessment, can be used as a stand alone tool outside of full life cycle assessment, or be a tool that leads to the use of full life cycle assessment. Impact assessment has three main aspects when used as an individual tool, strategic environmental impact assessment, project environmental impact assessment, and location environmental impact assessment.

Strategic environmental impact assessment is often focused on individual plans. The purpose of this form of impact assessment is to grade the effectiveness of waste management or electricity generation. By comparing the environmental effectiveness of these plans, the best option is made apparent [70].

Project environmental impact assessment is typically used to focus on a single facility. This would include the construction, use, and deconstruction of the facility. This means that all associated environmental impacts that would become apparent through the life of the facility would be included in the project environmental impact assessment [70].

Finally, there is the location environmental impact assessment. This version of impact assessment is fairly focused, neglecting most everything considered in a traditional impact assessment in favor of a detailed study on the location where a facility will be placed. The variation of many raw material costs can be very location dependent [70]. For example, a facility producing bottled water would be ill advised to set up in an area with a shortage of water; since the environmental impact of removing vast quantities of water from a dry ecosystem would cause great ecological damage.

- Assessments inform environmental management decisions
    - Assessments are comparative
    - Assessors must know about the decision, the decision maker(s), and the bases for the decision
    - The form of the assessment results must be appropriate to the decision
    - Assessment results must be understandable by the decision maker
    - Assessments must convent the importance and urgency of the results
    - Resources are limited
        - Results should not be more complex than necessary to inform the decision
- Assessments are science based
    - Science explains the past or predicts the future
    - Scientific quality must be assured
    - Assessors must be unbiased
- Assessments inform decision processes and are science based
    - Assessments must be based on causal relationships
        - Assessments must address exposure
        - Assessments must define a functional relationship between exposure and effects
    - Uncertainty is always present and must be presented in a way that is useful to the decision
    - Policy is input to assessments, not generated by assessors
        - Assessors must translate goals and policies into operational terms
    - Management decisions must accommodate multiple goals and constraints
        - assessments must integrate across discipline
        - assessments must integrate across sources of information
        - assessments must integrate across scales and levels of organization

Table 3 The axioms and principles of a theory of environmental impact assessment (Sutter II and Cormier, 2008)

4.1.2 History of Environmental Impact Assessment

The origin of environmental impact assessment begins with the study of rational planning theory, developed in the mid-1950’s [71]. This eventually led to the environmental aspirations that where put into place through the U.S. National Environmental Policy Act of 1969 [53]. Following this was a propagation of the theory, ideals, and procedure during the

1970’s [72]. The propagation of environmental impact assessment reached a critical point when the European Commission enacted its first environmental action program underlining the importance of environmental impact assessment in 1973. Nearly a decade later in 1985 EIA directive (85/337/EEC) [73] mandated the use of environmental impact assessment at a project level. A few years later in 1987 this mandate was extended beyond the initial project level to encompass policies and plans as well. The European Commission set an environmental action plan for 1993 to 2000, in the hopes of integrating environmental impact assessment with the macro planning process. The hope behind this action plan was to encourage the optimization of resource management, and to reduce inconsistencies in the international and interregional competition for development projects [62]. In 1992 environmental impact assessment was introduced into Danish environmental policy as a follow-through for the U. N. Conference on Environment and Development, held at Rio de Janeiro during that year [74]. During the 1990’s Denmark saw a considerable increase in their environmental expenditures, doubling from 700 to 1400 million Euro per year in the years proceeding the 1992 U.N summit [75]. In 1995 the Canadian government enacted the Canadian Environmental Assessment Act, or CEAA. This act required that an environmental impact assessment be performed on all physical works or regulated activities that are begun by the Canadian government, use federal funds, located on lands administered by the federal government, or require a federal permit or license [65].

4.1.3 Strategic Environmental Impact Assessment

Strategic environmental impact assessments encroach upon the realm of the life cycle assessment more closely than normal environmental impact assessments, meaning that both life cycle assessment and strategic environmental impact assessment deal with the entirety of production systems [47]. Strategic environmental impact assessment is a decision making tool that assists in the formulation of sustainable environmental policies, plans and programs [76]. Strategic environmental impact assessment is usually relegated to the plan level of decision making, and focuses on such things as waste management and electricity generation [47,70].

There are many benefits gained when using strategic environmental impact assessment. While the benefits are similar to those gained from both life cycle assessment and normal environmental impact assessment, they bear enough importance to be given their own mention [62]:

- Provides a systematic method to review relevant environmental issues
- Improves the basic concepts and refines strategies involved with the policy, plan or program
- Provides a better understanding of possible environmental outcomes
- Improves the project's balance between environmental, social, and economic factors
- Simplifiies environmental investigations around the project
- Accelerate the decision making process
- Improves transparency of the planning process to increase popularity and accountability
- Gives guidance on developing methods of mitigating environmental damage
- Clearly defines what environmental objectives are to be monitored

Strategic environmental impact assessment is not a perfect tool; it suffers from technical problems and drawbacks. Dalkmann summarized these points from conclusions reached by the European Union's 1994 Workshop on EIA Methodology and Research, the European Union's study on an EIA/SEA research strategy [77] and the work done by Thérivel and Partidário in 1996 [78]:

- Large differences between sectors and decision making levels within individual countries, much less multiple nations
- Lack of a formal decision making process for the policies, programs, and plans that strategic environmental impact assessment will be used upon
- Large geographic areas
- Complex data collection and analysis, and many possible alternative methods
- Uncertain future environmental, technological, economic and social conditions
- Uncertain outcome of the pollution prevention practices
- Limitations imposed when statistical data is incomplete or of low quality

4.2 Politics and Environmental Impact Assessment

Impact assessment is not a method that produces one clearly identifiable correct answer. Rather, it produces many answers that are conditionally the best options. When all the work behind a life cycle assessment is done, the impact assessment might find itself ignored. There are many reasons – both valid and foolish – for those in charge to ignore impact assessment. Planners might deign to discard an impact assessment when the alternatives studied are considered to be narrow, or the consequences from the alternatives are considered to be non-comprehensive. Planners might even know that the majority of politicians favor a specific course of action that is not highly ranked, leading to the impact assessment being ignored to curry political flavor [79].

To protect impact assessment from removal, there are some changes that may be implemented. First, financial budgets should be considered from the start. This simple addition prevents wasted time on possible strategies that will be dismissed later as financially unfeasible, and grounds the assessment in reality. Second, the guidelines of the assessment should emphasize the need for each alternative to be assessed, because among them is a preferable strategy. Third, when the possible strategies are all unacceptable, several new options should be created and considered. One strategy is not enough, there must always be at least one other to compare and choose the best practice. Finally, the initial guidelines of the assessment should suggest how the impact assessment results can be used to obtain useful and relevant data to the case in hand [79].

CHAPTER 5

SOFTWARE MODELING OF COMPLEX SYSTEMS

When seeking to optimize a system, the benefits that can be gained through computerized simulation are linked to the level of complexity of the system. Because the number of variables that must be considered when modeling a complex system is large, modeling such systems is often facilitated by the use of computers. Though the use of simulation is frequently motivated by a desire to improve or design a system, sometimes a simulation may be used solely as a means to understand and illustrate the behavior of a system. Representing the system in this orderly structure allows a deeper understanding of what drives the process and what can be changed. Regardless of the underlying motivations, computer simulation facilitates the modeling of complex systems, generally resulting in a system representation that is more thorough than can be achieved by other means [80].

Large systems are often comprised of smaller, discrete subsystems and components. Changes made to these subcomponents affect the behavior of the larger integrated system, thereby serving as control points for the overall system behavior. At the subcomponent level, alterations can be something as simple as changing the flow rate of water or as complex as reworking a portion of a production process to use new machinery. Because of the complex interactions of subcomponents in the larger system structure, changes at the component level may not result in the desired effect at the system level. Simulations provide an environment within which to study the interaction effects of proposed changes without incurring the costs, both tangible and intangible, associated with unintended changes to system behavior. The savings in time and money that are seen from the use of simulation to justify actions are reason enough to encourage their use in manufacturing [80].

The size and complexity of a model determines the amount of computing power required. Very small, simplistic models can be worked out by hand or using a simple spreadsheet program. More complex models, however, require specialized software. Computing power and sophistication also depend on the type of model that is to be used. If model behavior can be determined analytically, that is, calculated deterministically, computing requirements may be reduced because results will be deterministic. However, in cases where the model is stochastic in nature, accrual of inaccuracies may occur through averaging errors [81]. Iterations of stochastic models are necessary to account for model variation, thereby requiring a greater commitment of computing resources.

Simulations done by hand are static and must be reworked to represent different scenarios; a computer simulation requires little effort in comparison. Individual data points within a dynamic system can often be modeled using a spreadsheet analysis. However, these results will typically only represent a single quantitative result at a given time, largely neglecting the dynamics of the system. By contrast, an advanced simulation program such as Arena™ or ProModel™ can be used to create a dynamic model that can be observed at any time in the simulation [81].

