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The Potential of Life Cycle Assessment Tools in Sustainable Product Development

Master of Science Thesis in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2009
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Berkeley, CA, USA, 2009

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Chalmers Reproservice
Göteborg 2009

Acknowledgements

The Berkeley Expert Systems Technology (BEST) Laboratory was provided support for conducting this thesis. Financial support for the author as a visiting scholar/researcher at the University of California, Berkeley was partially provided by the Engineering Research Support Organization (ERSO).

The following people provided support throughout this thesis work:

- Prof. Alice M Agogino; provided supervision for this thesis from the University of California, Berkeley, USA.
- Lars Almefelt, PhD; provided supervision for this thesis from the Chalmers University of Technology, Sweden.
- Andreas Dagman, PhD; was the examiner for this thesis work from the Chalmers University of Technology, Sweden.

The author sincerely thanks the mentioned people and organizations for their continuous support for conducting this thesis work. The author also wants to thank the following people for their occasional support during this thesis.

- Sara Beckman, PhD, Haas School of Business, University of California, Berkeley
- Kimberly Lau, PhD student, University of California, Berkeley
- Lora Oehlberg, PhD student, University of California, Berkeley
- Corinne Reich-Weiser, PhD Candidate, University of California, Berkeley, Climate Earth Inc.
- Christine Rosen, PhD, Haas School of Business, University of California, Berkeley
- Tobias Schultz, MSc, University of California, Berkeley
- Ryan Shelby, PhD student, University of California, Berkeley
- Stefan Stetz, MSc, Chalmers University of Technology

Finally I would like to thank my friends and family for their support during the thesis and studies at Chalmers University of Technology, Gothenburg, Sweden and University of California, Berkeley, CA, USA, especially Grannaz.

Abstract

Sustainable design is one of the most important issues in new product development projects. The importance of environment friendly products is becoming more and more critical. This thesis work is focused on the role of computer tools in green design. After a brief literature review on sustainability and environmental friendly design, two different life cycle assessment methods are presented. The literature review follows by eight important areas of environmental impacts such as global warming, air pollutants and toxic releases. These eight areas conclude the theoretical framework of this thesis. The thesis continues by presentation of four computer tools that were studied during this research. The first one is the Climate Earth Enterprise Carbon Accounting which is a consultation package focused on carbon footprints of organizations. It prepares a deep analysis of CO_2 emissions generated by a firm and its supply chain. The second software called CES Eco Selector is a specialist version of the material selection software called CES selector. This tool delivers precise assessments of different environmental impacts based on the material and processes used in production of products. This tool helps engineers to substitute materials in their design in order to reduce their environmental impacts. The third software is a set of computer tools from Green House Gas Protocol Initiative, 19 different tools addressing green house gases in different activities or industries. These tools generate general assessments for promotional uses. The last computer tools studied in this thesis is a web-based offering from Carnegie Mellon University called Carnegie Mellon Economic Input Output LCA tool. This tool is capable of calculating the overall environmental impacts of each product throughout its supply chain in the entire economy. In addition a practical case study comparing asphalt and concrete road pavements represents the importance of comprehensive lifecycle assessments and shows how a partial assessment misleads efforts towards sustainability. The study continues by several comparisons between available tools. First each tool is compared by a set of criteria addressing important aspects of environmental impact assessment and afterwards cross-comparisons show the differences between these tools. Cross comparisons cover a wide range of assessments from simply the addressed environmental impacts to how well each tool assesses three different scopes of environmental impacts. A process mapping completes the comparisons during which these tools are mapped on a spiral product development process. By this mapping it is shown where and when each tool can be used during the product development process. When the inputs are ready and where the outputs can be used. After comparisons which show capabilities and limitations of tools, a discussion delivers the authors insights of current tools and future needs. Open insights like the need for hybrid life cycle assessment approaches or inclusion of lifespan of the products in comparing life cycle impacts of them will be presented here. The final chapter brings conclusions and recommendations for further research and developments. The need for further research on addressing imports and exports in economic input-output life cycle assessments is an example of recommendations brought in the final chapter.

Keywords: *Lifecycle assessment, LCA, sustainable product development, sustainable design, green design, environmental design, environmental impact assessment*

Table of Contents

1 Chapter One: Introduction ... 1
1.1 Background ... 2
1.2 Purpose ... 2
1.3 Research questions ... 2
1.4 Scope and limitations ... 3
1.5 Thesis roadmap ... 3
1.6 Report layout ... 4
2 Chapter Two: Literature Review ... 7
2.1 Introduction to literature ... 8
2.2 Sustainable product development ... 8
2.2.1 Concept of sustainability ... 8
2.2.2 Concept of green design ... 9
2.2.3 Importance of green design ... 9
2.3 Life cycle perspective on environmental impacts ... 9
2.3.1 Process LCA vs. Economic Input Output LCA ... 10
2.3.2 Waste hierarchy ... 11
2.4 Areas of focus in sustainability ... 12
2.4.1 Global warming ... 13
2.4.2 Acidification ... 13
2.4.3 Smog ... 13
2.4.4 Ozone layer depletion ... 14
2.4.5 Eutrophication ... 14
2.4.6 Habitat destruction ... 14
2.4.7 Land degradation ... 15
2.4.8 Depletion of minerals and fossil fuels ... 15
2.5 Literature summary ... 15
3 Chapter Three: Software, tools and methods ... 17
3.1 Introduction to tools and methods ... 18
3.2 Tools and Methods ... 18
3.2.1 Climate Earth Enterprise Carbon Accounting ... 19
3.2.2 CES Eco Selector ... 21
3.2.3 Green House Gas Protocol tools ... 23
3.2.4 Carnegie Mellon EIO-LCA Tool ... 25

3.3 Case study: concrete vs. asphalt 31
3.3.1 Basic economic data 31
3.3.2 EIO LCA analysis 32
3.3.3 Green house gases 32
3.3.4 Conventional air pollutants 32
3.3.5 Toxic releases 33
3.3.6 Energy consumption 33
3.3.7 Case study conclusion 34
3.4 Tools and methods summary 35
4 Chapter Four: Comparison and Analyses 37
4.1 Introduction to comparison and analyses 38
4.2 Individual comparison 38
4.2.1 Climate Earth ECA 38
4.2.2 CES Eco Selector 39
4.2.3 GHG protocol tools 39
4.2.4 Carnegie Mellon EIO-LCA 39
4.2.5 Individual comparisons matrix 40
4.3 Group comparison / cross comparison 40
4.3.1 Addressed impacts 41
4.3.2 Product development type vs. optimization method 43
4.3.3 Level of detail vs. level of optimization 44
4.3.4 Depth of analysis for different scopes 45
4.4 Mapping the tools on product development process 47
5 Chapter Five: Discussion 51
5.1 Available tools 52
5.2 The missing links 53
6 Chapter Six: Conclusion and recommendations 55
6.1 Conclusion 56
6.1.1 Research question one, available tools 56
6.1.2 Research question two, capabilities and Limitations 57
6.1.3 Research question three, use in product development process 58
6.1.4 Summary of conclusion 58
6.2 Recommendations 59

Table of figures

Figure 1: The roadmap of thesis in five phases 4
Figure 2: The three dimensions (pillars) of sustainability 9
Figure 3: Waste hierarchy 12
Figure 4: Cisco systems GHG emissions assessment (tons of CO_2e per year) 19
Figure 5: Life cycle carbon footprint breakdown for automobile manufacturing 21
Figure 6: CES Eco Selector two step methodology 22
Figure 7: Relative environmental burden of asphalt comparing to concrete 34
Figure 8: Relative ability of the computer tools to address different environmental impacts 43
Figure 9: Comparison on type of product development and optimization 44
Figure 10: Comparison on level of detail vs. level of optimization 45
Figure 11: Relative capabilities of each tool analyses on each of the three scopes of the impacts 47
Figure 12: Generic product development process 47
Figure 13: Mapping the tools on a generic product development process 48

1

Chapter One: Introduction

1.1 Background

Currently, there is great emphasis being placed upon reducing the environmental impacts associated with human activity in order to reduce the effects of catastrophic climate change. Unfortunately, information concerning sustainability and renewable energy technology is decentralized and unclear (CARES, 2009)[1].

Sustainable design is one of the most important issues in new product development projects. The importance of environment friendly products is becoming more and more critical. Previously, most of the research on sustainability was focused on recyclability of the products. A broader view considering the whole life cycle of the products has emerged recently. In this view, not only the post use phase of the products is being considered but also the use phase and even the production and pre production phases are being considered.

The new life cycle view on sustainability imposes the inclusion of tools in the early stages of new product development. It might be too costly or even impossible to reduce environmental impacts of a product if sustainability is not considered in its design from the beginning. It is important to make environmental impact assessment tools accessible for concept developers and designers in early stages of product development. Usually, early decisions create the most impacts on the products while the late changes make the least but are more expensive.

1.2 Purpose

The purpose of this thesis is; to find the currently available software and computer tools in sustainable design; to describe how each of them can be used and how they can be implemented during the process of new product development. This is an effort to show what computer tools are currently available for greening the products. The aim of this thesis is to introduce the useful computer aided green design tools, currently available in the market, to product developers to be practiced in development projects.

By conducting research on different computer tools, their capabilities and limitations, at the end, the thesis will propose different comparisons between computer tools to show how each tool can contribute to greening the products during the product development process. The comparisons show the product developers how each tool can be used and what each tool is good for.

1.3 Research questions

Three main research questions which this thesis intends to answer are:

1. What computer tools addressing environmental sustainability in product development are currently available for the engineers to use?
2. What capabilities and limitations do these computer tools have?
3. How they can be used in the process of product development?

1.4 Scope and limitations

There might be other tools on the market that are not addressed in this thesis. The limitations of this work did not allow the author to probe more and include other tools. There are different reasons behind this.

- The vendors did not respond to requests for information.
- The responses were not received in the time frame of this thesis.
- The author did not manage to find enough data about those tools in the resources.

The author worked on the thesis in the University of California, Berkeley as a visiting scholar. The available data was mostly for the United States. There might be other CAD tools for green design in Europe or other parts of the world that are not addressed in this thesis simply because of the limitations of access.

Since underlying methodologies and real capabilities of computer tools sometimes considered sensitive data by vendors, the analyses and included tools are limited to those which the required information was made available by the vendors. There were a number of architectural tools for designing green buildings. The author decides to exclude those tools from the scope of this thesis since they were less mechanical and more architectural.

This thesis was conducted during the winter and spring 2009 when the US economy was facing recession. Most of the companies limit their research activities and collaborations with universities. This fact creates more limitations on the availability of data needed for conduction of this thesis.

1.5 Thesis roadmap

In this thesis the following phases will be completed (see figure 1). In the *first phase*, a literature study will be done focusing on sustainability and lifecycle assessment. In the *second phase*, different tools for green design and their areas of applicability will be reviewed. In the *third phase* these tools will be compared together using case studies, benchmarking, etc. where possible. Having all of these phases complete in the *fourth phase* a matrix will be proposed mapping tools and areas for and at the end the *fifth phase* will complete this thesis by suggesting recommendations for use and further studies.

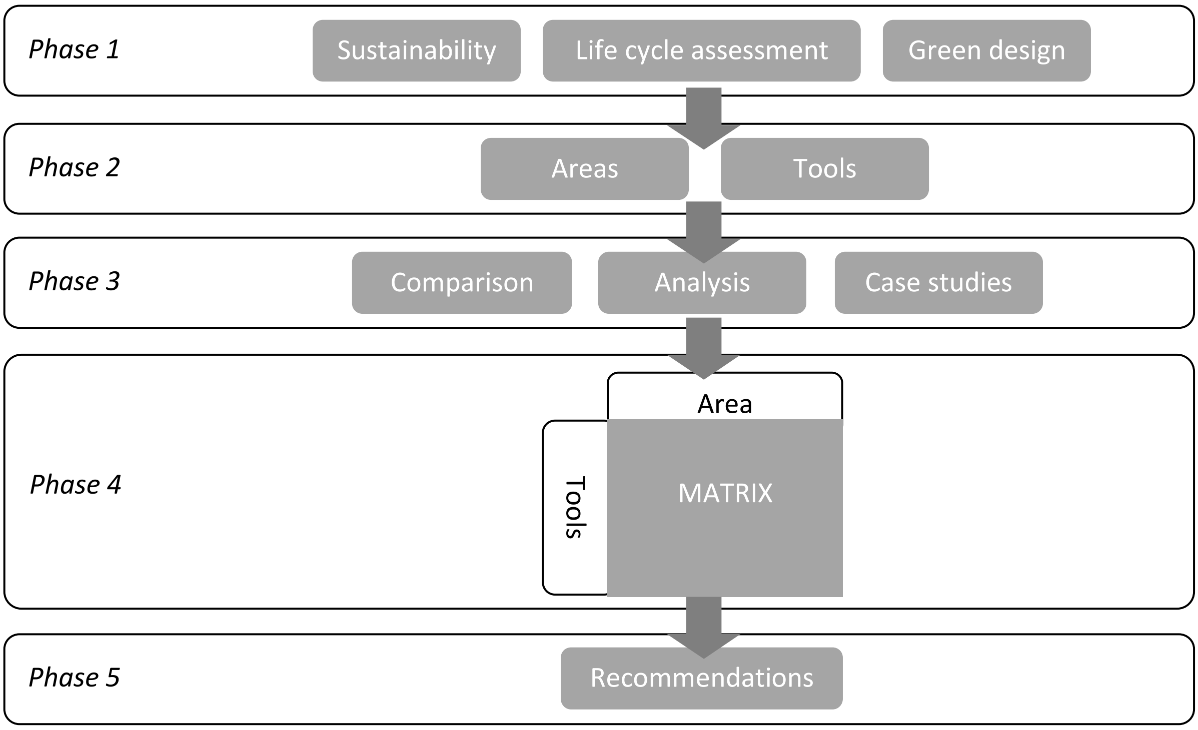

Figure 1: The roadmap of thesis in five phases

1.6 Report layout

The five phases of thesis roadmap represent the natural sequence of research steps during this thesis work. The layout of the report does not fit exactly on this natural sequence of steps. The chapters of this thesis and their contents meant to fit to the generic thesis chapters, from introduction and literature review to analyses and conclusions.

This chapter, the chapter one, includes the introduction to the thesis work. Most of the basic foundations like scope and limitations are presented here. After this first chapter on introduction of the thesis work and its basics, the chapter two continues by reviewing the literature. In chapter two, some fundamental information on theoretical framework of green design and environmental friendliness will be provided. Most of the literature is included in chapter two while more literature will be provided where needed during the later chapters. By completion of the fundamental principles, in the third chapter the author talks about software, tools and methods in the area of green and sustainable design. During this chapter each tool will be represented and pros and cons of each tool will be discussed. Chapter three contains a case study which clarifies some current issues in the software and tools and also put emphasis on some major issues in the studied tools.

After this, in the forth chapter these tools and software will be compared by different criteria. During this chapter the capabilities and limitations of each tool will be showed. The next chapter,

chapter five, provides the discussion of the author's findings, thoughts and suggestions. Finally in chapter six conclusion of this thesis work and author's recommendations will be provided. The appendices and references will be presented at the end.

2

Chapter Two:
Literature Review

2.1 Introduction to literature

As an opening to the research, in this chapter the need for sustainable product development will be presented as a foundation of this thesis work. Concept of sustainability and the role of design in creating sustainable products will be discussed. The environmental friendliness of the products will be described and then a common categorization of environmental impacts will be presented to highlight the focus areas for product developers to design greener products. The basic definitions in literature and the methodology in conducting this thesis work will be briefly described as well.

2.2 Sustainable product development

In order to define the sustainable product development or green product development some basic ideas need to be described. The concept of sustainability is an important notion as well as green design and its importance. These ideas will be described briefly as follows.

2.2.1 Concept of sustainability

Sustainability is defined in Merriam-Webster dictionary as "A method of using a resource so that the resource is not depleted or permanently damaged" (Merriam-Webster, 2009)[2]. The idea of sustainability dates back more than 30 years. It was a key theme of the United Nations Conference on the Human Environment in Stockholm in 1972. The concept was coined explicitly to suggest that it was possible to achieve economic growth and industrialization without environmental damage. In the ensuing decades, mainstream sustainable development thinking was progressively developed through the World Conservation Strategy (1980), the Brundtland Report (1987), and the United Nations Conference on Environment and Development in Rio (1992)(W.M. Adams, 2006)[3]. The Brundtland Commission quoted the definition of sustainable development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs (Smith and Rees, 1998)[4].

