Integrating Environmentally Responsible Design with Life Cycle Assessment in Product and Process Development for Sustainability

by

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A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved April 2014 by the
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ARIZONA STATE UNIVERSITY

May 2014

ABSTRACT

Industrial activities have damaged the natural environment at an unprecedented scale. A number of approaches to environmentally responsible design and sustainability have been developed that are aimed at minimizing negative impacts derived from products on the environment. Environmental assessment methods exist as well to measure these impacts. Major environmentally responsible approaches to design and sustainability were analyzed using content analysis techniques. The results show several recommendations to minimize product impacts through design, and dimensions to which they belong. Two products made by a manufacturing firm with exceptional commitment to environmental responsibility were studied to understand how design approaches and assessment methods were used in their development. The results showed that the company used several strategies for environmentally responsible design as well as assessment methods in product and process machine design, both of which resulted in reduced environmental impacts of their products. Factors that contributed positively to reduce impacts are the use of measurement systems alongside environmentally responsible design, as well as inspiring innovations by observing how natural systems work. From a managerial perspective, positive influencing factors included a commitment to environmental responsibility from the executive level of the company and a clear vision about sustainability that has been instilled from the top through every level of employees. Additionally, a high degree of collaboration between the company and its suppliers and customers was instrumental in making the success possible.

DEDICATION

I dedicate this dissertation to my parents, Felicia and Oscar, my wife Cata, and my children Agustín, Olivia and the yet-to-be-born baby boy, for their love and inspiration.

ACKNOWLEGMENTS

I would like to express my deep appreciation and gratitude to my Co-Chairs, Dr. Jacques Giard and Professor Philip White, for the patience and the guidance they provided to me over these past years. The wonderful conversations I had with Dr. Giard always helped me to reflect about important topics of my research, as well as how they connect with my me personally, now and in the future. I am thankful for his thorough editions of my dissertation. Professor White introduced me to ecodesign and life cycle assessment, and shared with me valuable and hard-to-find literature. He also was a constant support as an academic advisor for my grant applications and facilitated contacts with companies to include in my research. He also provided important advice to improve my dissertation.

I would like to express my deep gratitude to my committee member Dr. Kevin Dooley, especially for his friendly guidance in helping me navigate the depths of qualitative research. He presented me valuable literature, helped me see things from different perspectives, and helped me contact companies for my research.

I must also thank the people at Interface Inc. for allowing me to conduct research about their projects and for sharing invaluable information. I am deeply grateful to Connie Hensler, who made possible the participation of the company and arranged my visit to their facilities and meetings with staff members; Erin Meezan, John Bradford, and Stuart Jones for participating as interviewees for my research; and Mary Anne Anderson Lanier from the Ray C. Anderson Foundation for allowing me to interview her.

I would like to thank Fulbright for my grant to study in the United States, LASPAU for administering my scholarship, and the Ministry of Education of Chile MECESUP program, which helped fund my studies.

I am grateful to Pontificia Universidad Católica de Chile for its support and funding to pursue this degree, and for my colleagues at the College of Architecture, Design and Urban Studies and also at the Design School who have supported me to make this possible, most notably José Rosas, Mario Ubilla, and José Manuel Allard.

I wish to thank Kent Blaylock with the Office of Graduate Education of Arizona State University for the administration of my grant and for providing funding for the completion of my research.

Finally, I am eternally grateful to my wife Cata for her love and intellectual company throughout my studies and research. Without her hard and generous work in taking care of our children and home it would have been impossible for me to finish my degree.