5.1 History of Modeling

The history of simulation is tied to the development of computers by necessity. As computers grew from the use of vacuum tubes to today's complicated integrated circuits, simulation became more and more important. The use of computer simulation goes as far back as World War II. When Jon von Neumann and Stanislaw Ulam, a pair of mathematicians [82], needed to understand the behavior of neutrons, they still had the option of choosing between digital and analog computers [83]. Starting in the late 1940's computers began to see commercialized production, as many innovations from the war began to see commercial use. At that time computers were still too slow to make simulation much use to any company. The attempts to use simulation in the 1950's resulted in ambiguous results at the expense of a considerable amount of personnel and mainframe time [84]. It wasn't until 1961 that IBM introduced the "Gordon Simulator" to Norden, a systems design company. At the end of 1961 Geoffrey Gordon presented his paper on general purpose systems simulators, which led to the style of simulation used today [1]. Shortly after this, simulation groups were established at places of note such as [84]:

- Boeing
- Martin Marietta,
- Air Force Logistics Command,
- General Dynamics
- Hughes Aircraft
- Raytheon
- Celanese
- Exxon
- Southern Railway
- IBM
- Control Data
- National Cash Register
- UNIVAC

Through the 1960's, activity in simulation was dominated by the development of computer simulation languages. During 1967 the first Conference on the Application of Simulation using the General Purpose Simulation System was held. This annual conference would be a major driving force in the refining and propagation of simulation technology and techniques.

The fifth conference was the first to be titled the Winter Simulation Conference, which is still held to this day [1].

Simulation and computer technology continued to evolve and spread through the 1970's. In 1977 the Winter Simulation conference had a showing of forty sessions which included sessions on military and agricultural simulation, compared to the twelve sessions held in 1967. This number continued to grow through the decade [1]. The 1980's presented two major challenges to the use of simulation. First, the level of complexity required by simulation seemed to indicate that it would only be usable by experts. Secondly, the time required to use simulation was very intensive due to the quantity of programming and debugging that was required [83]. This was in addition to the cost, which could easily reach $50,000 U.S. [1]. These concerns were eventually dispelled with the advent of SIMAN, a programming language that employed a simplistic menu driven framework that allowed even novices to create simulations [80].

The 1990's saw simulation grow into a powerful and accessible tool. Software evolved to the point that simulations could be developed with almost no programming knowledge. Concurrently, the power of personal computers reached a level where they were capable of accurately modeling very complex systems. The advance of simulation programs continues even today as computers become more powerful, expanding what has become a widely accepted and influential tool.

5.2 The Use of Simulation Within Life Cycle Assessment

Life cycle assessment is a holistic approach that must integrate a total understanding of the life of a product and the process of production. Without an understanding of the life of a product, informed decisions cannot be made to improve the product and associated processes. However, it is a rare company that has a single person responsible for understanding how the entire production process works, much less the life of the product after it has been purchased. The creation of a computer model lends itself to building this needed understanding and is another reason to use simulation within life cycle assessment [80].

The use of simulation in life cycle assessment can be of great help to both inventory assessment and impact assessment. Simulation can be used to freely alter variables that cannot be easily changed in reality. Changing a variable in seconds within a simulation could take weeks or thousands of dollars in reality. These rapid changes allow many different scenarios to be considered and weighed in a relatively short amount of time. In some cases, the model may predict unintended consequences that would make a course of action undesirable. For example, a small change in the simulation could be observed to not only decrease the production of harmful gases, but also decrease the amount of product created. This option might be unacceptable, especially compared to another choice that drastically increases production while leaving air emissions the same. The ability to compare these options within a single framework is of great importance. Using a common framework, evaluators may freely change variables to represent competing plans to optimize the environmental impact of their products and systems. The structure of the framework allows users to objectively compare the possibilities.

The least standardized step of the life cycle assessment is the impact assessment, because it is where subjective influences are most prevalent. There are many methods that are currently in use to conduct impact assessment. These methods can place different levels of importance upon certain factors, or use highly different methods to reach similar, though not always identical, conclusions. As such, it would be beneficial to have an environment in which the parameters of a model could be easily changed to reflect differences in the underlying methodology and assumptions being applied. A simulation can be created and modified to compare more than one impact assessment method and to reconcile differences between the methods.

CHAPTER 6

PROBLEM STATEMENT

Rather than seeking to remedy a specific problem with the methodology of life cycle assessment, this work attempts to improve upon life cycle assessment with the introduction of computer simulation tools. Currently, life cycle assessment is a time intensive study that requires massive quantities of data and work. After the study has been completed, the findings may be contested by groups that disapprove of assumptions made within the study. These accusations are detrimental to the acceptance of life cycle assessment, and are difficult to rebuke with conventional methods due to the cost and time required to modify portions of the assessments.

6.1 Statement of Goals

The goal of this work is to show that the use of simulation in conjunction with life cycle assessment can lead to a more adaptable and defendable final product when compared to the use of simple mathematical calculations. To prove the feasibility of this concept, a simulation enhanced life cycle assessment must demonstrate both the validity and the adaptability of the life cycle's simulated model.

Proving that it is possible to simulate, even roughly, the life cycle of a product is an important step that cannot be overlooked. Without a valid model, any information gained through the use of the simulation is highly suspect. With a valid model, focus can be moved on to the next step of proving feasibility.

Creating a life cycle model is an in-depth process that requires a serious investment in time and energy. Moving it to the next step, a model that can be adapted easily takes a measure of foresight and some planning when creating the initial model. Adaptability relies on the ability of the model to be changed in specific ways without severely impacting facets of the model that are not related to the changes. Keeping variables separate and leaving modules open for modification allow for rapid adaptation of an existing model to defend against accusations, or to allow for a sensitivity analysis. The adaptability of a computer model is far superior to that of repeatedly performing mathematical calculations by hand or running them through a program, one step at a time.

To prove these points, examples of computer simulation enhanced life cycle assessment are used. A contested real world life cycle assessment is used as a basis for these examples. This displays both the adaptability and validity of the models as a means of proving the feasibility of this method.

6.2 Tools Available

Computer aided simulation is a growing field of study, one that is finding use in many new areas through continuing research. The potential benefits of simulation to life cycle assessment have been covered previously in Chapter 5. Computer simulation is the primary tool used in this study. In addition to Rockwell Automation’s Arena software, Microsoft Excel was an important tool in the identification of important data and the verification of the computer simulation.

6.3 Problem Introduction

In 2005 the Environment Agency of the UK released a comparative study of life cycle assessment of home washed reusable diapers, disposable diapers, and reusable diapers cleaned by a laundry service. Figures 1, 2 and 3 show the graphical representation of the computer models created to mimic the British study. The British team found that there was essentially no difference between the three choices except that each choice exhibited its primary impact at a different time. The primary cost of using disposable diapers was seen in the creation phase, while the primary costs of reusable diapers were attributed to their cleaning phase over the course of their life. The study compared the life cycles of each choice, taking the inventory assessment for each and using a database called WISARD to obtain equivalency factors for the impact assessment. The impact assessment focused on nine separate areas of environmental effect:

- Abiotic Resource Depletion
- Global Warming
- Ozone Layer Depletion
- Photochemical Oxidation
- Acidification
- Eutrophication
- Human Toxicity
- Fresh Water Aquatic Ecotoxicity
- Terrestrial Ecotoxicity