During years the sustainability has became the idea of three dimensions (see figure 2); environmental, social and economic sustainability (W.M. Adams, 2006). In this thesis work, only the environmental dimension of sustainability will be considered and the focus will be on different tools addressing it. The economic bases will be considered when needed but sustainability of the economy will not be studied. The social sustainability is totally outside of the limitations of this thesis and will not be discussed anymore. The following figure illustrates three dimensions of sustainability.

Although the other two pillars of sustainability will not be addressed during this thesis, they are interconnected. The environmental sustainability cannot be achieved without considering economic sustainability. Consider an environmentally sustainable source of energy that is so expensive to provide an economically sustainable mean of electricity generation. Obviously such a resource cannot be considered as "sustainable" because harnessing it will damage the economy and sooner or later people cannot afford to use it, hence it will be abandoned. On the other hand consider an environmentally sustainable method of living that endangers the foundations of a society. It might be a viable way of living from the environmental point of view but obviously a threat for the society. The society cannot sustainably continue by such a way of living, therefore abandons it to maintain its social sustainability. This thesis is focused on the environmental sustainability while is aware of the interconnectivities between social, economical and environmental sustainability. Areas of social and economical sustainability are in some ways relevant but out of the scope of this thesis work.

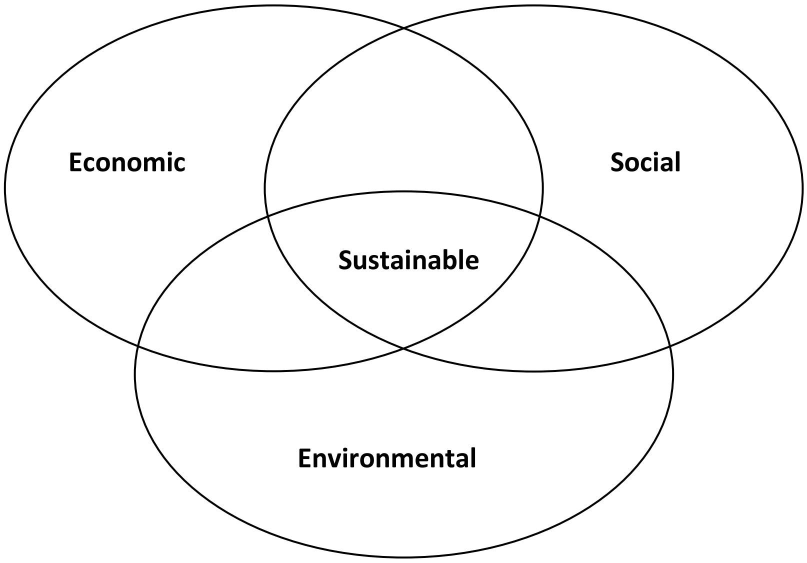

Figure 2: The three dimensions (pillars) of sustainability

2.2.2 Concept of green design

The intention of green design or sustainable design is to "eliminate negative environmental impact completely through skillful, sensitive design" (McLennan, 2004)[5]. A number of other terms are being used instead of green design in both literature and industry like environmental design, environmentally sustainable design (ESD), Eco-design and environmentally-conscious design. Although there are some differences between them literally, the general intention of all of them is the same.

2.2.3 Importance of green design

Shu-Yang et al. proposed that, global environmental crises, the rapid growth of economic activity and human population, depletion of natural resources, damage to ecosystems and loss of biodiversity imposed the need for sustainable design mostly as a general reaction. Within this context, eco-design is recognized as a strategy that can be applied to reduce the impacts associated with the production and consumption of products (Shu-Yang et al, 2004)[6].

2.3 Life cycle perspective on environmental impacts

A life cycle assessment is the investigation and evaluation of the environmental impacts of a given product or service caused or necessitated by its existence. It is a variant of an input-output analysis, focusing on physical rather than monetary flows. The goal of LCA is to compare the full range of environmental damages assignable to products and services, to be able to choose the least burdensome one. The term 'life cycle' refers to the notion that a fair, holistic assessment requires the assessment of raw material production, manufacture, distribution, use and disposal including all intervening transportation steps necessary or caused by the product's existence. The sum of all those phases is the life cycle of the product. The concept also can be used to optimize the environmental performance of a single product or to optimize the environmental performance of a company

Life cycle assessments are being done in a variety of ways (European commission, 2009)[7]:

1. Cradle-to-grave, which is the full Life Cycle Assessment from manufacture (cradle) to use phase and disposal phase (grave).
2. Cradle-to-gate, which is an assessment of a *partial* product life cycle from manufacture (cradle) to the factory gate, before it is transported to the consumer. The use phase and disposal phase of the product are usually omitted. Cradle-to-gate assessments are sometimes the basis for environmental product declarations (EPD).
3. Cradle-to-cradle, which is a specific kind of cradle-to-grave assessment, where the end-of-life disposal step for the product is a recycling process. From the recycling process originate new, identical products or different products.
4. Gate-to-Gate, which is a partial LCA looking at only one value-added process in the entire production chain.
5. Well-to-wheel, which is the specific LCA of the efficiency of fuels used for road transportation. The analysis is often broken down into stages such as "well-to-station" and "station-to-wheel, or "well-to-tank" and "tank-to-wheel".
6. Economic Input-Output LCA, which uses aggregate sector-level data on how much environmental impact, can be attributed to each sector of the economy and how much each sector purchases from other sectors.

2.3.1 Process LCA vs. Economic Input Output LCA

In a process-based LCA, one itemizes the inputs (materials and energy resources) and the outputs (emissions and wastes to the environment) for a given step in producing a product. So, for a simple product, such as a disposable paper drinking cup, one might list the paper and glue for the materials, as well as electricity or natural gas for operating the machinery to form the cup for the inputs, and one might list scrap paper material, waste glue, and low quality cups that become waste for the outputs.

However, for a broad life cycle perspective, this same task must be done across the entire life cycle of the materials for the cup and the use of the cup. So, one needs to identify the inputs, such as pulp, water, and dyes to make the paper, the trees and machinery to make the pulp, and the forestry practices to grow and harvest the trees. Similarly, one needs to include inputs and outputs for packaging the cup for shipment to the store, the trip to the store to purchase the cups, and that result from throwing the cup in the trash and eventually being land-filled or incinerated. Even for a very simple product, this process-based LCA method can quickly spiral into an overwhelming number of inputs and outputs to include. Now, imagine doing this same process-based LCA for a product such as an automobile that has over 20,000 individual parts, or a process such as electricity generation.

Two main issues arise with process-based LCA methods. One is defining the boundary of the analysis. The other main issue is circularity effects. In our modern world, it takes a lot of the same "stuff" to make other "stuff." So, to make the paper cup requires steel machinery. But to make the steel machinery requires other machinery and tools made out of steel. And to make the steel requires machinery made out of steel. Completing a broad, robust life cycle assessment thus requires many assumptions and decisions that make life cycle assessment a very complex and time consuming endeavor. This is where economic input-output LCA approaches enter and help simplify LCAs.

Economic input-output (EIO) models represent the monetary transactions between industry sectors in mathematical form. EIO models indicate what goods or services (or output of an industry) are consumed by other industries (or used as input). As an example, consider the industry sector that produces automobiles. Inputs to the automobile manufacturing industry sector include the outputs from the industry sectors that produce sheet metal, plate glass windshields, tires, carpeting, as well as computers (for designing the cars), electricity (to operate the facilities), etc. In turn, the sheet metal, plate glass windshield tire, etc. industry sectors require inputs for their operations that are outputs of other sectors, and so on. Each of these requirements for goods or services between industry sectors is identified in an EIO model.

EIO models are usually presented in matrix form where each row and each column represent a single industry sector, and the intersection of a row and column identifies the economic value of output from the row sector that is used as input to the column sector. In this form, EIO models have two helpful characteristics. First, EIO models indicate if output of an industry sector is required as input to the same industry sector (i.e., a value along the diagonal of the matrix is non-zero). For example the oil and gas extraction industry may produce the oil and gas to power its own facilities, Secondly, using some basic linear algebra techniques. , EIO models identify the direct, the indirect, and total effects of changes to the economy. Direct effects are the first-tier transactions, the transactions between one sector and the sectors that provide it output. Indirect effects are the second-tier, third-tier, etc. transactions, the transactions among all sectors as a result of the first-tier transactions. Total effects are the sum of direct and indirect effects.

The traditional economic input-output model indicating economic transactions between industries can be appended with information on emissions to the environment. In effect on EIO matrix, this creates an additional column representing "the environment" sector, and the value in each row represents the pollutant "output" from an industry sector that is "input" to "the environment" sector. Just as one can model how increased demand for output from one sector influences the output of other sectors, with an appended model one can also model how increased demand for output from one sector influences the output of pollutants to the environment.

This EIO-LCA approach eliminates the two major issues of boundary definition and circularity effects of process-based models. First, since transactions and emissions of all industry sectors among all other industry sectors are included, the boundary is very broad and inclusive. Second, since the self-sector transactions are included, circularity effects are included in the analysis (Carnegie Mellon Green Design Institute)[8].

2.3.2 Waste hierarchy

The waste hierarchy refers to the 3Rs of *reduce*, *reuse* and *recycle*, which classify waste management strategies according to their desirability. The 3Rs are meant to be a hierarchy, in order of importance in eliminating environmental impacts (Tim Lang, 2007)[9]. The aim of the waste management is to extract the maximum practical benefits from products and to generate the minimum amount of waste. Waste hierarchy (see figure 3) defines different levels of avoiding waste release to the environment.

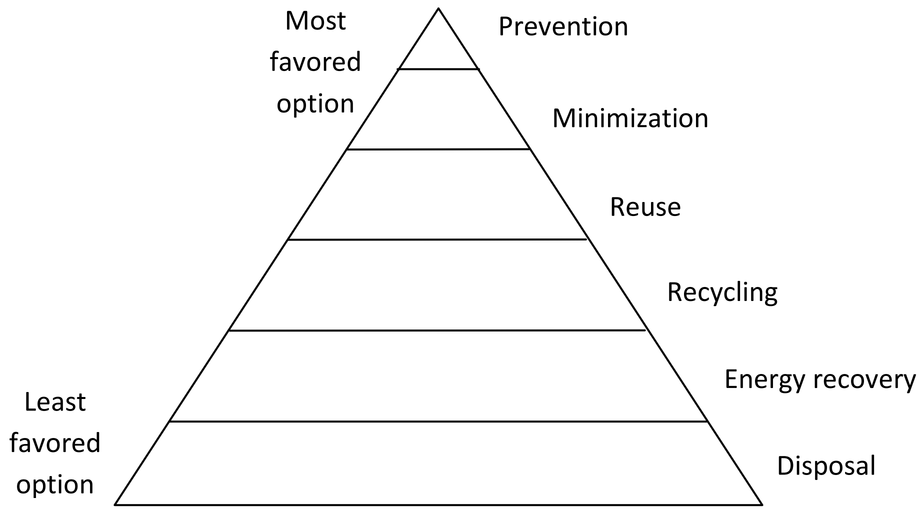

Figure 3: Waste hierarchy

2.4 Areas of focus in sustainability

Environmental impacts of the products can be categorized in many different ways. Exceptional emphasis on a particular area might be needed in a specific industry since certain environmental impacts might be dominant in those industries. N. Bey suggests the following generic categorization for life cycle assessment of products environmental impacts (Niki Bey, 2004)[10]:

1. Global warming
2. Acidification
3. Eutrophication
4. Smog
5. Abiotic resource depletion
6. Waste
7. Toxic emissions

Niki Bey didn't mention categories such as Ozone layer depletion, Habitat destruction and Land Degradation in his studies while these are among most important areas of focus for environmentalists. Moreover, the Abiotic resource depletion is a sub-category of the broader resource depletion which includes both biotic and abiotic resources. Each of these categories will be described briefly.

2.4.1 Global warming

Global warming is the increase in the average temperature of the Earth's near-surface air and oceans and its projected continuation. Global surface temperature increased 0.74 ± 0.18 °C (1.33 ± 0.32 °F) during the last century (Wikipedia, 2009)[11]. The Intergovernmental Panel on Climate Change (IPCC) concludes that greenhouse gases are responsible for most of the observed temperature increase since the middle of the twentieth century, and that natural phenomena such as solar variation and volcanoes probably had a small warming effect from pre-industrial times to 1950 and a small cooling effect afterward (IPCC, 2007)[12].

The greenhouse effect was discovered by Joseph Fourier in 1824 and first investigated quantitatively by Svante Arrhenius in 1896 (Spencer Weart, 2009)[13]. It is the process by which absorption and emission of infrared radiation by atmospheric gases warm a planet's lower atmosphere and surface. Naturally occurring greenhouse gases have a mean warming effect of about 33 °C (59 °F), without which Earth would be uninhabitable. The major greenhouse gases are water vapor (not including clouds) which causes about 36–70 percent of the greenhouse effect, carbon dioxide which causes 9–26 percent, methane which causes 4–9 percent and ozone which causes 3–7 percent (Kiehl and Trenberth, 1997)[14].

2.4.2 Acidification

Ocean acidification is the name given to the ongoing decrease in the pH of the Earth's oceans, caused by their uptake of carbon dioxide from the atmosphere (Caldeira and Wickett, 2003)[15]. Within the carbon cycle, there are two specific classifications;

1. The organic carbon cycle
2. The inorganic carbon cycle

The inorganic carbon cycle is particularly relevant when discussing ocean acidification for it includes the many forms of dissolved present in the Earth's oceans. When carbon dioxide dissolves, it reacts with water to form a balance of ionic and non-ionic chemical species. Dissolved free carbon dioxide, carbonic acid, bicarbonate and carbonate which acidify the earth oceans.

2.4.3 Smog

Smog is a kind of air pollution. The word "smog" is a short word for smoke and fog. Classic smog results from large amounts of coal burning in an area caused by a mixture of smoke and sulfur dioxide. Modern smog does not usually come from coal but from vehicular and industrial emissions that are acted on in the atmosphere by sunlight to form secondary pollutants that also combine with the primary emissions to form photochemical smog.

In the 1950s a new type of smog, known as photochemical smog, was first described. This forms when sunlight hits various pollutants in the air and forms a mix of unfavorable chemicals that can be very dangerous. Smog is a problem in a number of cities and continues to harm human health. Ground-level ozone, sulfur dioxide, nitrogen dioxide and carbon monoxide, all included in smog, are especially harmful for senior citizens, children, and people with heart and lung conditions (Wikipedia, 2009)[16].

2.4.4 Ozone layer depletion

The ozone layer is a layer in Earth's atmosphere which contains relatively high concentrations of ozone. This layer absorbs 93-99% of the sun's high frequency ultraviolet light, which is potentially damaging to life on earth. Over 91% of the ozone in Earth's atmosphere is present here. It is mainly located from approximately 10 km to 50 km above Earth, though the thickness varies seasonally and geographically. Ozone concentrations are greatest between about 20 and 40 km, where they range from about 2 to 8 parts per million. If all of the ozone were compressed to the pressure of the air at sea level, it would be only a few millimeters thick.

The ozone layer can be depleted by free radical catalysts, including nitric oxide, hydroxyl, atomic chlorine, and atomic bromine. While there are natural sources for all of these species, the concentrations of chlorine and bromine have increased markedly in recent years due to the release of large quantities of manmade halogens, compounds, especially chlorofluorocarbons (CFCs) and bromofluorocarbons. These highly stable compounds are capable of surviving the rise to the stratosphere, where chlorine and Bromine radicals are liberated by the action of ultraviolet light. Each radical is then free to initiate and catalyze a chain reaction capable of breaking down over 100,000 ozone molecules. The breakdown of ozone in the stratosphere results in the ozone molecules being unable to absorb ultraviolet radiation. Consequently, unabsorbed and dangerous ultraviolet-B radiation is able to reach the Earth’s surface (Wikipedia, 2009)[17].

2.4.5 Eutrophication

Eutrophication is an increase in chemical compounds containing nitrogen or phosphorus in an ecosystem, and may occur on land or in water. However, the term is often used to mean the increase in the ecosystem's primary productivity which means excessive plant growth and decay, and further effects including lack of oxygen and severe reductions in water quality, fish, and other animal populations.

Eutrophication was recognized as a pollution problem in European and North American lakes and reservoirs in the mid-20th century. Surveys showed that 54% of lakes in Asia are eutrophic, in Europe, 53%, in North America 48%, in South America 41% and in Africa 28%. Human activities can accelerate the rate at which nutrients enter ecosystems. Runoff from agriculture and development, pollution from septic systems, and other human-related activities increase the flux of both inorganic nutrients and organic substances into terrestrial and aquatic ecosystems. Elevated atmospheric compounds of nitrogen can increase nitrogen availability (Wikipedia, 2009)[18].