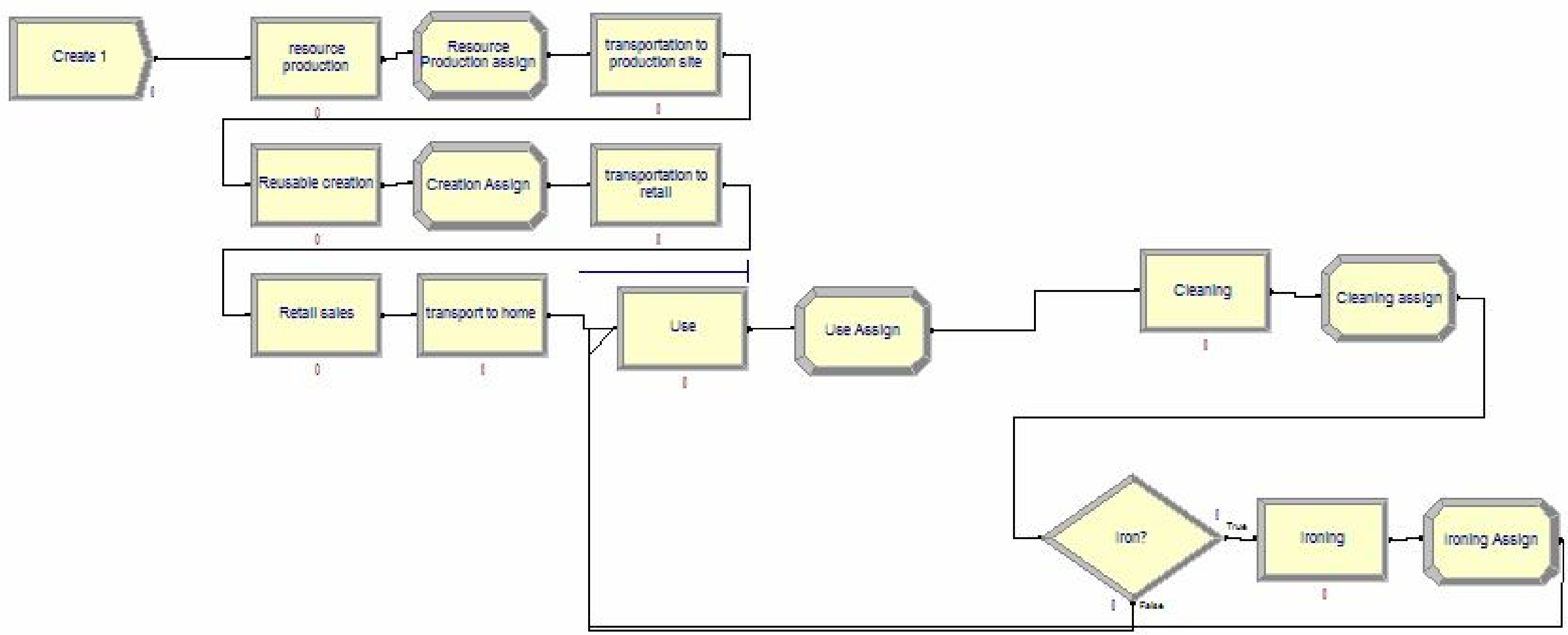

Figure 1 Home laundered diapers

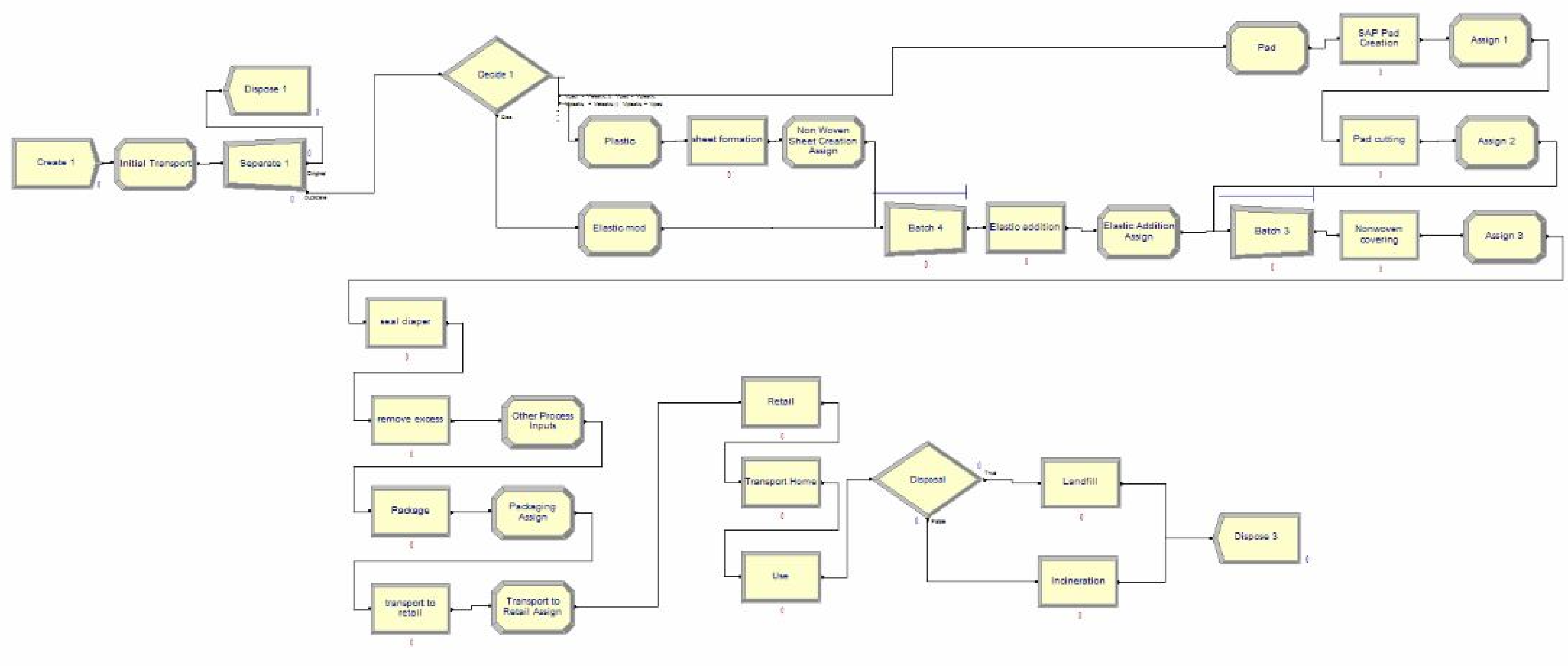

Figure 2 Disposable diaper model

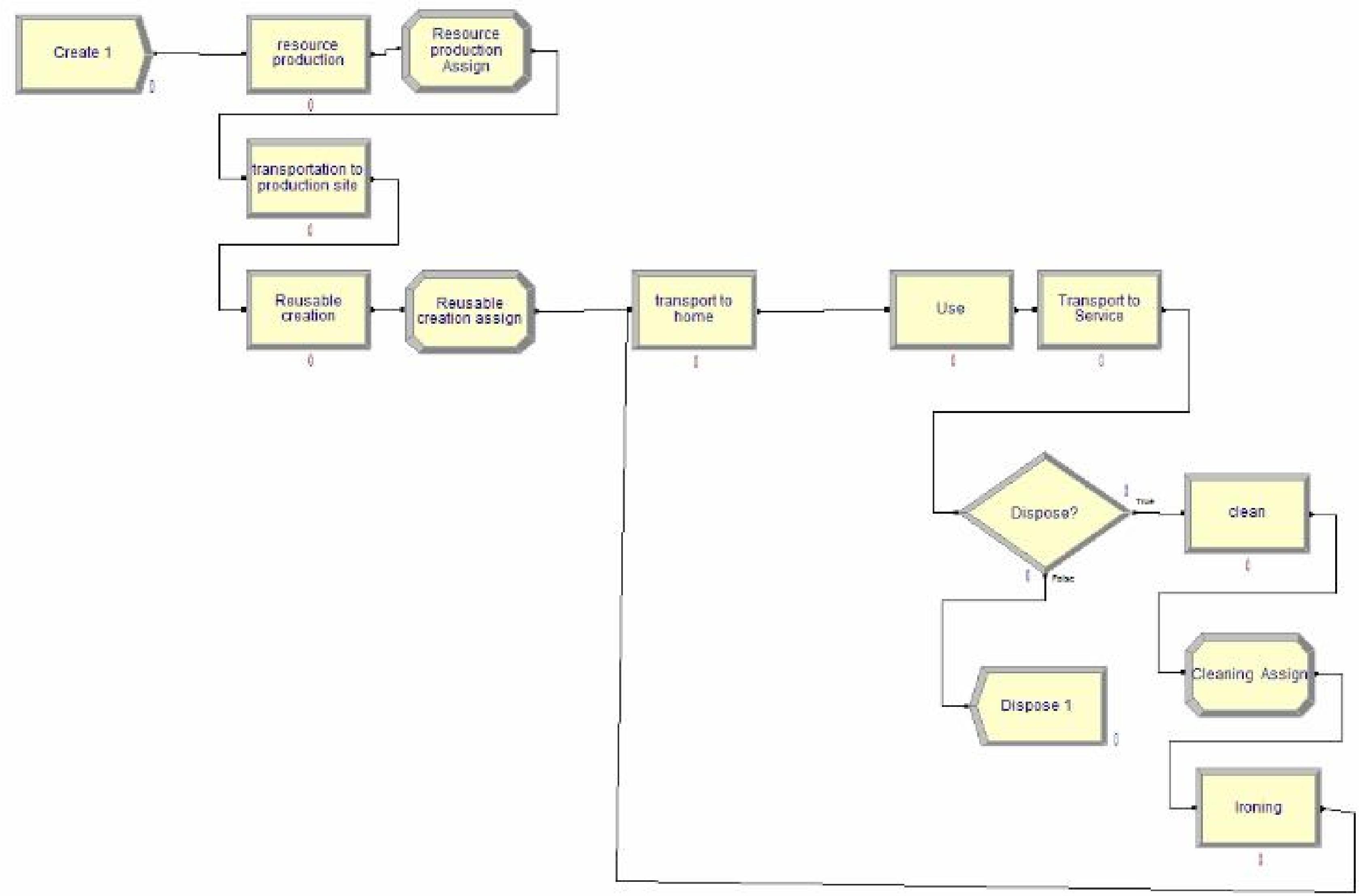

Figure 3 Service laundered diaper model

The British team took the data collected in the inventory assessment and divided them by their effect on each of these nine categories. Those values were then multiplied by an equivalency factor to convert and combine all the flows into one aggregate flow that impacts the environmental categories above. Following the compilation of the flows into their equivalent flow for each impact category, the mass of each category from each choice is compared. The importance of each impact category was taken into account during this comparison. Based on that comparison, the British team found that there was no significant reason to favor any one method over the other two. [86]

CHAPTER 7

METHODOLOGY BEHIND THE DESIGN OF THE ANALYSIS SYSTEM

Within life cycle assessment, the analytical portions of inventory assessment and impact assessment are the most data intensive [9]. They are also the most useful when trying to understand the flow and creation of waste and products. With this in mind it makes sense to address inventory assessment first. The best way to represent the components of a system is through a flow chart [10]. This is desirable because of its ease of interpretation and because it is the basis for the graphical user interface of the program used to create a working example problem. An example of the final result of such a flow chart may be seen in Figure 1.