2.4.6 Habitat destruction

Habitat destruction is the process in which natural habitat is rendered functionally unable to support the species originally present. In this process, plants and animals which previously used the site are displaced or destroyed, reducing biodiversity. Agriculture is the principal cause of habitat destruction. Other important causes of habitat destruction include mining, logging, trawling and urban sprawl. Habitat destruction is currently ranked as the most important cause of species extinction worldwide (Wikipedia, 2009)[19].

2.4.7 Land degradation

Land degradation is a concept in which the value of the biophysical environment is affected by one or more combination of human-induced processes acting upon the land. Natural hazards are excluded as a cause however human activities can indirectly affect phenomena such as floods and bushfires. It is estimated that up to 40% of the world's agricultural land is seriously degraded. Land degradation is a global problem, mainly related to agriculture. The major causes include (Wikipedia, 2009)[20]:

1. Land clearance, such as clear-cutting and deforestation
2. Agricultural depletion of soil nutrients through poor farming practices
3. Livestock including overgrazing
4. Urban conversion
5. Irrigation and over drafting
6. Land pollution including industrial waste
7. Weeds
8. Walking tracks

Two renowned types of land degradation are desertification and deforestation

2.4.8 Depletion of minerals and fossil fuels

Resource depletion is a term referring to the exhaustion of raw materials within a region. Resources are commonly divided between renewable resources and non-renewable resources. Use of either of these forms of resources beyond their rate of replacement is considered to be resource depletion. Resource depletion is most commonly used in reference to the farming, fishing, mining, and fossil fuels (Wikipedia, 2009)[21].

2.5 Literature summary

The critical role of lifecycle perspective is obvious in dealing with current environmental crises. The earth's ecosystem is too interconnected to be dealt with single perspectives. A reduction in a given domain of environmental impact could lead to a worse impact in other domains. A lifecycle perspective on computer tools for design is a key focus in the following chapters.

As it can be seen in the description of different categories of environmental impact, the role of material selection in design seems dominant. Sustainability cannot be achieved without careful material selection. Global warming, acidification, smog, ozone layer depletion and Eutrophication can be directly linked to "bad" material selection. Choice of environmental friendly materials in design will be another key focus of the upcoming chapters.

The energy consumption in manufacturing and delivering products in the whole supply chain from extraction of raw materials, manufacturing, retail, use and post use phase is a major contributor to global warming and resource depletion and will be considered as a key focus in this thesis.

In this thesis the term "CAD" is not considered only as the geometry modeling software in new product development (NPD). By CAD the broader view of practice of computer in NPD is meant. CAD could be simply any of; use of an excel sheet containing environmental data, use of a decision support system in choosing materials, or advanced computerized methods aiding designers to deliver greener products.

3

Chapter Three:
Software, tools and methods

3.1 Introduction to tools and methods

In this chapter computer software and tools available in the current market will be presented to create the basis for comparison between different available computer tools. There are many tools available for environmental impact assessments which will not be presented here. Some of them were either not addressing the design or product development or, they were too basic or out dated. There are many basic excel spread sheets containing environmental data available but since most of them are similar and have similar capabilities only one set of these tools will be presented in this research. There are also a number of tools addressing sustainability for architects, tools such as Autodesk's Ecotect and green building studio. Since the focus of this research was on product development these architectural tools were excluded from the scope. Additionally some of the tools were inaccessible due to budget limitations or other reasons such as GaBi 4. After all there also might be some tools available in the market that the author didn't found during the timeframe of this thesis research.

In this chapter, first an understanding on general rules and basics of the environmental impact assessment will be created. ISO standards on life cycle assessment, the importance of it and accepted terminology on differentiating between sources of impact will be presented. Following this foundation each tool will be presented individually. The focus areas for each tool, their capabilities as claimed by their vendors and perceived by the author and the nature of their input and outputs will be described. Finally a conclusion based on the difference between two major types of life cycle assessment will finalize the chapter. The rest of the comparison and main analyses will be left for the next chapter.

3.2 Tools and Methods

Before digging deep into different software and tools, their capabilities and limitations, a standard categorization of the emissions needs to be defined. According to the ISO14064 and the green house gas (GHG) protocol, there are three scopes for categorizing the emissions, Scope 1, 2 and 3. For most reporting agencies Scopes 1 and 2 are considered mandatory while Scope 3 is considered optional.

Scope 1 emissions, also known as direct emissions, include any emissions that occur on-site or from company-owned assets. This includes the combustion of fuels, process emissions, and refrigerant leakage. These emissions are aggregated on a facility-level, with the company's vehicle fleet considered as one "facility."

Scope 2 emissions, also known as indirect emissions, include any emissions created directly on behalf of the company in the generation of electricity or the delivery of energy via hot water or steam. The reason for accepting responsibility for these emissions is because the company has ultimate control over "turning on the light switch" and they directly benefit from it. This example should start to demonstrate how complicated GHG legislation could become when ownership of emissions is itself a difficult concept to grasp.

The final scope, Scope 3, is a catchall for remaining emissions that result from the activities of the company. While some protocols recommend Scope 3 emissions sources worth including, what is ultimately included is entirely optional. Many companies choose not to account for and report their

Scope 3 emissions and most that do only include emissions from business travel. Some potential emissions sources that can fall under Scope 3 are the shipping of goods (inbound and outbound), emissions from contracted activities (outsourced production, etc.), and even the emissions from resource extraction and product disposal (Climate Pulse, 2009)[22].

A comprehensive approach toward environmental impact is very important. A limited point of view could result in partial optimization which could possibly generate more impacts and problems. Cisco systems in 2008 claim the company's gross carbon footprint of 724'000 tons CO2 (see figure 4). In this estimate Cisco calculated its direct emissions, direct electricity consumption and business travel. This approach missed a majority of Cisco's impact because of the limited scope of study. It failed to account for 74-83% of the Company's total GHG impact based in materials extraction, material processing, services, logistics, and manufacturing throughout their value chain (Chris Erickson, 2008)[23].

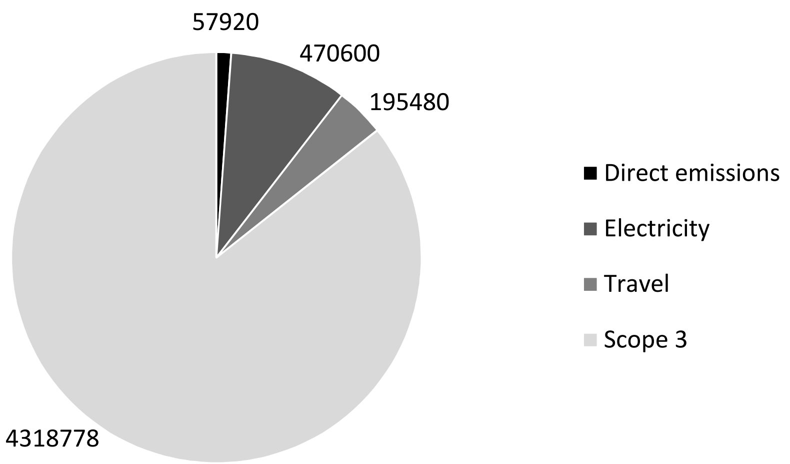

Figure 4: Cisco systems GHG emissions assessment (tons of CO_2e per year)

Obviously, if Cisco focuses its strategy on the narrow understanding of their environmental impacts, it could lead them to a series of sub-optimizations that are not necessarily reducing their total impacts. A reduction in impacts by outsourcing an activity could generate bigger impacts in scope 3 emissions. That's why considering the total picture is critical in green strategic planning.

3.2.1 Climate Earth Enterprise Carbon Accounting

Climate earth Inc. is a new company focused on environmental impact assessment. Enterprise Carbon Accounting (ECA) (Formerly called Climate Earth Business Carbon Footprint calculator) is an internal tool being used by them for environmental impact assessment of their clients. It's part of an offering from them as a consultant firm to assist companies to realize the total picture of their carbon footprint. The tool itself will be used internally to assist clients while used in accordance with their reviews and follow ups by their professional teams.

This computer tool is focused on carbon footprint calculations, which is a major contributor to global warming, acidification, smog, etc. The software builds a total picture of enterprise carbon footprint considering scope 1, 2 and 3 emissions. It considers the total supply chain containing raw materials, transport, processing, manufacturing, warehousing, and services. Therefore it's capable to calculate scope 3 emissions. Scope 3 emissions usually account for a bigger share of enterprises total impacts than scope 1 and 2 yet hard to get hold of. Indirect emissions are typically 80-90% of a typical manufacturer's total impact of operating the enterprise (Climate Earth Inc, 2009)[24].

Climate Earth's ECA can analyze the corporate and product line data, and provide a detailed enterprise carbon footprint and an analysis that includes firm's top contributors from all operations, direct and indirect emissions, an analysis by department and a look at each product line. From this, their professional team recommends a comprehensive climate strategy and immediate actions to reduce enterprise carbon footprint.

Climate earth suggests future environmental impact evaluation systems must meet the following seven strategic requirements:

1. They should be comprehensive and incorporate Scope 1, 2 and 3 emissions
2. Work periodically to enables updates at regular intervals and comparisons across reporting periods
3. Externally auditable to trace transactions and enable independent reviews for compliance
4. They should be flexible to incorporate data from multiple approaches to life cycle analysis
5. Follow a standards-Base in order to accommodate existing generally accepted standards and emerging standards
6. They should be scalable to accommodate growing volume and complexity of business operations
7. Efficient enough to deliver data in the timeframe required for decision making

Instead of focusing on process life cycle assessment or economic input output (EIO) life cycle assessment, Climate Earth ECA has a hybrid approach toward Life cycle assessment. They use process LCA when it's useful and EIO LCA when it shows it strength. Process LCA is more practical in micro level, when dealing with company's direct impacts from its processes while EIO-LCA is more practical on macro level, when dealing with industry averages or economic sector impacts. The underlying database of Climate Earth includes 480 sectors in U.S economy and stores GHG emissions for each of them.

Based solely on industry average data in their database, for instance when a consumer pays $30'000 to buy an automobile, there's a corresponding 27 tons of CO_2 which is spread through the lifecycle as illustrated in the following figure. Obviously, depending on the type of the vehicle, the manufacturer, the production site or where it's used, the numbers vary, but the result is solely based on industry averages. This will make sense more when taken into consideration in macro level. For instance if consumers spend $30'000'000 on new vehicles, then 27'000 tons of CO_2 will be the carbon footprint of their spending (Climate Earth Inc, 2009)[25].

Climate Earth ECA suggested a carbon footprint breakdown of the automobile manufacturing (see figure 5). The first portion of the pie chart (starting clockwise from 12 o'clock) addresses scope 1 emission which is responsible for about 10% of the impact. The scope 2 (second portion) is the electricity consumption which is roughly 2-3%. The scope 3 which is the impact through the supply chain and use is responsible for about 88% of carbon footprint. This diagram emphasizes the need for a comprehensive approach in assessing the impacts by covering total lifecycle of a product from its extraction of raw material to final disposal or recycling.

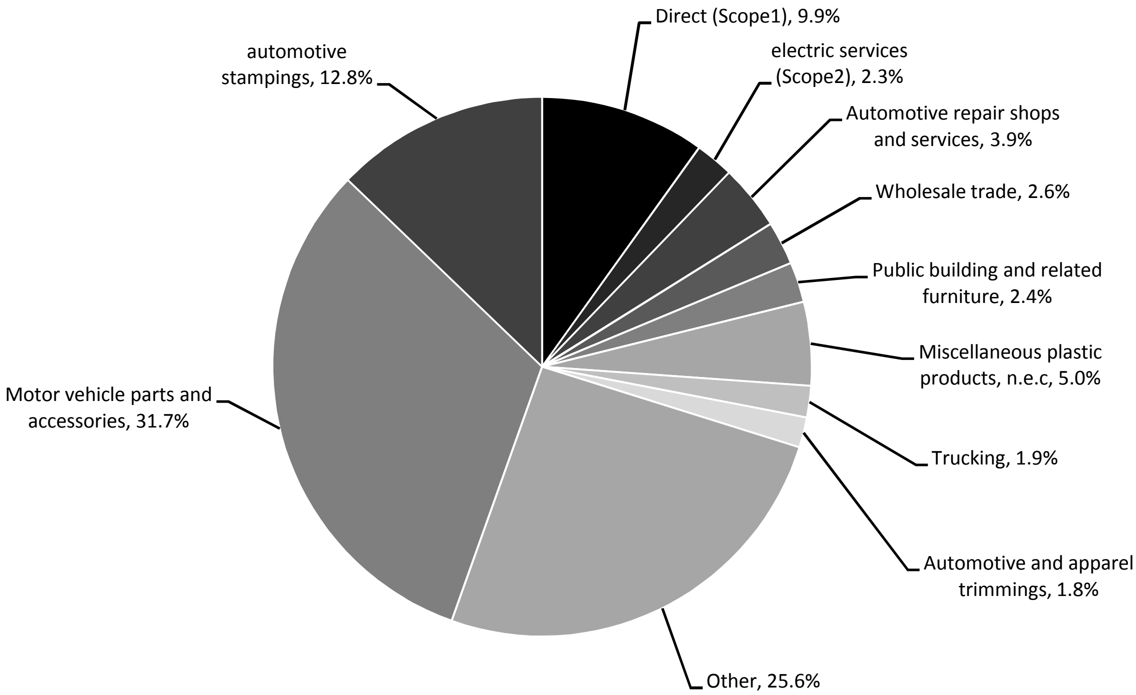

Figure 5: Life cycle carbon footprint breakdown for automobile manufacturing

3.2.2 CES Eco Selector

CES Eco Selector is a practical tool that helps to address increasingly important engineering and design Environmental objectives. To limit the carbon footprint of a product, reduce its energy usage, limit wastes and emissions, or specify the manner of its disposal. It is a specialist edition of Granta's CES Selector, combining CES Selector's materials and process selection capabilities with an Eco Audit Tool.

CES Eco Selector covers total materials lifecycle, during their production, manufacturing, use and - at the end of their life - recycling or discard. Since environmental impact takes place in all of these phases, green design demands consideration of the total lifecycle impact. But before product designers can minimize the impact, they need a quick and effective mean to estimate it and to focus their design efforts on the most significant impacts. CES Eco Selector brought a two step approach towards green design in order to estimate the impacts in the first step and then focus on it, to reduce the impact in the second step.

The user enters information about product composition, processing, usage, transportation, and disposal. The tool then combines this with eco property data on the materials and processes used in the design. It estimates the energy usage and CO_2 output resulting from each stage in the product lifecycle. Results are reported as graphs and tabular form, enabling further quantitative analysis. Generating this information early in the product development process helps to guide materials and process decisions when those decisions cost least and have the most impact (Granta Design Limited, 2008)[26]. Although they claimed the results are delivered in early product development phase, some of the inputs are not necessarily available in early stages such as processing methods or transportation. Still it is very practical since most of the data are available in engineering design phase where estimation of the environmental impact is based on.

After building an image of environmental impacts of the product showing the most significant impacts, the CES Eco Selector enters the second step (see figure 6). In this step the software helps designers to reduce the impact by material selection and substitution or even by rethinking the processes. From the results of the first step, designers have an understanding of the magnitude of the impacts from materials, manufacturing, transport, use and disposal. In this step CES Eco Selector helps to reduce the impacts by different measures. In material selection it helps to reduce the impacts by minimizing mass of parts, embodied energy and CO_2/Kg. In manufacturing it helps to reduce the impact by minimizing process energy and process CO_2/Kg. During transport it gives data to the designer to minimize the distance moved and energy mode of transport. On the use phase it helps to reduce the impact by minimizing the mass, thermal losses and electric losses. Finally in the disposal phase it helps by selecting non-toxic materials or materials that can be recycled. The following figure shows the CES Eco Selector method.