Following the initial layout of the system to be studied, values are entered for the input and output of raw materials, energy, air emissions, waste, and other similar flows and residues. These inputs and outputs should not be immediately aggregated upon the completion of the simulation, since aggregated data can mask site specific variations [14]. Before moving on to the addition of impact assessment data, the model should be tested and verified. This is for simplicity's sake, as the base model will be easier to verify and debug before it is fully loaded with the extra information associated with impact assessment.

The verification of the model is vital to assuring the accuracy of the model. When data are available from a system it is often advisable to test the output of the model by comparing it to the actual system information. A model can be verified in its implementation by reporting results that are close to actual system data. Accordingly, it can be said that the model is a valid representation of the system [85].

7.1 Basics of Simulation with Arena™

Arena™ is a highly versatile simulation package that allows for modular design of simulations with a minimum knowledge of programming languages. As such, it is well suited for use by those with minimal knowledge of computer programming and a basic grasp of the simulation methods used in Arena™.

Figures 1 through 4 are images captured directly from the Arena™ models; the basic form of an Arena™ simulation appears to be a simple flow chart. This design controls the direction of how "entities", the program's term for an individual unit, flow through the system. The models created to illustrate a product's life cycle consist of five separate modules, separate sections that control specific portions of the model's logic.

The first module used in each of the simulations is the "create" module. This portion of the model controls the production rate of new entities, which will then flow through the rest of the system. These entities then flow into a "process" module, which controls actual activities performed. These modules are used to simulate individual processes such as the production of super absorbent polymer (SAP) pads. Following process modules, there is typically an "assign" module. When an entity passes through this module, information on resource consumption and waste creation is added to a tally that is connected to the module it passed through by naming conventions. When there are several possible routes for an entity, such as in Figure 4, a "decide" module is used to split the flow of entities with either a deterministic or stochastic method. Finally, when it comes time for an entity to be disposed, a “dispose” module is useful. This module simply removes entities from the simulation, but leaves the data generated by them during their travel through the simulation.

7.2 Application of the Analysis System

Based upon the basic concepts of modeling and simulation presented above, an application of these methods for life cycle assessment may be presented. To illustrate the proposed concepts, a well-documented life cycle analysis case has been integrated into the proposed structure.

7.3 Creating the Simulated Examples

Based on data published in the British study, “Life Cycle Assessment of Disposable and Reusable Nappies in the UK”, computer models were developed as proposed above. The simulations, conducted using Rockwell Automation’s Arena software package, were designed around the system diagram outlines and inventory analyses performed for each of the alternative diaper choices. For purposes of comparison, the model systems were constructed to mimic the designs used by the British team. The decision was made to keep the computer simulations as close in design to the original method as possible for comparison purposes. Additionally, options were kept open to allow changes to be made to highlight the flexibility of the system.

After the base systems were designed, additional sections of the model were added to assist in the inventory assessment of the systems. The simulations model the flow of entities through their systems. (Arena refers to each discrete item that moves through the system as an “entity”). New entities are added to the systems by an Arena “create module.” As entities flow through the systems, they may be assigned “costs” by a component within Arena called an “assign module.” As the number of entities and their assigned costs increase, representing the production of new diapers, values representing the various waste flows accumulate. These waste variables are tracked through the use of variable text boxes. These text boxes total the individual waste variables as they increase entity by entity. The creation of a diaper entity illustrates this creation and tallying process. When a diaper passes through the create process module and the subsequent assign module the “cost” of a waste variable such as “WaterUsage” is increased.

To validate the model, the figures provided by the simulations were collected and compared to the values obtained by the British team in 2005. Because both sets of numbers were obtained from using roughly the same set of starting numbers, it is to be expected that they are similar when compared. The difference between the two number sets can be seen in Tables 4, 5, and 6. This slight difference is explained by accumulation of rounding errors through the various steps of the simulations. The computer models were further validated by independently running calculations in Microsoft Excel™. The validation mimicked the number sets found in both the Arena™ simulations and the British team’s inventory analyses. The validation of the work through Excel was performed by cross referencing the work performed by the British team and their process figures, and checking the figures of the Excel version against the simulations and British study.

	Simulation Data	Original Data	Units
Fluff Pulp	72.11	72.17	kg
SAP	52.48	52.53	kg
PP	24.45	24.47	kg
PE	19.72	19.74	kg
Adhesives	5.30	5.30	kg
Calcium Carbonite	3.74	3.74	kg
PDT PET	2.25	2.25	kg
Tape	1.78	1.78	kg
Electricity	114.14	114.25	kWh
Gas	8.42	8.42	kWh
Water	74.54	74.61	L

Table 4 Comparison of disposable diaper results

USE		Simulation Data	Original Data	Units
Electricity	Wash	391.70	391.70	kWh
	Dry	68.31	68.60	kWh
	Iron	4.98	4.70	kWh
Water				
	Wash	21379.99	21380.00	L
Softener		15.27	15.27	kg
Detergent		31.31	30.79	kg
CREATION				
Mfg. Chemicals		0.76	0.79	kg
Water		99.36	99.50	kg
Electricity		9.98	9.91	kWh
Natural Gas		62.08	62.20	kWh

Table 5 Comparison of home laundered diaper results

Creation	Simulation Data	Original Data	Units
Hydrogen peroxide	1.17	1.16	kg
Water	167.90	166.50	kg
Grid Electricity	204.28	202.50	kWh
Natural Gas	42.19	41.83	kWh
Cleaning			
Electricity	330.35	331.60	kWh
Natural Gas	1089.38	1093.50	kWh
Water	16036.27	16097.00	kg
Detergent	6.08	6.10	kg
Sodium Perborate	2.47	2.48	kg
Sodium Hypochlorite	2.82	2.83	kg
Neutrilizer	1.06	1.07	kg

Table 6 Comparison of diaper service results

7.4 Stochastic Modeling Applied to Life Cycle Assessment

Reality is not a single deterministic set of data. It is a stochastic process that changes as time progresses. The ability to show this through simulation can substantially enhance the realism of life cycle assessment. Realistically modeling stochastic variables is an important aspect of computer simulation because it allows for a more lifelike range of inventory assessment data to be characterized, thus allowing for a more realistic life cycle assessment to be performed. In addition to keeping the model true to reality, the use of variables results in a range of possibilities that show the tendencies of a system. This means that a study that uses stochastic data is more likely to be able to describe or predict behavior of a highly variable system, a task that is difficult for traditional life cycle assessment [19].

7.4.1 Home Laundered Stochastic Example

The British study did not include characterization of random variations within the process. That capability is a significant benefit offered by simulation techniques. To illustrate the stochastic ability of computer simulation, consider Figure 1, the flow chart of how cloth diapers are made, used, and washed at home. In this system a large amount of energy is used during the cleaning phase when the diapers are washed. Because there was no clear leading temperature that diapers were washed at an average number was derived and used to calculate the energy used in washing. Using the Arena™ model and information obtained from the British study it was possible to create Figure 4, whith a stochastic process to determine at what temperature the diapers will be washed. Table 7 shows the percentage of parents surveyed that used each temperature range, which was used to create a probability for each diaper to be washed at a different temperature.

Arena™ uses the data in Table 7 to use a random water temperature on each diaper washed, the random nature of this data is based off the distribution shown. This method shows less than half a per cent difference than using an alternative method where the simulation is run with each temperature individually and the related inputs are tallied separately.

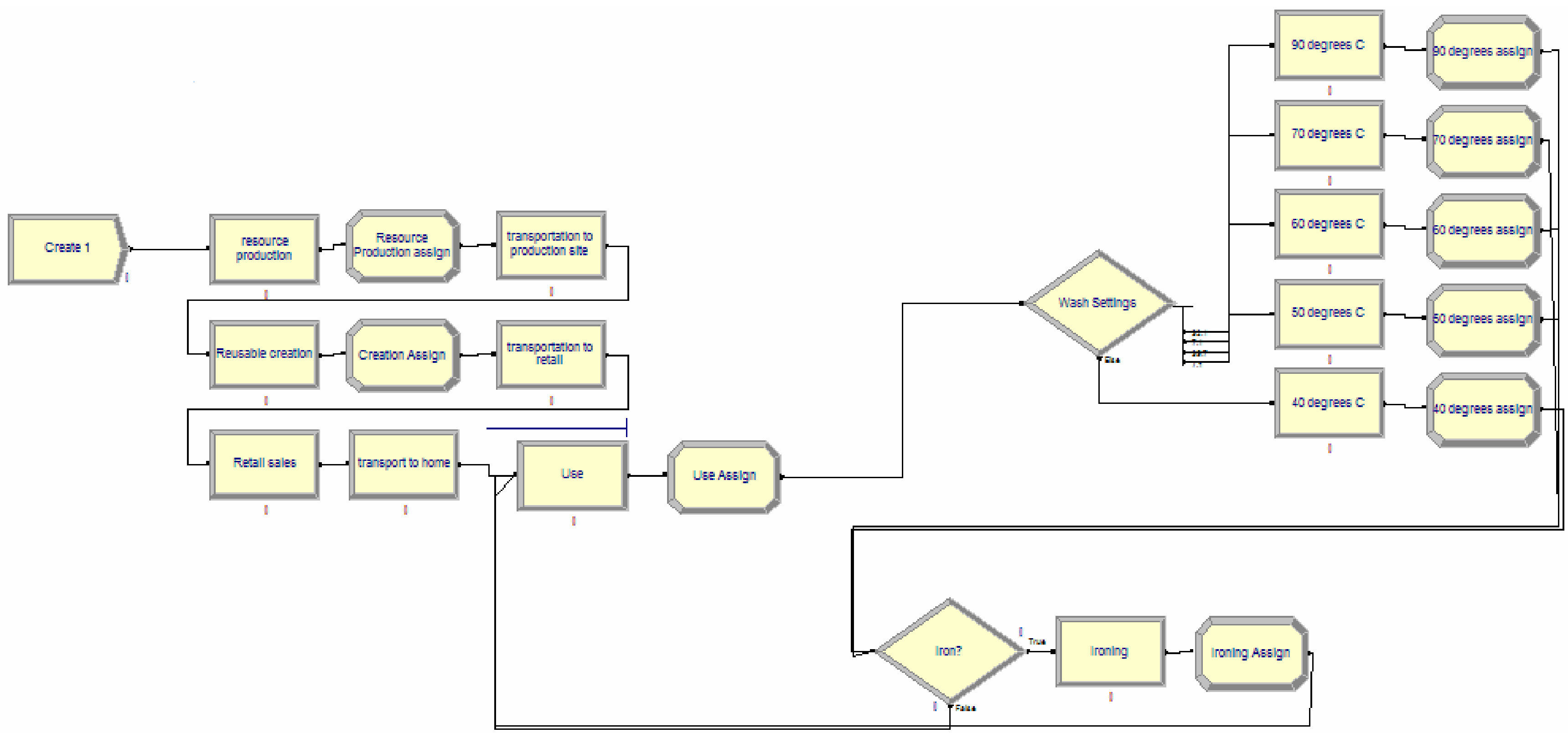

Figure 4 Modified home laundered diaper model

Temp.	Probability	Quantity	Units	St. Dev.
90° C	32.1%	1.77	kWh	0.177
80° C	0.0%	1.63	kWh	0.163
70° C	7.1%	1.5	kWh	0.15
60° C	35.7%	1.36	kWh	0.136
50° C	7.1%	1.09	kWh	0.109
40° C	17.9%	0.82	kWh	0.082
Average per load		1.38	kWh	

Table 7 Washing machine simulation inputs

7.4.2 Service Laundered Stochastic Example

Continuing the conversion of the original deterministic models leads to the modification of the diaper cleaning laundry service simulation into a stochastic simulation. The graphical display of the system may be seen in Figure 3. This flow chart of the product's life cycle is considered to be identical for both the deterministic and stochastic models. This is because there is no place in the life of the product that would benefit from increasing the size of the model, the "assign" modules alone give the power to add or alter variables used in the inventory assessment or impact assessment. The modifications made to this simulation are all based on the simulation's area of greatest environmental impact, the repeated laundering of diapers. This choice was made because any changes in the creation of the diaper or in the harvesting of its raw materials would be minor in comparison to the amount of water and electricity consumed by the repeated use and cleaning cycle.

With this in mind, one of the first changes made to the computer model was the modification of the detergent variables. The modified simulation used uniform distributions on the detergent powder, sodium perborate powder, sodium hypochlorite, and neutralizer, instead of using deterministic numbers. Uniform distributions, also known as rectangular distributions, give each number in a given rage the same probability of being used. Sadly, obtaining new real world data was not an option. Because of this, high and low bounds for the four variables where chosen to be 10% and 15% higher and lower than the data given by the British study. The values used for this example are shown below in Table 8.

	Lower bound	Higher bound	units
Detergent Powder	0.00099	0.00126	kg
Sodium Perborate Powder	0.00040	0.00051	kg
Sodium Hypochlorite	0.00046	0.00058	kg
Neutrilizer	0.00017	0.00022	kg

Table 8 New input for laundered diapers simulation

7.4.3 Disposable Diaper Stochastic Example

The next set of stochastic modifications were on the disposable diaper model. The life cycle of the disposable diaper can be seen in Figure 2, which was used for both the original and modified versions of the computer model. This is once again due to the flexibility of the “assign” modules, which allows for the change or addition of variables inside the model. The choice to leave the model’s form unchanged; was made because the system is so rigidly standardized.

Because of the nature of the disposable diaper, its greatest environmental impact area is the initial creation of the diaper itself. With this in mind, the stochastic modifications focused on the raw materials of the disposable diaper. In this way, the stochastic input for the raw materials would have a much greater impact on the end results. The modifications focused on four key raw materials used in the creation of the disposable diaper, super absorbent polymers (SAP), polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET). In this modification of the original simulation, a triangular distribution was used to further show the modifications that can be made through the use of stochastic modeling. The new values may be seen in Table 9.

	Lower bound	Midpoint	Higher bound
SAP	0.012	0.014	0.016
PE	0.005	0.005	0.006
PDTPET	0.001	0.001	0.001
PP	0.006	0.006	0.007

Table 9 New input for disposable diaper simulation

CHAPTER 8

RESULTS OF STOCHASTIC MODELING

8.1 Results of the Home Laundered Stochastic Model

As previously stated, the home laundered model was modified to account for several possible washing temperatures, and modified stochastic raw materials. The modifications can be seen in Tables 7 and 10. Table 7 shows the distribution of washing machine temperatures that was found through the 2005 study, while Table 10 shows the 2005 study's base data, the per cent decrease of each input per diaper, the resulting value per diaper, and an arbitrary standard deviation to provide a stochastic element to the simulation. The difference between the two is immediately seen upon the completion of the first simulation. Where the original study saw 391.7 kWh drawn to wash diapers, the stochastic addition to the model gives 422.8 kWh used, nearly an 8% overall increase in the energy consumption related to this step. The increased realism and predictive capability of the model is attributed to a better representation of the input variables. If subsequent sensitivity analyses conclude that wash temperature is an important factor, additional study of that aspect of the model may be justified. A more detailed review of the data can be seen in Table 11, which compares the data obtained in both simulations with that of the 2005 British study.

USE		Original Data	% decrease	per diaper	Std. Dev.	Units
Electricity	Wash	391.70	15%	0.06	0.00	kWh
	Dry	68.60	15%	0.06	0.00	kWh
	Iron	4.70	10%	0.01	0.00	kWh
Water						
	Wash	21380.00	5%	3.65	0.18	L
Softener		15.27	4%	0.00	0.00	kg
Detergent		30.79	5%	0.01	0.00	kg
CREATION						
Water		99.50	15%	1.76	0.09	kg
Grid Electricity		9.91	10%	0.19	0.01	kWh
Natural Gas		62.20	10%	1.17	0.06	kWh

Table 10 Home laundered diapers example modifications

USE		2005 Data	Deterministic Simulation	Stochastic Simulation	Units	% Difference
Electricity	Wash	391.70	391.7	332.95	kWh	15.00%
	Dry	68.60	68.31	58.06	kWh	15.36%
	Iron	4.70	4.98	4.41	kWh	6.17%
Water						
	Wash	21380.00	21379.99	20311.1	L	5.00%
Softener		15.27	15.27	14.67	kg	3.93%
Detergent		30.79	31.31	29.25	kg	5.00%
CREATION						
Mfg Chemicals			0.76	0.76	kg	
Water		99.50	99.36	84.57	kg	15.01%
Grid Electricity		9.91	9.98	8.92	kWh	9.99%
Natural Gas		62.20	62.08	55.98	kWh	10.00%

Table 11 Comparison between original and modified home

Further modification of the model also allows for stochastic data to be input for each of the five washing temperatures. The study upon which this work is based did not included actual data on the variation of energy consumption of washing machines used. Regardless, arbitrary values were used for the purposes of illustrating the application of stochastic computer simulation in this way. The standard deviations shown in Table 10 were then placed into the corresponding assign modules and the simulation was run again. The resulting energy consumption seen from the simulation was at 383.6 kWh, roughly a 2% decrease from what the original study recorded. As with wash temperatures, sensitivity analyses may be applied to the energy models to determine whether further data are required or if energy consumption can be safely estimated as a lumped parameter.

8.2 Results of the Service Laundered Stochastic Example

The modified simulation used uniform distributions on the detergent powder, sodium perborate powder, sodium hypochlorite, and neutralizer, instead of using deterministic numbers. Low and high bounds for the four variables where chosen to be 10% lower and 15% higher than the data given by the British study. Table 12 shows the output from the computer model compared to the data given from the original British study. The per cent difference between each variable is roughly + 2.5%, which is where the values would be expected for the uniform distribution used. This difference of + 2.5% is expected because there should be an equal amount of simulations that resulted in both +15% and -10%, this makes the average values shown in Table 12 correct at +2.5%.