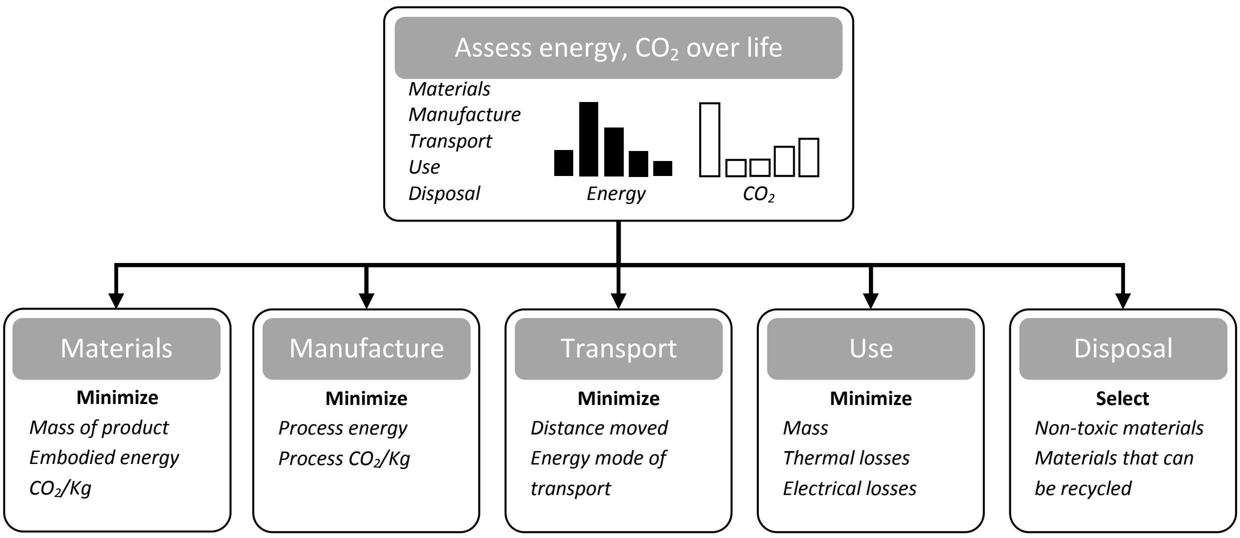

Figure 6: CES Eco Selector two step methodology

The CES Eco Selector is very powerful because it is based on a material database and selection tool called CES Selector. During the second step the CES Eco Selector is capable of providing its material engineering abilities to designers in order to choose better materials. Designers can plot engineering, economic, and environmental properties or combinations of them against each other. They can rank materials against a specific design objective (e.g. stiffness). CES Selector aids material selection decisions, (e.g. find the material that represents the best tradeoff between two conflicting objectives). It helps with materials substitution (e.g. to find materials that have a similar engineering performance to the current material in use, but with generating a lower environmental impact) (Granta Material Intelligence, 2008).

3.2.3 Green House Gas Protocol tools

The GHG protocol initiative offers a wide range of basic tools for environmental impact assessment on its website. These tools are mostly spreadsheets that help companies and individuals to assess their impacts on the environment. These tools are mostly basic yet practical. They're easy to use and quite straight forward. They basically use the industry or national averages for their calculations. The validity of the results solely based on the validity of the underlying data. The data sets are tables from government agencies containing different indices for different geographic zones of the U.S or simply different countries. These tools are incapable of delivering business specific analyses for environmental impacts since they are solely based on static national, regional or industry data. They are useful when a comparison between different geographic locations or supply options is needed. By comparing averages of different locations, the best compromise between different environmental impacts can be reached.

The first tool in this briefing is focused on "Indirect CO_2 Emissions from the Consumption of Purchased Electricity, Heat, and/ or Steam". The input for this tool is the use of purchased electricity and office use of electricity by KWh purchased. Based on its underlying data set from different electricity production regions and sub-regions of the U.S and national averages for other countries it calculates the corresponding CO_2 emissions in metric tons as the output.

Electricity, heat, and/or steam are produced when fossil fuels are burned in stationary combustion units or when other fuel sources (e.g., nuclear, hydro, wind, solar, etc.) are harnessed to produce energy. GHG emissions that result from the consumption of purchased electricity, heat or steam are emitted directly through the combustion of fossil fuels in stationary combustion units. These GHG emissions include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Sources of emissions from stationary combustion include boilers, heaters, furnaces, kilns, ovens, dryers, and any other equipment or machinery that uses fuel. Although CO_2, CH_4, and N_2O are emitted during the combustion of fossil fuels, CO_2 accounts for the majority of greenhouse gas emissions from most stationary combustion units that generate electricity, heat or steam. When weighted by their global warming potential (GWP), CO_2 typically represents over 99 percent of the greenhouse gas emissions from the stationary combustion of fossil fuels.

Different GHGs vary in their ability to trap heat in the atmosphere and therefore some GHGs are more harmful to the climate than others. Each GHG has a "global warming potential" or "GWP" which refers to this heat-trapping ability relative to carbon dioxide (CO_2). For example, CO_2 – which has a GWP of 1 – is the most prevalent GHG but methane (CH_4) is 21 time more damaging, thus the

GWP of methane is 21. GHGs should be reported as CO_2 or CO_2-equivalents (CO_2-e). Emissions factors for most sources of emissions can be found in these units. The approach required to estimate CO_2 emissions differs significantly from that required to estimate CH_4 and N_2O emissions. This tool therefore only estimates CO_2 emissions from the consumption of purchased electricity, heat or steam (GHG Protocol Initiative, 2007)[27].

The second tool in this package is for calculation of emissions from transport or mobile sources. This tool has based its calculation on fuel consumption, fuel efficiency and distance travelled by the mobile devices. The CO_2 emissions from transport sources are more accurately calculated with fuel-use data than with distance-travelled data. In contrast, the CH_4 and N_2O emissions are more accurately calculated using distance-travelled data. Because fuel economy factors can be used to convert distance data to and from fuel-use data, there are multiple ways in which, emissions can be calculated based on the same activity data.

For all mobile sources, one may apply either a fuel-based or distance-based methodology to calculate CO_2 emissions. In the fuel-based approach, fuel consumption is multiplied by the CO_2 emission factor for each fuel type. This emission factor is developed based on the fuel's heat content, the fraction of carbon in the fuel that is oxidized (generally approximately 99% but assumed to be 100% in this tool), and the carbon content coefficient. Since this approach uses previously aggregated fuel consumption data, it is considered "fuel-based." Fuel based approach can be used also when vehicle activity data and fuel economy factors are available that enables calculation of fuel consumption.

In the distance-based method, emissions can be calculated by using distance based emission factors to calculate emissions. Activity data could be in terms of vehicle kilometers (or miles) traveled, freight ton-kilometers (or miles), passenger-kilometers (or miles), etc. Because the data on fuel are generally more reliable, the fuel-based method is the preferred approach for this tool. The distance based method should only be used as a last resort as it can introduce considerably higher levels of uncertainty in the CO_2 estimates (GHG protocol, Mobile guide, 2005)[28].

There are a number of other tools offered for use on Greenhouse gas protocol initiative website. These tools are mostly static tools based on sector or national data. Their main purpose is to be used for scope 2 and 3 emissions estimations. Since they are not business specific, they are unable to deliver precise estimates of firm's direct emissions yet useful to build a rough estimate. Their reliance on national averages and standards gives them the possibility to be used for comparison between different options. Since the focus of this thesis is to address the abilities of available tools, a list of available tools from green house gas protocol initiative will be provided for future reference.

Cross sector tools (These tools are applicable to many industries and businesses regardless of sector):

1. GHG emissions from stationary combustion
2. Indirect CO_2 emissions from Purchased Electricity, Heat, or Steam
3. GHG emissions from transport or mobile sources
4. GHG emissions from refrigeration and air-conditioning
5. Emissions from employee commuting
6. Measurement and Estimation Uncertainty of GHG Emissions

7. CO_2 emissions from fuel use in facilities
8. CO_2 emissions from business travel
9. Allocation of Emissions from a Combined Heat and Power (CHP) Plant

Sector specific tools (These tools are principally designed for the specific sector or industry listed, though they may be applicable to other situations.):

1. GHG emissions from the production of aluminum
2. CO_2 emissions from the production of cement (US EPA)
3. CO_2 emissions from the production of iron and steel
4. CO_2 emissions from the production of lime
5. CO_2 emissions from the production of ammonia
6. CO_2 emissions from the production of cement (CSI)
7. N_2O emissions from the production of nitric acid
8. HFC-23 emissions from the production of HCFC-22
9. GHG emissions from pulp and paper mills
10. N_2O emissions from the production of adipic acid

3.2.4 Carnegie Mellon EIO-LCA Tool

Green design institute of the Carnegie Mellon University has provided an online assessment tool for calculating the life cycle impact of products. Results from using the EIO-LCA online tool provide guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain. The Economic Input-Output Life Cycle Assessment (EIO-LCA) method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in the entire economy. It is a technique for performing a life cycle assessment, an evaluation of the environmental impacts of a product or process over its entire life cycle. The method uses information about industry transactions - purchases of materials by one industry from other industries, and the information about direct environmental emissions of industries, to estimate the total emissions throughout the supply chain. The results from Carnegie Mellon EIO-LCA are based on the model being used. There are different models to use for calculating the economic transactions. During this thesis it has been decided that the "1992 US department of commerce industry benchmark" to be used in order to maintain consistency throughout the thesis.

- 1997 US Industry Benchmark by producer price
- 1997 US Industry Benchmark by purchaser price
- 1992 US Industry Benchmark
- 2002 Canada Industry Account
- 1995 Germany Industry Account (Carnegie Mellon EIO-LCA, 2009)[29]

In order to use this model in practice, one first needs to establish a firm understanding of underlying economic basics of the model. To base this understanding, an example of one million US dollars being spent on purchase of new automobiles is presented. There are four important economic factors to be addressed

1. Direct Economic effect

2. Total Economic effect
3. Direct economic effect percentage
4. Value Added

The Direct Economic effects represent the monetary amounts purchased by the Auto Manufacturing sector to make their product. So, it makes sense that sectors such as Motor vehicle parts manufacturing, other engine equipment manufacturing, tire manufacturing, and glass and glass products are in the top ten. The Auto Manufacturing sector is at the top of this list. The Direct Economic effects for the Auto Manufacturing sector includes the $1 million of economic activity entered for the Auto Manufacturing sector, as well as purchases within the sector which accounts for about a percent over 1 million dollar in this example. For Motor vehicle parts manufacturing, the Direct Economic effects are $0.461 million, or for every $1 million dollars in automobiles produced, $461'000 of parts are purchased.

Total Economic effects represent the total purchases from a sector by all other sectors in the economy due to the initial request for $1 million in the Auto Manufacturing sector (see table 1). This includes the direct economic purchases, as well as the indirect economic purchases. The direct economic purchases again are purchases by the Auto Manufacturing sector to produce the requested $1 million of goods. The indirect economic purchases are purchases further up the supply chain: the materials and services needed to produce the goods needed by the Auto Manufacturing sector. For example, the total economic effects from "Wholesale trade" are $0.131 million, while the Direct Economic effects from Wholesale trade are $0.051 million. About $0.08 million of Wholesale trade services are required for the purchasing, warehousing, and shipment of the indirect supply chain of goods.

Rank	Sector name	Total Economic (M$)	Value added (M$)	Direct Economic (M$)	Direct Economic (%)
1	Automobile and light truck manufacturing	1.008	0.157	1.007	99.9
2	Motor vehicle parts manufacturing	0.528	0.149	0.461	87.4
3	Wholesale trade	0.131	0.087	0.051	39.1
4	Management of companies and enterprises	0.063	0.045	0.013	20.6
5	Automotive repair and maintenance, except car washes	0.060	0.031	0.055	91.5
6	Iron and steel mills	0.054	0.013	0.000	0.7
7	Truck transportation	0.038	0.018	0.013	35.3
8	Semiconductors and related device manufacturing	0.037	0.023	0.009	24.8
9	Real estate	0.023	0.016	0.000	1.71
10	Lessors of nonfinancial intangible assets	0.021	0.020	0.011	54.4
…	…	…	…	…	…
	Total for all sectors	2.88	0.974	1.84	63.9

Table 1: Top 10 contributing economic sectors by total economic effect for 1M$ in automobile manufacturing

Direct Economic percentage helps to put the difference between direct and indirect contributions of the various sectors into perspective (see table 2). For example, 87.4% of the economic activity in the Motor vehicle parts manufacturing sector goes directly to the Auto Manufacturing sector; 90% of the economic activity in the Tire Manufacturing sector goes directly to the Auto Manufacturing sector. Conversely, only 0.7% of the economic activity from Iron and steel mills is purchased by the Auto Manufacturing sector directly; only 9.25% of the economic activity from the Power generation and supply sector is used in facilities of the Auto Manufacturing sector. In other words, 99.3% of steel mill product is purchased by other sectors in the economy, or 90.75% of electrical power is used elsewhere in the supply chain. This Direct Economic percentage number is important when considering environmental impacts, as discussed later.

Value added equals the difference between an industry's gross output (income, taxes, and inventory change) and the cost of its intermediate inputs (energy, raw materials, semi-finished goods, and services that are purchased).

Rank	Sector name	Total Economic (M$)	Value added (M$)	Direct Economic (M$)	Direct Economic (%)
1	Automobile and light truck manufacturing	1.008	0.157	1.007	99.9
2	Motor vehicle parts manufacturing	0.528	0.149	0.461	87.4
3	Automotive repair and maintenance, except car washes	0.060	0.031	0.055	91.5
4	Wholesale trade	0.131	0.087	0.051	39.1
5	Other engine equipment manufacturing	0.017	0.005	0.015	88.5
6	Truck transportation	0.038	0.018	0.013	35.3
7	Management of companies and enterprises	0.063	0.045	0.013	20.6
8	Tire manufacturing	0.013	0.004	0.012	90.2
9	Lassors of nonfinancial intangible assets	0.021	0.020	0.011	54.4
10	Glass and glass products, except glass containers	0.015	0.007	0.011	74.9
…	…	…	…	…	…
	Total for all sectors	2.88	0.974	1.84	63.9

Table 2: Top 10 contributing economic sectors by direct economic effect for 1M$ in automobile manufacturing

The economic sectors that contribute directly to a product are not necessarily the ones that contribute the most to the direct environmental burden of a product. Likewise, looking across the entire life cycle by examining the indirect supply chain contributions helps to identify other sectors that carry additional burden. So, if the Auto Manufacturing sector wanted to change its overall, life cycle impacts, it might consider negotiating with companies in the Motor vehicle parts manufacturing sector - after all, most of the purchases for a vehicle come from that sector. But the Motor vehicle parts manufacturing sector may not be the biggest generator of wastes and emissions in the supply chain. Changes in this sector may result in a minimal change in the overall, life cycle impacts (Carnegie Mellon, 2009)[30].

After understanding the economic base of the Carnegie Mellon EIO-LCA model, its environmental impact assessment capabilities are understandable. This model is the most sophisticated and broad model that the author found during this research. It's capable of addressing several environmental impacts that mostly are not available through most of the other tools.

It can provide data on conventional air pollutants (see table 3). These are air pollutants identified by the U.S. Environmental Protection Agency as air pollutants with major health and environmental concerns and are regulated under the Clean Air Act. The six conventional air pollutants are sulfur dioxide (SO_2), carbon monoxide (CO), nitrous oxides (several pollutants, designated NO_x), volatile organic compounds (VOC), lead (Pb), and particulate matter (PM) often identified by size in micrometers (e.g., PM10 or PM2.5).

Rank	Sector name	SO_2 (Ton)	CO (Ton)	NO_x (Ton)	VOC (Ton)	Lead (Ton)	PM10 (Ton)
1	Power generation and supply	1.017	0.050	0.460	0.004	0.000	0.022
2	Iron and steel mills	0.078	0.664	0.061	0.037	0.000	0.055
3	Primary smelting and refining of copper	0.050	0.001	0.000	0.002	0.000	0.005
4	Primary aluminum production	0.041	0.229	0.000	0.002	0.000	0.010
5	Alumina refining	0.038	0.000	0.009	0.009	0.000	0.004
6	Automobile and light truck manufacturing	0.026	0.012	0.014	0.400	0.000	0.003
7	Adhesive manufacturing	0.018	0.005	0.008	0.001	0.000	0.001
8	Petroleum refineries	0.014	0.008	0.003	0.011	0.000	0.001
9	Oil and gas extraction	0.013	0.023	0.010	0.015	0.000	0.000
10	Truck transportation	0.013	4.132	0.298	0.307	0.000	0.007
	…	…	…	…	…	…	…
	Total for all sectors	1.46	7.73	1.45	1.52	0.002	0.419

Table 3: Top 10 contributing economic sectors by SO_2 pollution for 1M$ in automobile manufacturing

It can provide data on green house gases (see table 4). The four major greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs). The tool also provides the results considering the global warming potential (GWP) of the GHGs in CO_2 equivalent.