	2005 Data	Deterministic Simulation	Stochastic Simulation	units	% difference
Detergent Powder	6.1	6.08	6.26	**kg**	2.6%
Sodium Perborate Powder	2.48	2.47	2.54	**kg**	2.4%
Sodium Hypochlorite	2.83	2.82	2.9	**kg**	2.5%
Neutrilizer	1.07	1.06	1.1	**kg**	2.8%

Table 12 Comparison of models and the British study

8.3 Results of the Disposable Diaper Stochastic Example

The modifications of this section focused on four key raw materials used in the creation of the disposable diaper – super absorbent polymers (SAP), polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET). The resulting information can be seen in Table 13. All of the results are within 2% of the British study's reported numbers. This slight increase in the overall use of raw materials is to be expected, this is because the values shown in Table 9 are weighted on the higher bound. The triangular distribution used in this method includes the same mid point as the original 2005 study, but also includes a lower and higher bound at 10% lower and 15% higher than the midpoint. Unlike the uniform distribution, where 2.5% was expected, the per cent difference should appear between the original mean and +2.5%.

	2005 data	Deterministic Simulation	Stochastic Simulation	Units	% difference
SAP	52.53	52.48	53.39	kg	1.6%
PE	19.74	19.72	22.79	kg	1.6%
PDTPET	24.47	24.45	24.86	kg	1.6%
PP	2.25	2.25	2.29	kg	1.8%

Table 13 Comparison of models and the British study

8.4 Impact Assessment

Impact assessments for the deterministic and stochastic inventory assessments of the three diapers types were performed following the accumulation of the initial data taken from the simulations. The impact assessment was done using the equivalency technique, where inventory items were converted into an equivalent amount of a chosen category indicator. For example, when considering global warming, all the impact factors are converted into specified amounts of CO_2 . The conversion factors were derived from Tables 14, 15, and 16 which are copies of the British study's impact assessments for the three diaper types. Because some items in these figures are aggregated, or unclear as to their exact composition, only the items that are individually represented are used to determine the equivalency factors.

Equivalency factors that allow the masses of emissions detailed in the inventory assessment stage to be converted into comparable environmental loading factors can be seen in Tables 17, 18 and 19. From here it is a simple matter to take the information gathered from the simulations and multiply it by the equivalency factors, resulting in Tables 20, 21, and 22. By comparing the numbers in each table it can be seen that both sets of simulated data are comparable to the data received from the 2005 British study, verifying the method used.

Impact Category	Unit	Fluff Pulp	SAP	PE	Adhesives	Adhesive Tape
Abiotic resource depletion	kg Sb eq	0.003	0.030	0.036	0.038	0.045
Global warming (GWP100)	kg CO2 eq	0.513	3.122	2.634	3.208	3.371
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.000	0.001	0.001	0.001	0.001
Acidification	kg SO2 eq	0.005	0.020	0.021	0.023	0.028
Eutrophication	kg PO4 eq	0.001	0.001	0.002	0.002	0.002
Human toxicity	kg 1,4-DP eq	0.035	0.198	0.041	0.415	0.169
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.025	0.002	0.001	0.002	0.000
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.001	0.015	0.010	0.008	0.011

Impact Category	Unit	PET	PP	Cardboard and Plastic Packaging	Electricty	Heat Gas
Abiotic resource depletion	kg Sb eq	0.031	0.041	0.051	0.005	0.002
Global warming (GWP100)	kg CO2 eq	4.444	3.515	2.058	0.639	0.238
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.001	0.001	0.000	0.000	0.000
Acidification	kg SO2 eq	0.062	0.038	0.024	0.003	0.000
Eutrophication	kg PO4 eq	0.000	0.002	0.001	0.000	0.000
Human toxicity	kg 1,4-DP eq	0.400	0.069	0.120	0.140	0.024
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.009	0.001	0.005	0.017	0.000
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.009	0.012	0.002	0.002	0.000

Table 17 Disposable diaper equivalency chart

Impact Category	Unit	Detergent	Softner	Mains water supply	Home electricity use
Abiotic resource depletion	kg Sb eq	0.018	0.004	0.000	0.005
Global warming (GWP100)	kg CO2 eq	2.403	0.262	0.000	0.675
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.000	0.000	0.000	0.000
Acidification	kg SO2 eq	0.019	0.003	0.000	0.003
Eutrophication	kg PO4 eq	0.004	0.000	0.000	0.000
Human toxicity	kg 1,4-DP eq	0.390	2.161	0.000	0.148
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.027	0.005	0.000	0.018
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.010	0.000	0.000	0.002

Table 18 Home laundered diaper equivalency chart

Impact Category	Unit	Laundry detergent	Perborate	Sodium hypochlorite
Abiotic resource depletion	kg Sb eq	0.0098	0.0121	0.0035
Global warming (GWP100)	kg CO2 eq	1.1475	1.6129	0.3534
Ozone layer depletion (ODP)	kg CFC-11 eq	0.0000	0.0000	0.0000
Photochemical oxidation	kg C2H2 eq	0.0002	0.0004	0.0000
Acidification	kg SO2 eq	0.0066	0.0121	0.0035
Eutrophication	kg PO4 eq	0.0005	0.0012	0.0000
Human toxicity	kg 1,4-DP eq	0.3279	0.0000	0.0000
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.0525	0.0081	0.0106
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.0016	0.0000	0.0035

Impact Category	Unit	Neutralizer	Heat gas	Electricity
Abiotic resource depletion	kg Sb eq	0.0000	0.0019	0.0029
Global warming (GWP100)	kg CO2 eq	0.0000	0.2096	0.3932
Ozone layer depletion (ODP)	kg CFC-11 eq	0.0000	0.0000	0.0000
Photochemical oxidation	kg C2H2 eq	0.0000	0.0000	0.0000
Acidification	kg SO2 eq	0.0000	0.0002	0.0016
Eutrophication	kg PO4 eq	0.0000	0.0000	0.0001
Human toxicity	kg 1,4-DP eq	0.0000	0.0229	0.0880
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.0093	0.0002	0.0105
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.0000	0.0002	0.0012

Table 19 Service laundered diaper equivalency chart

Impact Category	Unit	SAP	PE	PET	PP
Abiotic resource depletion	kg Sb eq	1.559	0.709	0.070	0.999
Global warming (GWP100)	kg CO2 eq	163.844	51.947	10.000	85.930
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.035	0.014	0.002	0.031
Acidification	kg SO2 eq	1.049	0.420	0.140	0.919
Eutrophication	kg PO4 eq	0.073	0.031	0.000	0.057
Human toxicity	kg 1,4-DP eq	10.390	0.799	0.900	1.699
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.120	0.020	0.020	0.030
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.789	0.190	0.020	0.290

Table 20a Deterministic disposable diaper impact assessment

Impact Category	Unit	SAP	PE	PET	PP
Abiotic resource depletion	kg Sb eq	1.586	0.820	0.071	1.016
Global warming (GWP100)	kg CO2 eq	166.685	60.034	10.178	87.371
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.036	0.016	0.002	0.031
Acidification	kg SO2 eq	1.067	0.485	0.142	0.935
Eutrophication	kg PO4 eq	0.074	0.036	0.000	0.058
Human toxicity	kg 1,4-DP eq	10.570	0.924	0.916	1.727
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.122	0.023	0.020	0.030
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.803	0.219	0.020	0.295

Table 20b Stochastic disposable diaper impact assessment

Impact Category	Unit	Detergent	Softner
Abiotic resource depletion	kg Sb eq	0.569	0.060
Global warming (GWP100)	kg CO2 eq	75.250	4.000
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.007	0.001
Acidification	kg SO2 eq	0.610	0.050
Eutrophication	kg PO4 eq	0.128	0.004
Human toxicity	kg 1,4-DP eq	12.203	33.000
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.844	0.080
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.305	0.000

Table 21a Deterministic home laundered diaper impact assessment

Impact Category	Unit	Detergent	Softner
Abiotic resource depletion	kg Sb eq	0.532	0.058
Global warming (GWP100)	kg CO2 eq	70.299	3.843
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.007	0.001
Acidification	kg SO2 eq	0.570	0.048
Eutrophication	kg PO4 eq	0.120	0.004
Human toxicity	kg 1,4-DP eq	11.400	31.703
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.788	0.077
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.285	0.000

Table 21b Stochastic home laundered diaper impact assessment

Impact Category	Unit	Laundry detergent	Perborate
Abiotic resource depletion	kg Sb eq	0.060	0.030
Global warming (GWP100)	kg CO2 eq	6.977	3.984
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.001	0.001
Acidification	kg SO2 eq	0.040	0.030
Eutrophication	kg PO4 eq	0.003	0.003
Human toxicity	kg 1,4-DP eq	1.993	0.000
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.319	0.020
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.010	0.000

Impact Category	Unit	Sodium hypochlorite	Neutrilizer
Abiotic resource depletion	kg Sb eq	0.010	0.000
Global warming (GWP100)	kg CO2 eq	0.996	0.000
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.000	0.000
Acidification	kg SO2 eq	0.010	0.000
Eutrophication	kg PO4 eq	0.000	0.000
Human toxicity	kg 1,4-DP eq	0.000	0.000
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.030	0.010
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.010	0.000

Table 22a Deterministic service laundered diaper impact assessment

Impact Category	Unit	Laundry detergent	Perborate
Abiotic resource depletion	kg Sb eq	0.062	0.031
Global warming (GWP100)	kg CO2 eq	7.184	4.097
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.001	0.001
Acidification	kg SO2 eq	0.041	0.031
Eutrophication	kg PO4 eq	0.003	0.003
Human toxicity	kg 1,4-DP eq	2.052	0.000
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.328	0.020
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.010	0.000

Impact Category	Unit	Sodium hypochlorite	Neutrilizer
Abiotic resource depletion	kg Sb eq	0.010	0.000
Global warming (GWP100)	kg CO2 eq	1.025	0.000
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000
Photochemical oxidation	kg C2H2 eq	0.000	0.000
Acidification	kg SO2 eq	0.010	0.000
Eutrophication	kg PO4 eq	0.000	0.000
Human toxicity	kg 1,4-DP eq	0.000	0.000
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	0.031	0.010
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.010	0.000

Table 22b Stochastic service laundered diaper impact assessment

8.5 Improvement Assessment

In a normal life cycle assessment, the impact assessment stage would be followed with an improvement assessment. However, because this simulation based life cycle assessment brings no new information or assumptions that strongly influence the outcomes there is no reason to expand upon the suggestions of the British team. An actual redesign of parts of the life cycles considered is also beyond the scope of this life cycle assessment. Redesign is not a part of life cycle assessment, rather an application of the information discovered through its use [10].

CHAPTER 9

COMPARISONS AND CONCLUSIONS

When comparing life cycle assessment aided through the use of computer simulation, one must compare not only the strengths and weaknesses of the chosen modeling platform, but also the requirements of the study as established by the goals and scope. Performing a life cycle assessment with too much information can be just as damaging and obfuscating as using too little data.

9.1 Capabilities of Simulation Enhanced Life Cycle Assessment

The current incarnation of computer simulation offers many capabilities and advantages not found in earlier versions of simulation software and beyond what is possible with traditional life cycle assessment methodologies. These capabilities arise from the development of increasingly powerful computer platforms.

The ability to quickly modify a life cycle system is a great advantage for the purposes of life cycle assessment. The easy modification allows for experimentation to occur. This affords analysts the opportunity to change the system in ways that reflect possible options determined in the impact assessment stage. Consideration of design alternatives allows for some prediction and comparison of the benefits gained through the use of these options. In addition to the use of the model as a method of prediction and testing ground for new ideas, the model can be used to perform sensitivity analysis. This allows analysts to vary certain input variables that feed the simulation to study how they affect the final output of the model. This can enhance understanding of the importance of specific input and output flows in the inventory assessment stage. In addition to these advantages, the ability to use stochastic information adds a new level of detail to the study. The use of stochastic input and output data in the inventory assessment stage results in a statistically likely range of answers rather than a single, deterministic valuation. This more closely mimics the natural variations of real systems and accounts for variables that cannot be controlled. In addition, the use of simulation is cost effective. It reduces burdens of time and funding when compared with alternative assessment methodologies.

The nature of simulation allows for it to be designed in a modular structure. This allows portions of a life cycle system to be created once and reused when needed. For example, the "material life cycle assessment" of a specific portion of a life cycle assessment, such as the creation of Portland cement material prior to its incorporation into a final use product, could allow for that portion of the simulation to be treated as an individual module. This would allow many life cycle assessments to bypass the design of certain parts of the study by using previously created and accepted modules [87]. This would eventually allow for more and more complex systems to be studied, a task that would be impossible without computer aid.

Finally, the use of advanced computer simulation programs allows for a superior visual representation of the life cycle of a product. The visual representation allows the process to be easily understood by clearly illustrating the steps involved in raw materials harvesting, production, use, re-use, disposal, and transportation. This understanding simplifies the task of educating policy makers and those with the power to effect the changes suggested in impact assessment.

9.2 Weaknesses of Simulation Enhanced Life Cycle Assessment

While there are many advantages to using computerized simulation methods in conjunction with life cycle assessment, there are some weaknesses inherent in the method. These weaknesses deal with the information and understanding required to create an adequate model, and the cost of the simulation software and training required to use the software. These difficulties must be considered and weighed against the requirements of the life cycle assessment that stands to benefit from the use of simulation. It is possible that a small study could be unnecessarily burdened by the use of extra technology.

The acquisition of data is often considered one of the most difficult parts of performing a life cycle assessment [40]. Though poor quality data may lead to unacceptable results in a traditional life cycle assessment, the use of a computerized framework for conducting the assessment makes the quality of the data that much more important. The classic adage “garbage in, garbage out” refers to the tendency to pump large amounts of poor data into a computer and to ignorantly expect those data to yield a meaningful answer. In the application of simulation techniques to the problem of life cycle assessment, due care must be taken to ensure that the value of the methodology is not undermined by poor quality data.

The overall cost of adopting simulation for life cycle assessment might be prohibitive for a small life cycle assessment, or a small company. In fact, depending upon the goals and scope of the life cycle assessment, there might be no need to go into the detail a simulation would provide when used. However, as simulation software and computer hardware becomes more powerful, the price of equipment needed to perform such life cycle assessments required by smaller companies should decrease. This, however, does not negate the cost or importance of appropriate training for those that will undertake the programming of the computer models.

9.3 Conclusions and Recommendations for Future Study

The pressure to embrace environmentally responsible business practices is mounting. The rewards of such practices are manifold and include societal, economic, and public image benefits [40]. This work has explored the possibility that simulation tools provide a unique framework for the comparison and evaluation of life cycle assessments. This use of simulation technology appears to be unique in the literature and offers significant potential to increase the effectiveness and objectivity of life cycle assessment. In so doing, it may increase the reliability and acceptance of life cycle assessment applications in industry.

The proposed life cycle assessment simulation technique has been illustrated in multiple examples through its application to a disputed life cycle assessment case using the Arena simulation package. These examples illustrate how simulation software can be used to characterize the environmental impact of a system as well as to predict the effect of changing variables within that system. The examples show that the current generation of simulation software is capable of presenting life cycle processes in a wide and encompassing scope, and that the models themselves can be altered with relative ease to accommodate challenges to assumptions and even update the data used within the model itself.

In the future it is perhaps possible that a truly complex item can be studied in this fashion. For example, a car is a complex piece of machinery requiring more construction processes than would ever be considered under anything but severely streamlined conditions. The use of simulation with life cycle assessment could lead to a gradual construction of such a massive life cycle assessment by the creation of modular simulations and life cycle assessments, studies that could be used as building blocks for future studies. Future research in modular simulation enhanced life cycle assessments could only help this goal.

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APPENDIX

Impact Category	Unit	Total	Fluff Pulp	SAP	PE	Adhesives	Limestone	Adhesive tape	PET
	%	61.500	4.900	33.600	15.400	4.300	0.000	1.700	1.600
Abiotic resource depletion	kg Sb eq	2.850	0.230	1.560	0.710	0.200	0.000	0.080	0.070
	%	61.200	7.900	35.200	11.100	3.500	0.000	1.300	2.200
Global warming (GWP100)	kg CO2 eq	286.000	37.000	164.000	52.000	17.000	0.000	6.000	10.000
	%	0.100	0.000	0.000	0.000	0.000	0.100	0.000	0.000
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	%	67.400	11.400	35.200	13.700	4.000	0.000	1.500	1.600
Photochemical oxidation	kg C2H2 eq	0.068	0.011	0.035	0.014	0.004	0.000	0.002	0.002
	%	59.500	10.300	29.100	11.600	3.300	0.000	1.300	3.900
Acidification	kg SO2 eq	2.150	0.370	1.050	0.420	0.120	0.000	0.050	0.140
	%	62.100	24.600	23.300	9.900	3.200	0.000	1.100	0.000
Eutrophication	kg PO4 eq	0.196	0.078	0.073	0.031	0.010	0.000	0.004	0.000
	%	42.300	6.200	25.700	2.000	5.500	0.000	0.800	2.100
Human toxicity	kg 1,4-DP eq	17.100	2.500	10.400	0.800	2.200	0.000	0.300	0.900
	%	12.600	6.500	4.200	0.700	0.500	0.000	0.100	0.600
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	1.970	1.800	0.120	0.020	0.010	0.000	0.000	0.020
	%	70.400	5.700	47.900	11.600	2.400	0.000	1.400	1.400
Terrerstrial ecotoxicity	kg 1,4-DP eq	1.150	0.090	0.790	0.190	0.040	0.000	0.020	0.020

Impact Category	Unit	Total	PP	Cardboard and Plastic Packaging	Transport	Electricty	Heat gas	Waste recycling	Waste disposal
	%	38.600	21.6	6.600	2.800	11.600	0.400	-3.500	-0.900
Abiotic resource depletion	kg Sb eq	1.790	1	0.300	0.130	0.540	0.020	-0.160	-0.040
	%	38.900	18.4	2.500	4.400	15.600	0.400	-2.900	0.500
Global warming (GWP100)	kg CO2 eq	181.000	86	12.000	20.000	73.000	2.000	-14.000	2.000
	%	99.700	0	2.900	75.300	8.300	0.100	0.000	13.100
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000
	%	32.700	30.9	0.300	3.000	1.900	0.100	-4.000	0.500
Photochemical oxidation	kg C2H2 eq	0.032	0.031	0.000	0.003	0.002	0.000	-0.004	0.000
	%	40.600	25.5	3.900	6.300	8.400	0.100	-3.400	-0.200
Acidification	kg SO2 eq	1.460	0.92	0.140	0.230	0.300	0.000	-0.120	-0.010
	%	37.900	17.9	1.100	13.700	7.400	0.100	-2.700	0.400
Eutrophication	kg PO4 eq	0.118	0.057	0.003	0.043	0.023	0.000	-0.009	0.001
	%	57.800	4.3	1.800	10.900	39.600	0.500	-0.900	1.600
Human toxicity	kg 1,4-DP eq	23.300	1.7	0.700	4.400	16.000	0.200	-0.400	0.700
	%	87.300	1.1	1.100	11.600	71.100	0.100	-0.300	2.600
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	2.360	0.03	0.030	0.310	1.930	0.000	-0.010	0.070
	%	29.600	17.4	0.400	0.600	13.700	0.100	-3.100	0.500
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.500	0.29	0.010	0.010	0.230	0.000	-0.050	0.010