Rank	Sector name	GWP CO_2e (ton)	CO_2 CO_2e (ton)	CH_4 CO_2e (ton)	N_2O CO_2e (ton)	CFCs CO_2e (ton)
1	Power generation and supply	187.555	185.300	0.000	0.000	2.255
2	Iron and steel mills	68.274	68.274	0.000	0.000	0.000
3	Truck transportation	58.523	57.629	0.089	0.804	0.000
4	Motor vehicle parts manufacturing	22.413	22.413	0.000	0.000	0.000
5	Air transportation	17.476	17.269	0.022	0.186	0.000
6	Automobile and light truck manufacturing	10.736	10.736	0.000	0.000	0.000
7	Wholesale trade	9.343	9.343	0.000	0.000	0.000
8	Petroleum refineries	8.318	8.272	0.046	0.000	0.000
9	State and local government electric utilities	8.022	8.022	0.000	0.000	0.000
10	Lime manufacturing	7.734	7.734	0.000	0.000	0.000
	…	…	…	…	…	…
	Total for all sectors	628	531.	57.1	12.5	26.6

Table 4: Top 10 contributing economic sectors by CO_2 pollution for 1M$ in automobile manufacturing

The energy analysis offering of the tool is comprehensive as well. It can provide results for Total energy consumption and differentiate the use by electricity, coal, natural gas, liquefied petroleum gas, motor gasoline, distillate fuel, kerosene, jet fuel and residential fuel (see table 5).

Rank	Sector name	Total (TJ)	Electric (GWh)	Coal (TJ)	Natural Gas (TJ)	LPG (TJ)	Motor Gas (TJ)	Distil. (TJ)	Keros. (TJ)	Jet Fuel (TJ)	Resid. (TJ)
1	Power generation and supply	2.224	0.000	1.762	0.394	0.000	0.000	0.000	0.000	0.000	0.067
2	Iron and steel mills	0.864	0.043	0.041	0.735	0.002	0.006	0.005	0.000	0.000	0.028
3	Motor vehicle parts manufacturing	0.512	0.080	0.000	0.317	0.009	0.058	0.037	0.000	0.001	0.001
4	Truck transportation	0.419	0.001	0.000	0.009	0.001	0.061	0.347	0.000	0.000	0.000
5	Air transportation	0.270	0.001	0.000	0.001	0.000	0.004	0.000	0.000	0.264	0.000
6	Automobile and light truck manufacturing	0.240	0.045	0.000	0.108	0.003	0.040	0.034	0.000	0.001	0.005
7	Wholesale trade	0.171	0.011	0.000	0.075	0.003	0.021	0.056	0.000	0.002	0.002
8	Petroleum refineries	0.155	0.003	0.000	0.075	0.070	0.001	0.000	0.000	0.000	0.006
9	Rail transportation	0.114	0.000	0.000	0.000	0.000	0.000	0.113	0.000	0.000	0.000
10	Plastics material and resin manufacturing	0.102	0.006	0.007	0.082	0.005	0.001	0.000	0.000	0.000	0.001
	…	…	…	…	…	…	…	…	…	…	…
	Total for all sectors	7.57	0.451	1.95	3.16	0.184	0.385	0.879	0.000	0.308	0.196

Table 5: Top 10 contributing economic sectors by energy consumption for 1M$ in automobile manufacturing

The tool's ability in addressing toxic releases is remarkable as well (see table 6). It provides data on toxic emissions differentiating non-point (mobile) and point (stationary) emissions. It differentiates emissions by air, water and land releases. It can also provide data on underground releases of toxic materials, publicly owned treatment works (e.g. water drains) and offsite tankers (i.e. disposal, recycling, energy recovery).

Rank	Sector name	Mob. Air (Kg)	Stat. Air (Kg)	Total Air (Kg)	Total Water (Kg)	Total Land (Kg)	Under-ground (Kg)	Total (Kg)	Pub trans (Kg)	Off site (Kg)	Tot+ trans (Kg)
1	Automobile and light truck manufacturing	3.439	29.136	32.575	0.003	0.009	0.000	32.587	4.085	1.399	38.071
2	Power generation and supply	0.011	27.917	27.928	0.149	10.252	0.000	38.330	0.000	2.600	40.930
3	Motor vehicle parts manufacturing	3.533	17.160	20.693	0.269	1.162	0.000	22.123	5.215	12.804	40.142
4	Primary nonferrous metal, except copper and aluminum	0.626	19.518	20.144	1.556	26.864	0.000	48.564	0.199	14.661	63.424
5	Plastics plumbing fixtures and all other plastics products	1.027	4.637	5.664	0.014	0.006	0.000	5.684	0.233	0.491	6.409
6	Plastics material and resin manufacturing	1.643	3.559	5.202	0.388	0.021	1.898	7.509	3.090	0.456	11.055
7	Primary aluminum production	1.260	3.938	5.198	0.023	0.455	0.000	5.676	0.000	1.143	6.819
8	Motor vehicle body manufacturing	0.830	4.366	5.196	0.000	0.001	0.000	5.198	0.494	0.230	5.922
9	Paper and paperboard mills	0.169	4.611	4.780	0.529	0.474	0.000	5.784	0.585	0.174	6.543
10	Other basic organic chemical manufacturing	1.511	2.569	4.081	1.530	0.088	4.358	10.056	3.478	1.291	14.825
	…	…	…	…	…	…	…	…	…	…	…
	Total for all sectors	36.2	165	201	41.8	926	35.0	1200	48.8	172	1420

Table 6: Top 10 contributing economic sectors by toxic air release for 1M$ in automobile manufacturing

The Carnegie Mellon EIO-LCA shows its capabilities when combining economic and environmental data. Assume reducing sulfur dioxide emissions is a priority for the Auto Manufacturers. An initial focus might be to seek out sources of SO_2 emissions in a facility and determine ways of eliminating or capturing those emissions. But those actions would target a small portion of the total SO_2 emissions in the Auto Manufacturing supply chain (0.03 tones out of the 1.46 tones of SO_2 emitted throughout the supply chain (see table 7).

Sector name	Direct Economic %	Total SO_2	Direct SO_2	Total CO	Direct CO
Auto Manufacturing	99.9%	0.03	0.03	0.01	0.01
Power generation and supply	9.25%	1.02	0.09	0.05	0.00
Truck transportation	35.3%	0.01	0.00	4.13	1.46
Total for all sectors	63.9%	1.46	0.93	7.73	4.94

Table 7: Combining economic and environmental impact data

The results of the EIO-LCA tool indicate that majority of sulfur dioxide emissions are emitted from the Power generation and supply sector (1.02 tones of the total 1.46 tones). So, the Auto Manufacturing sector may be able to eliminate more SO_2 emissions by finding ways to reduce the amount of electricity consumed in its facilities, or switch the generating source of the electricity from high-sulfur sources (i.e., purchase electricity generated from wind or hydro). But even those actions still only target a small amount of the sulfur dioxide emissions. As shown in table 7 and 8, the direct SO_2 emissions from the Power generation and supply sector due to the demand for power from the Auto Manufacturing sector are only 0.09 tones (see table 8).

	SO_2 Emissions (ton)
All sectors, total	1.46
Power generation and supply, total	1.02
Power generation and supply, indirect	0.93
Power generation and supply, direct	0.09
Auto Manufacturing, direct	0.03

Table 8: Environmental impact breakdown for power generation and supply sector

More sulfur dioxide from the Power generation and supply sector is from indirect demand. So, getting supplier facilities (like the ones in the Motor vehicle parts manufacturing sector) to reduce their electricity consumption or switch their electricity provider to renewable sources could make a bigger difference in the overall sulfur dioxide emissions. This demonstrates why taking an EIO-LCA perspective of production is essential to analyses - without examining the full life cycle in the entire economy, efforts to reduce environmental emissions and waste may not be targeting areas where the most effects are created.

But, since EIO-LCA calculations are based on economic data in a macro level, it's incapable of delivering business specific data which is the most useful when one considers green design in early design stages. The lifecycle assessment of environmental impacts is bounded with macro economic data since accountability of supply chain impacts is only possible by this kind of data. It's impossible or at least, too complicated and costly, to consider business specific data when dealing with the supply chain. Conducting process LCA for each and every single product (final and intermediary) in the entire supply chain might be possible for extremely simple products such as a sheet of paper but for complex products such as an automobile is currently unrealistic if not impossible at all.

3.3 Case study: concrete vs. asphalt

It's hard to find a simple product to compare a regular version and greener version of it in order to raise the interest about how much the environmental burden of a simple product can be reduced. It definitely needs to be simple since life cycle assessments are easily became large and costly. I chose to bring a very simple product for this thesis work, the road pavement. Based on industry data I create a case study to calculate the environmental burden of two methods by using the Carnegie Mellon EIO LCA method. This tool was chose because of its ability to address different environmental impact assessments. The base numbers are from an assignment for a study from Carnegie Mellon University and the calculations are my work.

In Europe most of roads are paved with asphalt but in US steel reinforced concrete pavement is used in large scale as well as asphalt. For a case study, here I'll compare these two types of pavements in terms of their environmental impacts to show, not only their difference for environment but also how complex and hard is to run a full lifecycle study.

3.3.1 Basic economic data

Starting with some economic figures, in this case, pavements of 1km long, 7.2m wide on 15cm cement treated sub-bases will be compared. Equivalent designs of this type would require differing amounts of the two materials being considered.

- The asphalt pavement would need to be 30 cm thick which would require 5018 tons of asphalt.
- The steel-reinforced concrete (SRC) pavement would need to be 22cm thick requiring 3680 tons of concrete and 77 tons of steel bars.

The current prices for standard asphalt, concrete and steel bars are as follows:

- 5018 tons of asphalt cost: $220,500
- 3680 tons of concrete cost: $161,700
- 77 tons of steel bars cost: $35,500(Noellette, Conway-Schempf, 2009)[31]

In order to use the EIO-LCA model for calculating the environmental burden the prices need to be adjusted. 1 ton of asphalt has the same environmental impact now and in 1992 but the price of it varies now from 1992. The EIO-LCA method is based on the 1992 US department of commerce industry benchmark prices. X dollar spending on asphalt generates different environmental impacts now and in 1992 because it buys different amounts of asphalt. So in order to use the EIO LCA model, the prices need to be adjusted to 1992 prices. The consumer price index in 1992 was 140.3 (compared to 100 for 1982-84 in US). The current consumer price index in 2009 is 212.6 (W.E Upjohn institute, 2009)[32].

Price in 1992 = Price in 2009 x (Consumer price index in 1992/ Consumer price index in 2009)

Or

$$P_{1992} = P_{2009} \text{ x } (CPI_{1992} / CPI_{2009})$$

$$P_{1992} = P_{2009} \text{ x } (140.3/212.6)$$

$$P_{1992} = P_{2009} \text{ x } (0.6599)$$

In 1992 the prices were as follows:

- 5018 tons of asphalt cost: $145,500
- 3680 tons of concrete cost: $106,700
- 77 tons of steel bars cost: $23,400

3.3.2 EIO LCA analysis

By using the EIO LCA method the economic figures above can be transformed to environmental impacts in the entire economy. By deciding on asphalt for paving the road (1Km long, 7.2m wide), spending $145,500 on it will cause certain amounts of environmental burden. On the other hand instead of asphalt a steel reinforced concrete can be chose for the pavement in this case $106,700 on concrete and $23,400 on steel bars is needed to pave the road which have their own environmental burden. Here I'll start with their green house gas effects.

3.3.3 Green house gases

The major green house gas impacts based on global warming potential (GWP) in CO_2e resulted from asphalt came from, Asphalt paving mixture and block manufacturing sector (scope 1): 77.6 tons, Power generation and supply sector (scope 2): 57.2 tons, Oil and gas extraction sector (scope 3): 37.7 tons, Petroleum refineries (scope 3): 36.3 tons, etc. the total green house gas emission for all sectors is 280 tons in the entire economy.

For concrete the major green house gas emissions came from, Cement manufacturing sector (scope 1): 114 tons, Power generation and supply sector (scope 2): 31.7 tons, Ready-mix concrete manufacturing sector (scope 3): 17.4 tons and Truck transportation (scope 3): 17.1 tons, etc. the total green house gas emission for all sectors is 216 tons in the entire economy.

For steel bars the major green house gas emissions came from, Iron and steel mills sector (scope 1): 33 tons, Power generation and supply sector (scope 2): 11 tons, etc. the total green house gas emission for all sectors is 64.2 tons in the entire economy.

Adding up the figures for concrete and steel bars says the entire economy will generate 280.2 tons of CO_2e emission. This means regarding the green house gas emissions this model suggests using the steel reinforced concrete and asphalt for pavements does not have a significant difference.

3.3.4 Conventional air pollutants

Contrary to green house gases that have a common measurement unit (GWP), the conventional air pollutants don't have such a common unit. For simplifying reasons I only consider SO_2 emissions in this case study. The SO_2 emissions resulted from asphalt came from Power generation and supply sector (scope 2): 0.31 tons, and Asphalt paving mixture and block manufacturing sector (scope 1): 0.206 tons, etc. the total SO_2 emission for all sectors is 0.704 tons in the entire economy.

For concrete the major SO_2 emissions came from, Cement manufacturing sector (scope 1): 0.4 tons, Power generation and supply sector (scope 2): 0.172 tons and Stone mining and quarrying sector (scope 3): 0.061 tons, etc. the total SO_2 emission for all sectors is 0.672 tons in the entire economy.

For steel bars the major SO_2 emissions came from, Power generation and supply sector (scope 2): 0.06 ton and Iron and steel mills sector (scope 1): 0.038 ton, etc. the total SO_2 emission for all sectors is 0.11 tons in the entire economy.

Adding up the figures for concrete and steel bars says the entire economy will generate 0.782 tons of SO_2 emission. This means regarding the SO_2 emissions this model suggests using the steel reinforced concrete generated roughly 10% more SO_2 emissions than using asphalt for the pavements.

3.3.5 Toxic releases

The major toxic releases to the environment resulted from asphalt came from, Copper, nickel, lead, and zinc mining sector (scope 3): 15.2 tons, Power generation and supply sector (scope 2): 11.7 tons and Petroleum refineries sector (scope 3): 11.1 tons, etc. the total toxic releases for all sectors is 61.2 tons in the entire economy.

For concrete the major toxic releases came from, Copper, nickel, lead, and zinc mining sector (scope 3): 19.4 tons, Cement manufacturing sector (scope 1): 17.2 tons and Power generation and supply sector (scope 2): 6.47 tons, etc. the total toxic releases for all sectors is 62.6 tons in the entire economy.

For steel bars the major toxic releases came from, Copper, nickel, lead, and zinc mining sector (scope 3): 27 tons, Iron and steel mills sector (scope 3): 21.1 tons and Gold, silver, and other metal ore mining sector (scope 3): 6.44 tons, etc. the total toxic release for all sectors is 70.2 tons in the entire economy.

Adding up the figures for concrete and steel bars says the entire economy will release 132.8 tons of toxic materials to the environment. This means regarding the toxic releases this model suggests using the steel reinforced concrete more than doubles these toxic releases.

3.3.6 Energy consumption

The energy consumption on the other hand showed different results. For asphalt the major energy consumption came from, Asphalt paving mixture and block manufacturing sector (scope 1): 1.48TJ, Power generation and supply sector (scope 2): 0.678TJ and Petroleum refineries sector (scope 3): 0.676TJ, etc. the total energy consumption for all sectors is 3.8TJ in the entire economy.

For concrete the major energy consumption came from, Cement manufacturing sector (scope 1): 0.981TJ, Power generation and supply sector (scope 2): 0.376TJ and Ready-mix concrete manufacturing sector (scope 3): 0.333TJ, etc. the total energy consumption for all sectors is 2.3TJ in the entire economy.

For steel bars the major energy consumption came from, Iron and steel mills sector (scope 1): 0.418TJ, Power generation and supply sector (scope 2): 0.131TJ and Iron ore mining sector (scope 3): 0.027TJ, etc. the total energy consumption for all sectors is 0.704TJ in the entire economy.

Adding up the figures for concrete and steel bars says the entire economy will consume 3.004TJ energy. This means regarding the energy consumption this model suggests using the steel reinforced concrete consumes 21% less energy than asphalt for pavements.

3.3.7 Case study conclusion

The following table summarizes the case results. It shows how much environmental burden will be generated from each pavement method (see table 9).

Pavement method	Green house gases (Ton)	Sulfur dioxide (Ton)	Toxic Releases (Ton)	Energy consumption (TJ)
Asphalt	280.0	0.704	61.2	3.800
Steel reinforced concrete	280.2	0.782	132.8	3.004

Table 9: Environmental burden of each road pavement method

For comparison, the environmental impacts need to be normalized to show how big the difference between the mentioned methods is. The following figure illustrates the relative impact of each road pavement method assuming asphalt impact equals one (see figure 7). As it can be seen both pavements roughly generate same green house gases, the difference on conventional air pollutants is small as well while asphalt creates much more toxic releases but consumes less energy.

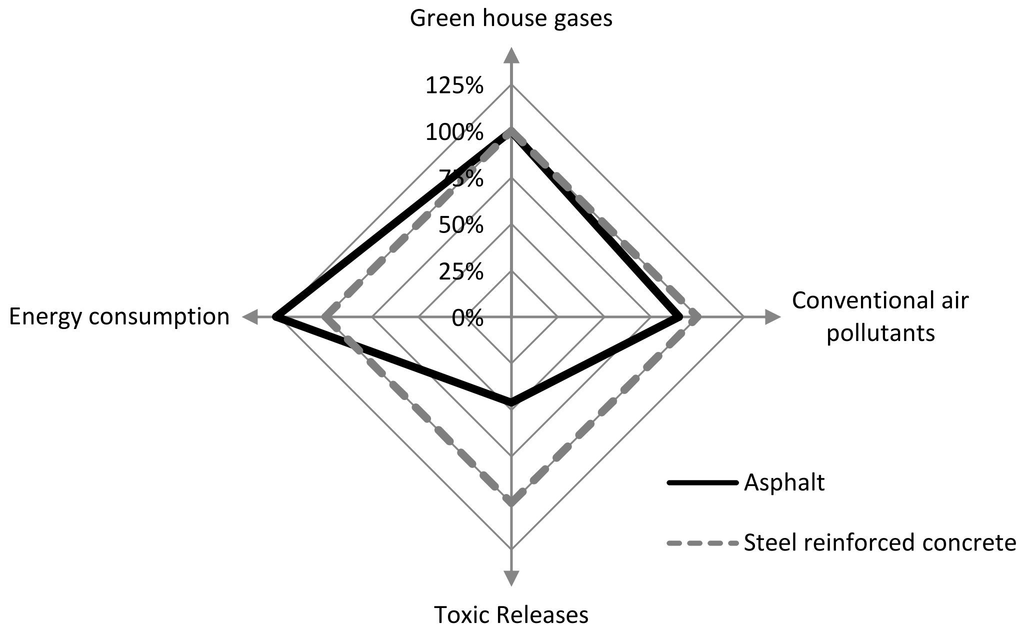

Figure 7: Relative environmental burden of asphalt comparing to concrete

This chart clearly demonstrates how important a complete perspective is. If only the energy consumption was taken into consideration, one could possibly argue in favor of steel reinforces steel while a study solely focused on toxic releases could soundly show absolute opposite results. The importance of each axis based on the overall goals for the entire economy of at least the enterprise strategies. Based on the current, near future or long term targets a reduction on one environmental impact might be preferred over another.

The mentioned case is a simplified example of how complex a lifecycle analysis could become. The products were simple (contain one or two materials), and the construction itself was not taken into consideration. But, that's not all! Answering the questions like "how long does a steel reinforced pavement last?", "How long does an asphalt pavement last?", "How many repair works needed during each lifetimes", "How each of them can be reconstructed, removed, disposed or recycled?" When it comes to life cycle analysis comparison between options is not always easy. Sometimes subjective measures or even uncertain objective measures interfere with the validity of the results.

3.4 Tools and methods summary

As a general rule Process based life cycle assessment tools and Economic Input Output based life cycle assessment tools both have their fundamental advantages and disadvantages. The following advantages and disadvantages were proposed for the process LCA and Economic Input Output LCA methods:

Process LCA

- Advantages:
  1. Results are detailed, process specific
  2. Allows for specific product comparisons
  3. Identifies areas for process improvements, weak point analysis
  4. Provides for future product development assessments
- Disadvantages:
  1. Setting system boundary is subjective
  2. Tend to be time intensive and costly
  3. Difficult to apply to new process design
  4. Use proprietary data
  5. Cannot be replicated if confidential data are used
  6. Uncertainty in data

Economic Input Output LCA:

- Advantages:
  1. Results are economy-wide, comprehensive assessments
  2. Allows for systems-level comparisons
  3. Uses publicly available, reproducible results
  4. Provides for future product development assessments

5. Provides information on every commodity in the economy

- Disadvantages:
  1. Product assessments contain aggregate data
  2. Process assessments difficult
  3. Must link monetary values with physical units
  4. Imports treated as products created within economic boundaries
  5. Availability of data for complete environmental effects
  6. Difficult to apply to an open economy with substantial non-comparable imports
  7. Uncertainty in data (Hendrickson, Lave and Matthews, 2006)[33]

As it was presented in this chapter, a number of tools addressing different environmental impact assessments methods are available in the current market. Each of which has their own capabilities and limitations. In some cases tools are addressing the impacts using same set of data (e.g. US Dept of Commerce 1997 Industry Benchmark) but generate different outputs based on their own methodology. The following chapter represents individual comparisons on each tool by summarizing its capabilities and delivers tables and graphs for comparisons between tools.

4

Chapter Four:
Comparison and Analyses

4.1 Introduction to comparison and analyses

In this chapter software and tools will be compared. The comparison will be started by individual comparison, where a set of questions will be answered for each tool. This comparison will serve as a summary of previous chapter. What each tool can do and how are the basic characteristics of them will be presented here. The chapter continues with cross comparisons of tools with each other. A set of criteria will be used as comparison base. Tools will be assessed against addressed impacts, product development type, optimization method, level of detail, scopes covered, etc.

After the cross comparisons, software and tools will be mapped to a generic product development process to show where during the development process they fit. This serves as a guideline for designers and engineers to use these tools where they are capable of contributing to the development process.

4.2 Individual comparison

During individual comparison, each of the tools presented in the previous chapter will be compared according to the following 11 criteria. In this section the following questions will be answered for each tool.

1. What Pros and Cons each computer tool has?
2. What each tool claimed to do?
3. Works on global or local optimization?
4. Works on detail, component or product or system optimization?
5. Works with services or products only or a combination of them?
6. Is it suitable for inventive, radical product development or incremental product development?
7. Which scopes are addressed in it?
8. In what type of organization it can be used?
9. Is it useful in small or long projects?
10. Does the user needs to be expert or everyone can use it?
11. Is the evaluation a precise in depth one or just a promotion or assessment of the impact?

4.2.1 Climate Earth ECA

1. It is focused only on carbon footprint.
2. It claimed that incorporates both Process LCA and EIO-LCA approaches. It uses Process LCA for intra-business calculations and EIO-LCA for extra-business evaluations.
3. Since it is focused solely on carbon footprint and doesn’t consider other environmental impacts, it delivers local optimization. Yet its lifecycle approach claims to be so effective that it captures any carbon footprint in its calculations.
4. It works on both product and system optimization level.
5. It addresses environmental impacts for both services and products.
6. Incremental PD, It evaluates the current situation and incapable of

7. Scope 1, 2 and 3
8. It can be used in a team work project.
9. It can be applied to, small/short and big/long projects.
10. The user needs expertise in environmental impacts to interpret the results into action.
11. It delivers precise in depth analysis.

4.2.2 CES Eco Selector

1. It addresses carbon footprint, energy usage, wastes and the manner of its disposal and it encompasses a powerful material database for its analyses by which it suggests material or process substitution.
2. It claimed to deliver results on material and process selection for products based on environmental impact data. It covers production, manufacturing, use and end of life phases.
3. It addresses several environmental issues, it's not complete but it targets global optimization.
4. It works on component and product optimization level.
5. It addresses environmental impacts of products only.
6. It can support both inventive, radical product development and incremental product development.
7. Scope 1, 2 and 3
8. It can be used in a team work project or individually depending on the complexity of the products.
9. It can be applied to, small/short and big/long projects.
10. The user needs expertise in material properties and environmental impacts to interpret the results into action.
11. It delivers precise in depth analysis.

4.2.3 GHG protocol tools

1. They address green house gases only. Several tools address different environmental impacts in different situations.
2. They claimed to offer cross sector tools which can be used in many circumstances and also some sector specific tools to be used in certain industries or situations.
3. Local optimization, each tool is focused on one environmental issue in one situation.
4. They work on system optimization level.
5. It addresses environmental impacts of products, services and organizations.
6. They can support incremental product development.
7. Scope 2 and 3 (sometimes scope 1 is included but not in every tool)
8. They can be used in a team work but suitable to be used individually.
9. They can be applied to, small/short projects.
10. They target general user. No specific expertise is needed for their user.
11. It delivers basic analyses mostly for promotion purpose.

4.2.4 Carnegie Mellon EIO-LCA

1. It addresses several environmental impacts such as conventional air pollutants, green house gases, energy consumption and toxic releases.

2. It claimed that based on the economic transactions in the whole economy using emission factors for each economic sector it can provide the overall lifecycle environmental impacts of the products and services.
3. It provides global optimization.
4. System optimization.
5. It addresses environmental impacts of products, services and organizations.
6. They can support both inventive and incremental product development.
7. It covers scope 1, 2 and 3.
8. They can be used in a team work.
9. They can be applied to big/long projects while might be useful in small projects as well.
10. The user needs expertise in basic economics and environmental impacts.
11. It delivers precise in depth analyses.

4.2.5 Individual comparisons matrix

The following matrix summarizes the individual comparison results for these four tools (see table).

Questions	Climate Earth ECA	CES Eco Selector	GHG Protocol Tools	Carnegie Mellon EIO-LCA
1	Focused only on carbon footprint	Encompasses a powerful material database	Addresses green house gases only	Addresses several environmental impacts
2	Incorporates both Process LCA and EIO-LCA	Delivers results on material and process selection	Offer cross sector tools	Provides the overall lifecycle environmental impacts
3	Local optimization	Global optimization	Local optimization	Global optimization
4	Product and system optimization	Component and product optimization	System optimization	System optimization
5	Services and products	Products only	Products, services and organizations	Products, services and organizations
6	Incremental PD	Inventive and incremental PD	Incremental PD	Inventive and incremental PD
7	Scope 1, 2 and 3	Scope 1, 2 and 3	Scope 2 and 3	Scope 1, 2 and 3
8	In a team work	In a team work or individually	Suitable to be used individually	In a team work
9	Small/short and big/long projects	Small/short and big/long projects	Small/short projects	Big/long projects (might be useful in small ones)
10	User needs expertise in environmental impacts	User needs expertise in material properties and environmental impacts	No specific expertise is needed	User needs expertise in basic economics and environmental impacts
11	Precise in depth analysis	Precise in depth analysis	basic analyses mostly for promotion purpose	Precise in depth analyses

Table 10: Individual comparison matrix

4.3 Group comparison / cross comparison

In this chapter, previously mentioned tools will be compared to each other. Different charts will be used to show the differences among tools and to compare their capabilities.

4.3.1 Addressed impacts

The ability to evaluate environmental impact varies among tools. Some focused on one impact while others address multiple impacts. The following chart illustrated the relative capabilities of these tools (see figure 8). The five categories in the figure 8 were derived from the Carnegie Mellon EIO LCA tool since it addresses the most impacts amongst all plus waste which was derived from CES Eco Selector. Note that the chart is not quantitatively measure computer tools ability to address each environmental impact. There is no quantitative comparison method used here to evaluate one tool's ability to estimate environmental impact to another. Instead, the following radar chart illustrates their relative power to address environmental impacts in each of the five different impact categories by using a set of qualitative criteria.

	Values			
	0	**1**	**2**	**3**
Business specific or average data	None	Average data	Business specific	Both
Detail level	None	General	Moderate	Very detailed
Products and/or services	None	One of them	Both of them	N/A
Scopes covered	None	One scope	Two scopes	All three scopes
Depth of analysis	None	Not in depth	Medium	Very deep

Table 11: Comparison criteria and relative values for each environmental impact

There are other areas on which none of the mentioned software is able to evaluate impacts. For example none of them addressed issues on land degradation or habitat destructions. The following table shows the criteria used for comparison and the values given. Each tool was relatively compared to the others in each impact category and then the total points were normalized for each impact given 1 to the highest possible value (i.e. 14).

For example, most of these tools address the environmental impact from green house gases. The GHG protocol provides some tools to evaluate some impacts while the CES Eco Selector provides comprehensive measurements based on its material database. The Carnegie Mellon EIO-LCA goes further ahead and accounts the full lifecycle of the products in the entire economy while lacks the business specific analyses. In this respect the Climate Earth ECA provides the most comprehensive measurements. It considers both EIO-LCA and process LCA to capture all the environmental impact in area of green house gases. The following table shows the comparison data of which the radar diagram of figure 18 is derived.

	Possible values	Climate Earth ECA	CES Eco Selector	GHG Protocol Tools	Carnegie Mellon EIOLCA
Green house Gases					
business specific/averages	0-1-2-3	3	2	1	1
detail level	0-1-2-3	3	3	1	2
products or/and services	0-1-2	2	1	2	2
scopes	0-1-2-3	3	2	2	3
depth of analysis	0-1-2-3	3	3	1	3
Sum	**Max 14**	**14**	**11**	**7**	**11**
Normalized sum	**Max 1**	**1.00**	**0.79**	**0.50**	**0.79**
Air Pollutants					
business specific/averages	0-1-2-3	0	0	0	1
detail level	0-1-2-3	0	0	0	2
products or/and services	0-1-2	0	0	0	2
scopes	0-1-2-3	0	0	0	3
depth of analysis	0-1-2-3	0	0	0	3
Sum	**Max 14**	**0**	**0**	**0**	**11**
Normalized sum	**Max 1**	**0.00**	**0.00**	**0.00**	**0.79**
Toxic Emissions					
business specific/averages	0-1-2-3	0	2	0	1
detail level	0-1-2-3	0	3	0	2
products or/and services	0-1-2	0	1	0	2
scopes	0-1-2-3	0	3	0	3
depth of analysis	0-1-2-3	0	3	0	3
Sum	**Max 14**	**0**	**12**	**0**	**11**
Normalized sum	**Max 1**	**0.00**	**0.86**	**0.00**	**0.79**
Waste					
business specific/or averages	0-1-2-3	0	2	0	0
detail level	0-1-2-3	0	3	0	0
products or/and services	0-1-2	0	1	0	0
scopes	0-1-2-3	0	3	0	0
depth of analysis	0-1-2-3	0	3	0	0
Sum	**Max 14**	**0**	**12**	**0**	**0**
Normalized sum	**Max 1**	**0.00**	**0.86**	**0.00**	**0.00**
Energy					
business specific/averages	0-1-2-3	2	2	1	1
detail level	0-1-2-3	2	3	1	2
products or/and services	0-1-2	2	1	2	2
scopes	0-1-2-3	2	2	2	3
depth of analysis	0-1-2-3	3	2	1	3
Sum	**Max 14**	**11**	**10**	**7**	**11**
Normalized sum	**Max 1**	**0.79**	**0.71**	**0.50**	**0.79**

Table 12: Relative scores of tools on set of criteria for different impacts categories

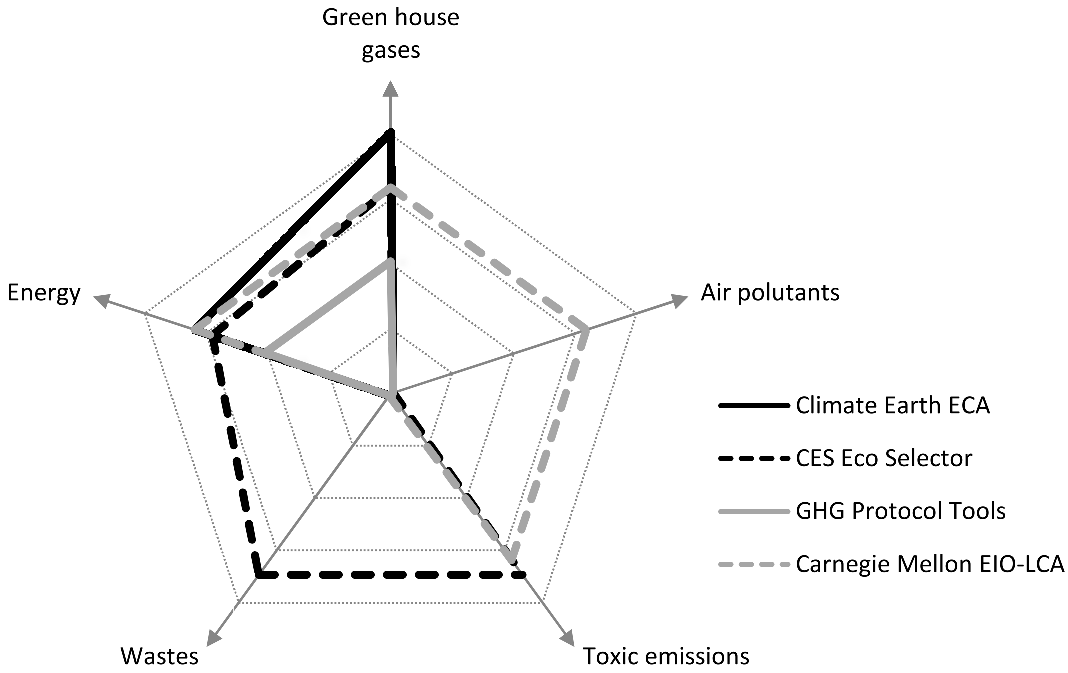

Figure 8: Relative ability of the computer tools to address different environmental impacts

4.3.2 Product development type vs. optimization method

An interesting cross comparison of these tools is to see what kind of optimization they provide in relation to the type of product development they can be used in (see figure 9). Can any of the tools that bring global optimization be used in radical product development or they can only be used in incremental product development projects?