Table 14 Disposable diaper conversion factors

Impact Category	Unit	Total	Terry towel manufacture	Sanitizer	Detergent	Liners	Softner	Mains water supply
	%	36.700	12.900	3.000	13.700	4.500	1.500	1.100
Abiotic resource depletion	kg Sb eq	1.490	0.530	0.120	0.560	0.180	0.060	0.040
	%	34.100	13.200	2.800	13.100	3.300	0.700	1.000
Global warming (GWP100)	kg CO2 eq	193.000	74.000	16.000	74.000	19.000	4.000	6.000
	%	41.600	5.500	11.700	21.500	1.000	1.600	0.300
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	%	36.500	7.100	4.100	14.000	9.300	1.700	0.300
Photochemical oxidation	kg C2H2 eq	0.017	0.003	0.002	0.007	0.004	0.001	0.000
	%	52.500	19.500	3.300	19.200	8.200	1.500	0.800
Acidification	kg SO2 eq	1.640	0.610	0.100	0.600	0.260	0.050	0.020
	%	53.400	10.200	1.600	37.700	2.100	1.200	0.600
Eutrophication	kg PO4 eq	0.178	0.034	0.005	0.126	0.007	0.004	0.002
	%	44.300	4.400	3.800	9.400	0.600	25.100	1.000
Human toxicity	kg 1,4-DP eq	58.000	6.000	5.000	12.000	1.000	33.000	1.000
	%	20.600	2.400	8.600	7.300	0.200	0.700	1.400
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	2.340	0.270	0.980	0.830	0.020	0.080	0.160
	%	32.000	4.700	3.800	19.800	2.200	0.300	1.200
Terrerstrial ecotoxicity	kg 1,4-DP eq	0.480	0.070	0.060	0.300	0.030	0.000	0.020

Impact Category	Unit	Total	Transport to retail	Consumer transport home	Home electricity use	Sewage treatment	Waste management
	%	63.600	2.200	3.500	57.100	1.100	-0.300
Abiotic resource depletion	kg Sb eq	2.590	0.090	0.140	2.330	0.040	-0.010
	%	65.800	2.300	4.500	56.100	1.800	1.100
Global warming (GWP100)	kg CO2 eq	368.000	13.000	25.000	314.000	10.000	6.000
	%	58.300	6.300	0.000	18.400	0.300	33.300
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000
	%	63.400	1.500	36.800	16.600	2.800	5.700
Photochemical oxidation	kg C2H2 eq	0.031	0.001	0.018	0.008	0.001	0.003
	%	47.600	2.300	3.000	41.700	0.800	-0.200
Acidification	kg SO2 eq	1.480	0.070	0.090	1.310	0.020	-0.010
	%	46.700	3.000	0.000	30.100	13.500	0.100
Eutrophication	kg PO4 eq	0.156	0.010	0.000	0.101	0.045	0.000
	%	55.800	2.100	0.000	52.700	1.000	0.000
Human toxicity	kg 1,4-DP eq	73.000	3.000	0.000	69.000	1.000	0.000
	%	79.300	2.600	0.000	73.300	1.400	2.000
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	9.040	0.300	0.000	8.350	0.160	0.230
	%	68.000	2.000	0.000	64.200	1.200	0.600
Terrerstrial ecotoxicity	kg 1,4-DP eq	1.040	0.030	0.000	0.980	0.020	0.010

* The methodology for fresh water aquatic ecotoxicity is not well developed and does not include characterisation factors for many detergent chemicals that are likely to pass through waste water treatment works unchanged. Work conducted by Procter and Gamble and CML (Jeroen Guinee and Arjan de Koning) suggest that the toxicity loading that would arise per wash would amount to 1.49 kg 1,4-dichlorobenzene eq (DCBeq). This would result in the aquatic toxicity increasing to more than 400 kg 1,4-dichlorobenzene for the nappy use system. Detergent use would therefore contribute 100% of the life cycle aquatic toxicity impact.

Table 15 Home laundered diaper conversion factors

Impact Category	Unit	Total	Prefold diaper manufacture	Wraps	Liners	Laundry detergent	Perborate	Sodium hypochlorite	Neutralizer
	%	22.000	16.200	1.000	3.200	1.000	0.500	0.100	0.000
Abiotic resource depletion	kg Sb eq	1.280	0.940	0.060	0.180	0.060	0.030	0.010	0.000
	%	23.600	18.400	1.300	2.400	0.900	0.500	0.100	0.000
Global warming (GWP100)	kg CO2 eq	181.000	140.000	10.000	19.000	7.000	4.000	1.000	0.000
	%	73.400	70.000	0.100	0.500	1.200	0.600	0.700	0.300
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	%	26.000	8.000	3.800	9.200	1.900	3.000	0.100	0.000
Photochemical oxidation	kg C2H2 eq	0.012	0.004	0.002	0.004	0.001	0.001	0.000	0.000
	%	48.700	34.200	3.100	8.400	1.500	1.100	0.300	0.100
Acidification	kg SO2 eq	1.480	1.040	0.100	0.260	0.040	0.030	0.010	0.000
	%	26.200	20.900	0.600	2.500	1.000	1.000	0.200	0.000
Eutrophication	kg PO4 eq	0.073	0.058	0.002	0.007	0.003	0.003	0.000	0.000
	%	29.100	26.500	0.100	0.600	1.300	0.300	0.200	0.100
Human toxicity	kg 1,4-DP eq	36.000	33.000	0.000	1.000	2.000	0.000	0.000	0.000
	%	38.600	35.100	0.100	0.200	2.700	0.200	0.200	0.100
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	4.500	4.090	0.010	0.020	0.320	0.020	0.030	0.010
	%	61.100	58.900	0.100	1.200	0.400	0.100	0.300	0.100
Terrerstrial ecotoxicity	kg 1,4-DP eq	1.640	1.590	0.000	0.030	0.010	0.000	0.010	0.000

Impact Category	Unit	Total	Heat gas	Electricity	Laundry vehicles	Home care	Mains water	Sewage Treatment
	%	78.000	36.700	27.200	8.500	4.000	0.800	0.800
Abiotic resource depletion	kg Sb eq	4.490	2.110	1.560	0.490	0.230	0.050	0.050
	%	76.300	31.300	27.600	9.800	5.400	0.800	1.400
Global warming (GWP100)	kg CO2 eq	581.000	238.000	210.000	75.000	41.000	6.000	11.000
	%	26.600	2.400	6.600	0.000	17.200	0.200	0.200
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	%	74.200	13.700	11.000	36.700	9.600	0.300	2.900
Photochemical oxidation	kg C2H2 eq	0.036	0.007	0.005	0.018	0.005	0.000	0.001
	%	51.200	8.700	28.700	7.000	5.200	0.800	0.800
Acidification	kg SO2 eq	1.570	0.270	0.870	0.210	0.160	0.030	0.030
	%	73.700	10.900	24.600	0.000	20.400	0.700	17.100
Eutrophication	kg PO4 eq	0.203	0.030	0.068	0.000	0.056	0.002	0.047
	%	71.000	20.900	37.700	4.700	5.500	1.100	1.100
Human toxicity	kg 1,4-DP eq	88.000	26.000	47.000	6.000	7.000	1.000	1.000
	%	61.200	1.700	48.100	0.400	8.200	1.400	1.400
Fresh water aquatic ecotoxicity	kg 1,4-DP eq	7.130	0.200	5.600	0.040	0.960	0.160	0.170
	%	38.800	8.200	24.400	0.600	4.200	0.700	0.700
Terrerstrial ecotoxicity	kg 1,4-DP eq	1.050	0.220	0.660	0.020	0.110	0.020	0.020

*The methodology for fresh water aquatic ecotoxicity is not well developed and does not include characterisation factors for many detergent chemicals that are likely to pass through waste water treatment works unchanged. Work conducted by Procter and Gamble and Leiden University (Jeroen Guinee and Arjan de Koning) suggest that the toxicity loading that would arise per wash would amount to 2.19 kg 1,4-dichlorobenzene eq (DCBeq) per laundry wash and 1.49 kg 1,4-dichlorobenzene eq (DCBeq) per home wash . This would result in the aquatic toxicity increasing to more than 100 kg 1,4-dichlorobenzene for the nappy use system. Detergent use would therefore contribute more than 90% of the life cycle aquatic toxicity impact.

Table 16 Service laundered diaper conversion factors

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