The CES Eco Selector and Carnegie Mellon EIO LCA provide global optimization while both can be used, relatively similar, in incremental or radical product development projects. The CES Eco selector is relatively more practical in radical PD projects than Carnegie Mellon EIO LCA while the later brings a broader global optimization. Two other tools, Climate Earth ECA and GHG protocol tools both work on local optimization and are more applicable in incremental product development projects. The Climate Earth ECA well considers the lifecycle of products and organization in search of carbon footprints but since it only targets CO_2, it’s still a local optimization tool.

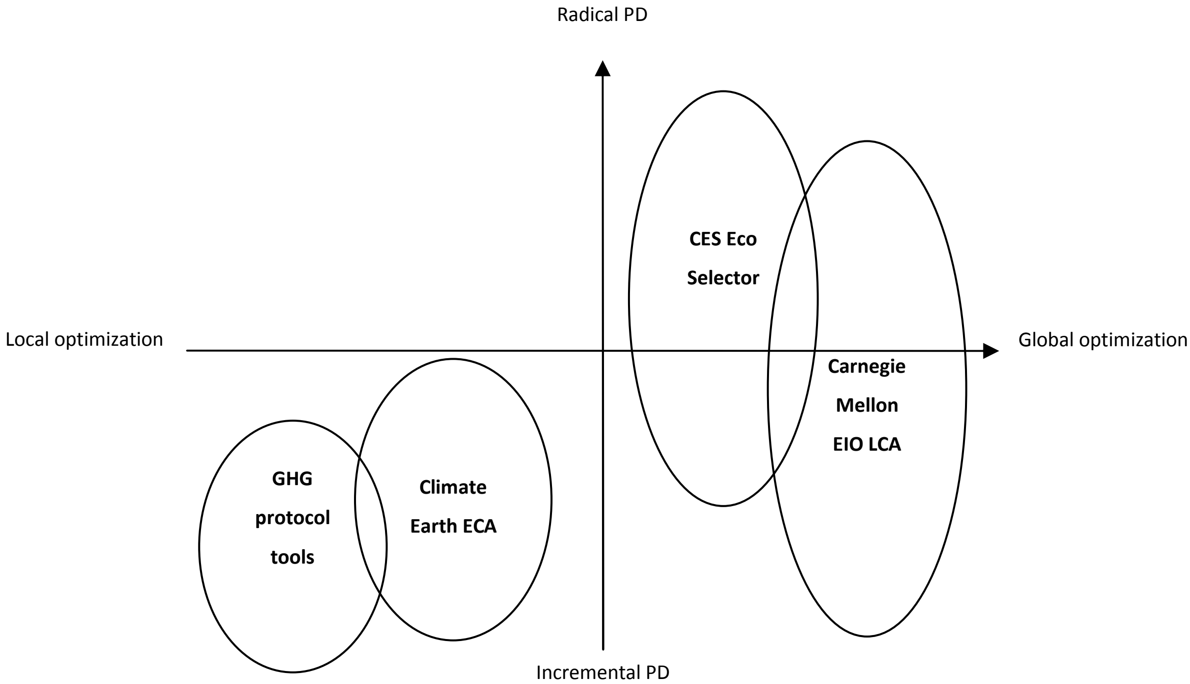

Figure 9: Comparison on type of product development and optimization

4.3.3 Level of detail vs. level of optimization

Comparing level of optimization and level of detail between tools can be a useful comparison to better understand their capabilities (see figure 10). CES Eco selector is a global optimization tool but it doesn't address system level issues. It works from detail components up to products. On the other hand, Carnegie Mellon EIO LCA is similarly a global optimization tool but it is incapable of evaluating impacts on detail or specific product's level. Both of the Climate Earth ECA and GHG protocol tools are local optimization tools yet their levels of detail varies. GHG protocol tools address issues only on system level while Climate Earth ECA covers product level as well.

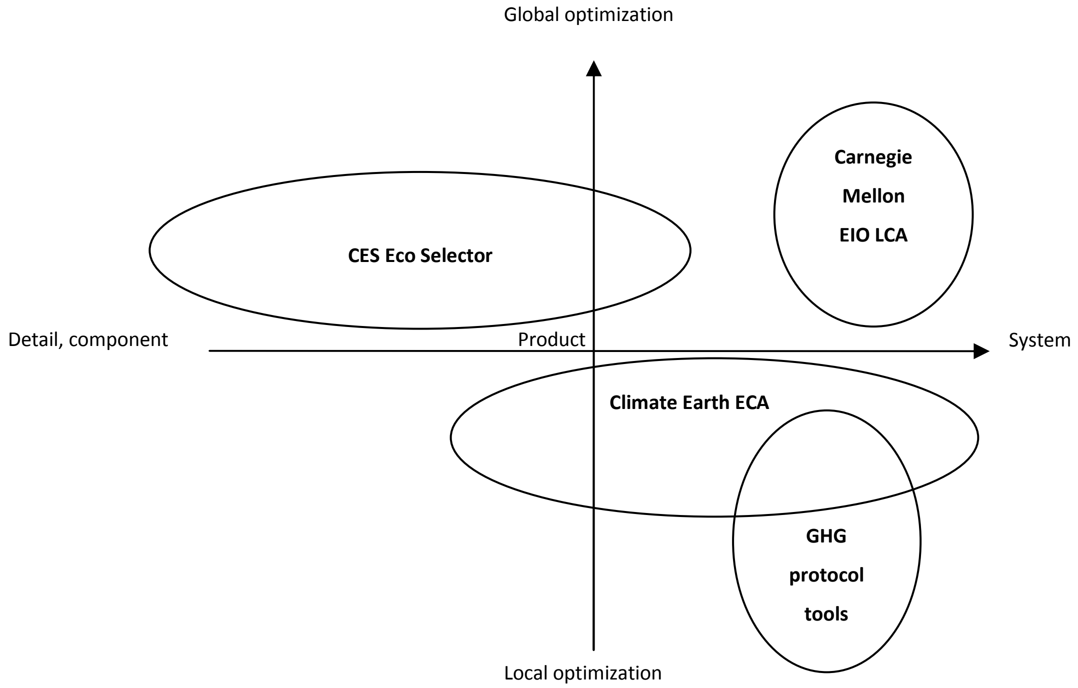

Figure 10: Comparison on level of detail vs. level of optimization

4.3.4 Depth of analysis for different scopes

Comparing the depth of environmental impact analysis each tool delivers on each scope create interesting results (see figure 11). The comparison of tools on the three scopes of impacts was derived from the relative scoring against five criteria as described in table 13.

	Values			
	0	**1**	**2**	**3**
Business specific or average data	None	Average data	Business specific	Both
Detail level	None	General	Moderate	Very detailed
Products and/or services	None	One of them	Both of them	N/A
Single/some/many impacts addressed	None	One impact	Some impacts	Many impacts
Depth of analysis	None	Not in depth	Medium	Very deep

Table 13: Comparison criteria and relative values for each of the three impact scopes

The scoring was based on relative scores of the tools. The total points achieved by each tool then normalized by the maximum possible score (i.e. 14). Table 14 shows the data of which the radar chart of the figure 11 was derived from. Please note that score of 3 on detail level, impacts addressed and depth of analysis criteria was given only to the best tool.

	Possible values	Climate Earth ECA	CES Eco Selector	GHG Protocol Tools	Carnegie Mellon EIOLCA
SCOPE 1					
business specific/averages	0-1-2-3	3	2	0	1
detail level	0-1-2-3	3	3	0	2
products or/and services	0-1-2	2	1	0	2
Single/some/many impacts	0-1-2-3	1	3	0	3
depth of analysis	0-1-2-3	3	3	0	2
Sum	**Max 14**	**12**	**12**	**0**	**10**
Normalized sum	**Max 1**	**0.86**	**0.86**	**0.00**	**0.71**
SCOPE 2					
business specific/averages	0-1-2-3	1	1	1	1
detail level	0-1-2-3	2	3	1	2
products or/and services	0-1-2	2	1	1	2
Single/some/many impacts	0-1-2-3	1	2	1	3
depth of analysis	0-1-2-3	3	2	1	2
Sum	**Max 14**	**9**	**9**	**5**	**10**
Normalized sum	**Max 1**	**0.64**	**0.64**	**0.36**	**0.71**
SCOPE 3					
business specific/averages	0-1-2-3	1	1	1	1
detail level	0-1-2-3	1	2	1	3
products or/and services	0-1-2	2	1	1	2
Single/some/many impacts	0-1-2-3	1	2	1	3
depth of analysis	0-1-2-3	1	2	1	3
Sum	**Max 14**	**6**	**8**	**5**	**12**
Normalized sum	**Max 1**	**0.43**	**0.57**	**0.36**	**0.86**

Table 14: Relative scores of tools on set of criteria for each of the three scopes

As it can be seen on the radar chart in scope 1 the CES Eco Selector and Climate Earth ECA generate the best evaluations. Based on CES Eco Selector's material database it's natural to provide best results in scope 1. The Climate Earth ECA on the other hand employs a hybrid approach towards LCA which combines process LCA and EIO-LCA capabilities therefore it creates very good evaluation of scope 1 emissions. Apparently since GHG protocol tools rely solely on averages they're incapable of delivering evaluations for scope 1. On the axes of scope 2 and 3, Carnegie Mellon EIO LCA dominates. Its ability to calculate each and every monetary transaction in the entire economy and transform them to the environmental impact data is the sole reason of its powerful in depth analysis. As it can be seen the Carnegie Mellon EIO-LCA dominates on both scopes 2 and 3. It is natural since it is based on industry average data it cannot be very powerful on scope 1 emissions. The GHG protocol tools are meant to be promotional so they're incapable of delivering very good analyses in any of the scopes.

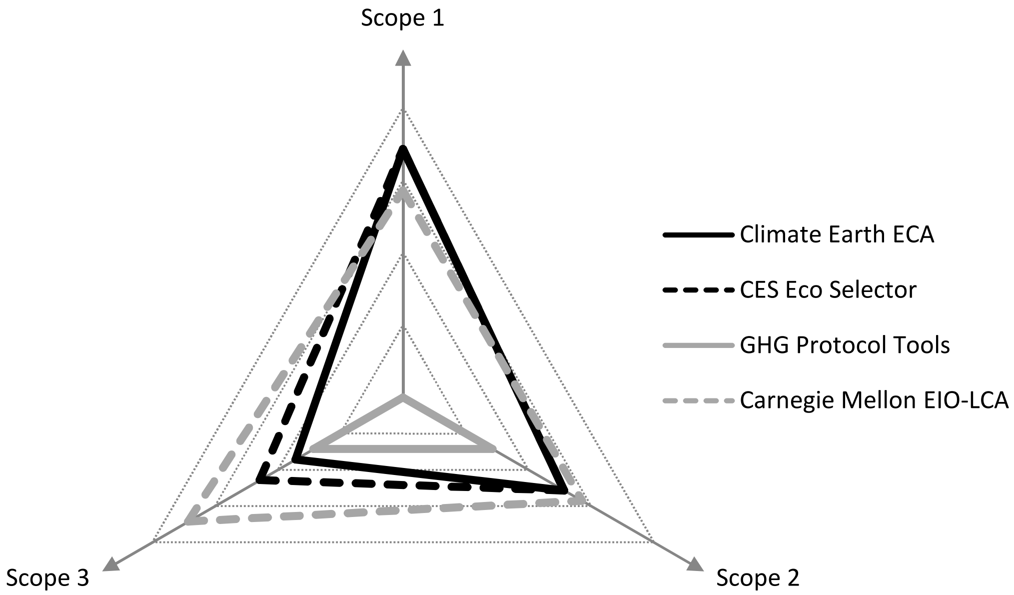

Figure 11: Relative capabilities of each tool analyses on each of the three scopes of the impacts

4.4 Mapping the tools on product development process

In this chapter the presented software and tools will be mapped to the process of product development. Ulrich and Eppinger suggested a seven stage spiral product development process. (Ulrich and Eppinger, 2004)[34] the following figure illustrates their spiral product development process. The mapping of these software and tools will be based on this process.

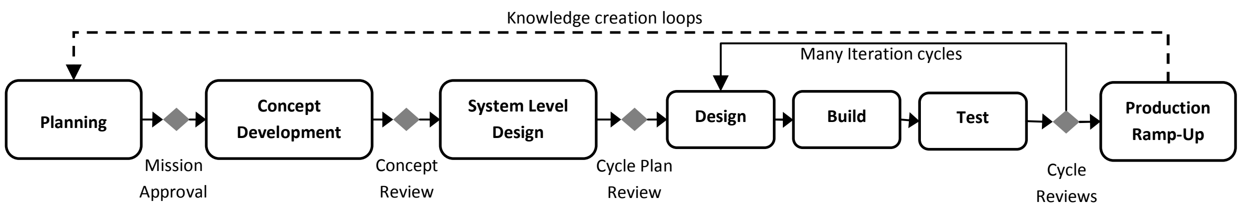

Figure 12: Generic product development process

As it was noted before, early changes usually create stronger influences on the outcome and are less costly while late changes has lesser influence and in most of the cases are more expensive. Early evaluation of environmental impacts is very useful for product developers. They can decide to substitute materials, processes and other production aspects in early stages where it costs less to make these changes.

The climate earth ECA is a tool that considers financial corporate data in evaluation of lifecycle environmental impacts. It considers production processes for its assessments as well. Obviously such data are not available for a startup company or a completely new product development effort. But, in most of the cases new products are derivatives of available products. Even though they are radical product developments, they still mostly use the same processes that are being used by other products. This kind of information is available during production ramp-up and testing and refinement. During the detail design phase all of the materials and processes data will be available and the Climate Earth ECA has enough data to analyze impacts. This kind of data will be generated gradually during system design phase and will be finalized in detail design iterations where several design build test cycles occur. The cycle will not be limited between design, build and test. There is another important cycle in the PD process where the knowledge will be generated during which a product is produced and still the environmental data about that product being used in the development of other products or later versions. This tool can be used during system design level until the end of product development process (see figure 13).

The Green House Gas Protocol tools are mostly based on industry or sector averages. They are not product or business specific. There is no need for detail product information to use these tools. They can simply be used from system level design phase where the overall characteristics of the products are defined. Obviously their results will be more precise when the detail design and characteristics of the product are available. They can be used as guidelines throughout the product development process during and after concept development phase.

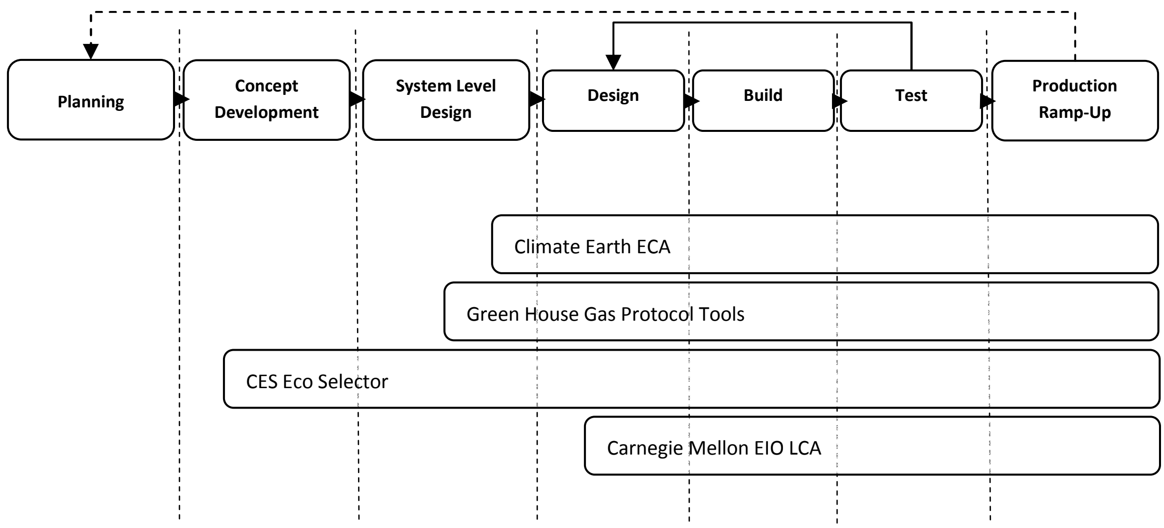

Figure 13: Mapping the tools on a generic product development process

The CES Eco Selector evaluates the environmental impacts by assessing the materials and processes. It can deliver raw estimates from early concept development phase when raw decisions about material selection are taken. The analyses will become more precise and in depth when further details are available during system design and detail design. The material substitution capability of

CES Eco Selector gives precise analyses of alternative materials during testing and refinement phase. The design team can decide on which materials to choose and which ones to avoid by its evaluations. The CES Eco Selector cannot deliver further detail during production ramp-up. The processes and production specifications do not influence its results. It can be used as a powerful tool to decide on impact of materials and processes but after the production starts its evaluations are final.

The Carnegie Mellon EIO LCA works with the economic transactions in the entire economic sectors. It needs specific monetary values to start its assessments. This kind of data will be available during detail design phase. During the iterations between design build and test phases, the EIO LCA tool delivers precise in depth analyses for lifecycle of the products and its true environmental impact in the entire economy. This tool delivers its assessments by monetary transactions in the economy. Every change during design build test cycles or production ramp-up phase has its effects on overall lifecycle environmental impacts and Carnegie Mellon EIO LCA will capture it and include it in its assessments. This tool can be used from design phase throughout the development process and afterwards.

The iterations during the design build test cycles and the loop between the production and planning are important considering their environmental assessment effects. During the design build test cycles, product developers test several ideas and designs, by environmental impacts assessment tools such as CES Eco Selector to find a more environmental friendly design for their products. Another important information cycle is when a product passed the detail design and went through the production. After this stage another type of valuable information addressing real environmental impacts will be generated that can be used in later product development efforts. This evaluation is of a kind that is most useful in derivative product developments. When a product is available in the market and next generation of it is under development. The environmental assessment data about the current product can be used in development of the new one from the earliest stage of planning.

The later cycle brings the evolutionary approach towards environmental friendly design. This serves the design team as a knowledge base that will be completed during time. Having this, product developers can calculate more precise estimates of environmental burden of a design during early stages of product development based on prior experiences.

5

Chapter Five: Discussion

5.1 Available tools

I think development of computer tools for environmental friendly design is in its early stages. The available tools are neither comprehensive nor solid enough. Software and tools are missing important modules. They are incapable of delivering clear certain results. They can be used as guidelines (yet not complete) but their analyses are not in depth enough for strategy making. The size of the problem and interconnectivities between modules and issues might be a problem. The problem here is more or less like “to find a design for a car which optimizes the transportation in the whole world”. Obviously it is not possible with current computer modeling and design tools.

The need for inclusion of different aspects and all interconnectivities between different environmental impacts before taking action makes the problem complex. It is easy to decide on a strategy to reduce CO_2 emissions for a factory but the drawback might be increase in toxic releases. The need for a tool that is comprehensive, addresses each and every known environmental impact, capable of delivering LCA analyses and has a decision support system is still unanswered. None of the current tools are this sophisticated yet.

There is a clear emphasis on green house gases among the environmental impact assessment tools. Thanks to the international awareness of global warming, its sources and effects, the green house gases are in the center of interest in any tool. Some tools are solely focused on green house gas emissions, while others assess other environmental impacts as well. During my research I found out that the assessment of green house gas emissions wasn’t absent in any tool.

Although special tools addressing a single environmental impact like CO_2 are useful, a multidimensional analysis which considers different environmental impacts is much more important. As it was discussed during the case study in chapter 3.3 a single dimensional approach toward lifecycle analysis of environmental impacts could mislead the efforts to reduce the environmental burden of the products. An LCA focused on CO_2 can show that product A is cleaner than B while A is a disaster for environment considering SO_2. The single approach tools are useful when they are following an established strategy for a reduction of impacts in that specific area. For instance if a company decides to reduce its green house gases by 20% during next year, a single approach tool could be useful yet risky.

Strategies focused on a single environmental impact are clear examples of local optimization which is not necessarily the total system optimization. A local optimization could lead to a system improvement in some cases especially with unbounded elements but it is not always the case. Complex interconnected systems; like environment, are built on bounded elements. A positive change in one element will impact many other elements not necessarily in positive terms. For example substitution of a wooden part with plastic parts could possibly save some trees and may be in a car lead to a lower weight and less fuel consumption but in the same time it could lead to toxic emissions, resource depletion, etc. Only comprehensive strategies addressing multiple environmental impacts could assure a system optimization.

But, comprehensive life cycle analyses are complex and costly. They can easily become multimillion dollar projects that last forever. Nowadays, supply chains are global. It is hard to find a complex product which does not consist of parts manufactured in China, European Union, United States, etc. The interconnectivity of world economies is a barrier for environmental impact assessment tools.

Different standards, different reporting methods and different definitions of pollutants make it hard to assess the impacts precisely. All of the current tools that were studied here assume the supply chain resides in the economy of the United States. Although this assumption creates error in evaluations, so far there is no better way to conduct life cycle assessment analysis.

5.2 The missing links

The most important missing link among the current offerings on the market is prioritization tools. Even if a design team has a comprehensive analysis of a product's impact, it is hard to decide which one is the most dangerous and how to assign budget for reductions. Which one is worse, one ton of CO_2 or a kilogram of SO_2? There are some indices in each category for comparison. For example among the green house gases, the GWP index is capable of comparing CO_2, CH_4, CFC's, etc. I have not found similar measures for toxic releases, etc.

Even though these indices are present, the important missing links are indices capable of comparing emissions from different categories. Indices that can quantitatively show the designers if it is better to reduce CO_2 emissions by X tons at the cost of releasing Y kilograms of mercury to the environment. These are not easy straight forward problems. There might be geographic specific answers to them. For example conventional air pollutants are considered more dangerous in cities than rural areas, or toxic releases are considered more dangerous near water resources than land areas. Moreover these are dynamic indices. Reduction in ozone layer destructive compounds was more important couple of years ago, while now reduction in green house gases seems to be more important.

The other important missing link in current LCA analysis tools is the lifecycle itself. Using product B instead of A might reduce the overall environmental impact by 20%. This could be a strong case of "green" product development. The question is: what if product A lasts 50% more than B. As it was shown in the case study of road pavements in chapter 3.3 asphalt pavement was better in every aspect but energy consumption. The question is how long does an asphalt pavement last? If the concrete pavement needs repair 50% less than asphalt does or lasts 50% longer then the analysis results will be changed completely. Unfortunately none of the tools that I have studied in this thesis taken this into consideration. As far as I understand the inclusion of lifespan of products in LCA should not be hard.

Other important missing links in current tools are areas such as land degradation, habitat destruction, and resource depletion. Current tools do not assess impacts in these terms. A reason behind this could be that addressing these areas by quantitative measures is harder than other areas. I think resource depletion can be evaluated quantitatively at least for the endangered resources and lead efforts to avoid use of endangered scarce resources.

After all I think there is a big room for improvement in sustainable product development software and tools. The available products are not comprehensive enough and not all the areas addressed by the tools. The research and development teams should work more on the currently available tools to add comprehensiveness to them while concurrently work on developing other tools for the areas that are not addressed by current tools. I see a big unsatisfied demand for more practical and reliable tools addressing different impacts comprehensively in the market.

6

Chapter Six:

Conclusion and recommendations

6.1 Conclusion

This thesis is conducted to answer the following three main research questions as stated in chapter 1.3 and the thesis proposal.

1. What computer tools addressing environmental sustainability in product development are currently available for the engineers to use?
2. What capabilities and limitations do these computer tools have?
3. How they can be used in the process of product development?

A number of obstacles limited the scope of research in this thesis. This research was conducted in the Berkeley Energy and Sustainable Technologies (BEST) Laboratory in the University of California, Berkeley which implied some geographic and resource limitations on this thesis. The main focus was given to the available tools in the United States.

I was successful in answering these three research questions. The limited number of tools and their limited capabilities and scope of operation made it possible to clearly answer research questions 1 and 2 but made it hard to clearly describe how they can be used during product development process which is the aim of research question 3. The results for each research question are briefly presented in the following chapters

6.1.1 Research question one, available tools

During this research four tools were studied thoroughly which were presented in detail in chapter three. These tools were the Enterprise Carbon Accounting from Climate Earth, CES Eco Selector from Granta, Environmental assessment tools from Greenhouse Gas Protocol Initiative and finally Economic Input Output Life Cycle Assessment from Carnegie Mellon University. Availability of data and willingness of the providers of these tools to help made it possible to conduct a comprehensive study on each of them and bring their abilities and limitations into analysis.

There were other tools available on the market but during the time frame of this research the author did not succeeded to collect adequate information needed for a good enough study comparable to the other software and tools.

The Enterprise Carbon Accounting is an offering from Climate Earth consultants. It is part of a package offered by them to assess firm's carbon footprint. It is not only the assessment software. It is a software and database for an evaluation of enterprises accompanied by their team of assessment experts.

The CES Eco Selector from Granta is a tool for material selection focused on environmental impacts associated with materials in products and processes. It a specialist version of bigger software package from Granta for material selection and substitution.

The environmental assessment tools from Greenhouse Gas Protocol Initiative are a set of basic free web based tools focused on green house gas emissions evaluation. There are some business specific tools, some sector specific ones and some general assessment tools.

The Economic Input Output Life Cycle Assessment from Carnegie Mellon University is a comprehensive tool based on US economic sectors. It assesses environmental impacts by economic evaluation of monetary transactions between different economic sectors in the entire US economy.

6.1.2 Research question two, capabilities and Limitations

The second main research question was about each tool's capabilities and limitations. This was presented in detail in chapters three and four but as a concluding briefing the main strength and weaknesses of each tool is as follows.

The ECA from Climate Earth is not comprehensive, yet is very powerful. It is solely focused on carbon footprints. As it discussed during the case study on chapter 3.3, the comprehensiveness of a tool addressing different environmental impacts is critical for an informed decision on how to reduce the impacts. The Climate Earth ECA in powerful when it comes to greenhouse gases (especially CO_2). Their hybrid lifecycle assessment approach (refer to chapter 3.2.1) is a powerful method in capturing sources of impacts in evaluations. It combined abilities of process LCA and EIO LCA which gives a well understanding of the total picture of green house gas emissions. Climate Earth's experts thoroughly review all of the financial documents of their clients to address each and every source of impact. They believe everything has a footprint in financial documents. By reviewing them in detail, they will be capable of addressing the whole impact.

The CES Eco Selector is more comprehensive compared to Climate Earth's ECA considering its capability to address multiple impacts. But, it is less comprehensive considering its life cycle assessment method which is based solely on process LCA. It is incapable of delivering a lifecycle analysis which represents each impact in the whole economy. CES Eco Selector shows its advantage when it comes to material selection and substitution. The underlying materials' properties database of CES Selector gives it the ability to show objectively how designers can substitute a material by another to get the same mechanical characteristics but create less environmental burden. This ability is unique among the studied software in this research. Only the CES Eco Selector can help engineers and designers to change materials in order to reduce the product's impacts, the rest can show the impact only but are incapable of suggesting substitutes.

The tools offered from GHG protocol initiative are mostly useful for promotional purposes. They can only be used to raise the interest for companies or individuals. The result of their analysis are based on simple excel data sheets. They can show how much green house gases will be emitted from simple activities to the environment. They cannot deliver business specific analyses. They cannot bring detail life cycle assessments. Among studied tools in this research, the GHG protocol initiative set of tools are the most simple and incomprehensive tools but, they are easy to use and good enough to raise the interest for the users.

The EIO LCA tool from Carnegie Mellon University is the most powerful tool when it comes to life cycle assessments. Its ability to interconnect every monetary transaction in the whole economy, gives it the ability to calculate the resulted environmental impact of each activity in the entire economy. Each and every activity is accompanied by a monetary transaction. Any individual activity has its own environmental impact. By connecting each monetary transaction to all the preceding transactions, each environmental impact will be connected to all the impacts released to the environment because of that one. The Carnegie Mellon EIO LCA gives precise analyses of life cycle environmental impacts for all the economic sectors. The limitation of Carnegie's tool is that it is incapable of delivering a business specific evaluation. Whether a business buys its electricity from a solar power producer or not, the associated environmental impact from its purchased electricity will be similar to those businesses which bought it from other more polluting sources such as oil or coal based power plants. Regardless of this limitation the given analysis for the entire economy will still be valid. In calculation of the environmental impacts of the electric power generation sector the average was reduced because of the lesser impacts of solar power plants, but still Carnegie's tool cannot calculate business specific analysis.

6.1.3 Research question three, use in product development process

As it was presented in chapter 4.4 only Green House Gas Protocol tools and the CES Eco Selector can be used in early stages of product development. The GHG protocol tools on the other hand are good for promotional uses only. This study showed that the only tool that can be used as a hand on tool for the designers from early product development stages is the CES Eco Selector. Its powerful material database makes it possible for the designers and engineers to decide early on their choice of material in order to minimize their environmental impacts.

The Climate Earth ECA and Carnegie Mellon EIO LCA are both available for the designers from detail design phase where more in depth information about the product becomes available. ECA will address CO_2 footprints only while the EIO LCA delivers comprehensive analyses of the environmental impacts.

A combination of CES Eco Selector's hands on capabilities and Carnegie Mellon EIO LCA's comprehensiveness can be a good combination for product developers to both start evaluations early in the development process and keep track of different impacts in parallel.

The limited number of software and tools available for environmental impact assessments in the current market prevents the author to propose a matrix of tools that map each tool to each step in the product development process. Figure 10 in chapter 4.4 is the closest mapping to the matrix that has been aimed in the start of this thesis work.

6.1.4 Summary of conclusion

As a summary of the research and results of the mentioned research questions the following notes can be proposed about the current computer tools for sustainable product development:

- The main focus in environmental impact assessment tools is placed on green house gases. This area of impact which is directly connected to the global warming has been addressed frequently among available tools.
- A number of tools with different levels of complexity and capability address green house gas emissions.
- Energy is the other environmental impact which is being considered among the tools.
- The other areas such as air pollutants and toxic releases have not got enough interest and are addressed only in some of the tools.

- Areas such as land degradation, habitat destruction, resource depletion are almost forgotten or at least no tools were found in this research to address those issues, not even to be mentioned indirectly.

6.2 Recommendations

Here are a number of recommendations both for further research and further development based on authors analysis of the currently available tools in green product development.

Author believes there is a need for tools addressing different life cycle assessment methods together. Tools are mostly based on process LCA or Economic input output LCA. This study showed that the business specific analysis needs process based LCA, but process LCA is too complicated and almost impossible or at least unrealistic to be conducted throughout the entire economy. EIO LCA helps reduce the complexity of it and makes it possible to be executed. The problem is EIO LCA cannot be business specific. A hybrid method such as Climate Earth's approach to implement both LCA methods in an analysis can lead to a business specific analysis of life cycle impacts assessment which is precise, not too complicated, affordable and yet viable.

Development of new tools addressing other impacts such as resource depletion and land degradation is important and recommended by the author. It is important for designers to understand in early stages of design that their design, choice of material, use phase and even disposal will lead to degrade the land somewhere or increase the consumption of a scarce resource. Author thinks because addressing such issues need complex methods, none of the current tools include them. Mentioning these environmental impacts in EIO LCA tools could be the start of development.

In the current global economy products and services are traded globally from a country to another. Internationally traded products and services complicate life cycle assessment. It is not easy to differentiate between internally produced goods and services in one country's economy from imported and exported goods. When a product produced from an imported resource the supply chain impact for that resource is different from a local source. In the other hand when a product is exported the use and disposal phase have different impacts. Further research is needed to assess life cycle impacts for imports and exports.

Case studies which compare environmental impacts of a product that has been redesigned by green measures with its traditional design are scarce. The author has not found any case studies showing what will be the difference when a product is being redesigned considering its environmental impacts. Quantitative case studies are needed to show the difference especially when partial life cycle assessments were the reason for redesign. As it is showed in chapter 3.3 comparison between asphalt and concrete pavements showed different results depending on which impacts are being considered. Case studies can show objectively how green design can reduce environmental impacts of our products.

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