TABLE OF CONTENTS

Page

LIST OF TABLES ix

LIST OF FIGURES x

INTRODUCTION 1

Background to the research 1

Research problem 2

Justification for the research 2

Methodology 3

Outline of the dissertation 4

Definitions 4

Summary 7

LITERATURE REVIEW 8

Introduction 8

Parent fields of study 9

Design. 9

Environmental science. 14

Economics 22

Immediate fields of study and research questions 25

Page

Environmentally responsible approaches to design. 25

Sustainability. 41

Use of environmentally responsible design and assessments. 57

Summary 70

METHODOLOGY 72

Introduction 72

Justification for paradigms and research methods 72

Research about environmentally responsible design approaches. 72

Research about projects of an environmentally responsible business firm. 75

Research procedures 82

Content analysis of environmentally responsible design approaches. 82

Case studies of projects within an environmentally responsible business firm. 90

Ethical considerations 107

Summary 107

RESEARCH FINDINGS 108

Introduction 108

Environmentally responsible design and sustainability approaches. 108

Evolution of the Ecodesign Strategy Wheel. 108

Content analysis of Design for Environment Typology. 123

Page

Content analysis of Ecodesign Strategy Wheel version Okala 2013. 125

The Natural Step. 128

Research findings: Case studies of projects within Interface Inc. 138

Company information 138

Research participants 141

Main topics. 148

Transversal related themes. 181

Influencing factors for environmentally responsible design and development..... 188

Conclusion 201

Summary 202

CONCLUSIONS AND IMPLICATIONS 203

Introduction 203

Conclusions about the research questions 203

Environmentally responsible design theory. 203

Environmentally responsible design in Interface. 204

Use of life cycle assessment in Interface. 206

Conclusions about the research problem 207

Implications for theory 208

Implications for education. 208

Page

Implications for policy and practice 209

Private sector managers. 209

Public sector policy analysts and managers. 210

Further research 211

REFERENCE LIST 212

APPENDIX

A INSTITUTION REVIEW BOARD FORMS 220

LIST OF TABLES

Table Page

1. Sources of ecodesign strategies tools analyzed and short names assigned...............109

2. Environment-Targeted Product Development Design Strategies from the PROMISE Manual..111

3. Comparison of Promise 1994 with UNEP 1997..112

4. Comparison of UNEP 1997 with TU Delft 1998, strategies 1 to 5...........................114

5. Comparison of UNEP 1997 with TU Delft 1998, strategies 6 to DFE managerial actions...115

6. Comparison of UNEP 1997 with Okala 2007, strategies 1 to 3...............................117

7. Comparison of UNEP 1997 with Okala 2007, strategies 4 to 7...............................119

8. Comparison of Okala 2007 with Okala 2013, strategies 1 to 4................................121

9. Comparison of Okala 2007 with Okala 2013, strategies 5 to 8................................122

10. Financial information about Interface, Inc. for fiscal year 2012............................139

11. Interface’s markets per region for fiscal year 2012..139

12. Amounts of Interface’s personnel and their functions for fiscal year 2012...........140

13. Interviewees for research about Interface Inc., female participants.......................142

14. Interviewees for research about Interface Inc., male participants..........................143

LIST OF FIGURES

Figure Page

1. Classification model of the literature reviewed. 13

2. Names used to refer to ecodesign, literature sources, and relations by citations....... 86

3. Relationships between ecodesign strategies tools analyzed and compared.............112

4. Content analysis results of The Natural Step's system condition 1: recommendations for materials from the Earth's crust extraction and handling.......................................132

5. Content analysis results of The Natural Step's system condition 2: recommendations for production of substances created by society...133

6. Content analysis results of The Natural Step's system condition 2: recommendations for handling substances created by society..134

7. Interface's manufacturing plants and headquarters offices......................................140

8. Photograph of a TacTile holding four carpet tiles by the corners from underneath..149

9. Diagram of product construction...151

INTRODUCTION

Background to the research

Since the beginning of the Industrial Revolution human activities in the context of industrialized societies have damaged the natural environment at an unprecedented scale (Vitousek, Mooney, Lubchenco & Melillo, 1997). Our economy is based on extracting materials from nature and putting them to human use and disposal at increasing speed (Daly & Farley, 2011). Resource productivity is quite low and most materials extracted are lost before becoming part of products or providing human benefit (Schmidt-Bleek, 2000). As a result, we lose natural capital which is fundamental to sustain life on the planet long term, including human life (Stahel, 2010).

Businesses are powerful types of organizations that have provoked the largest part of this damage through their activities and for the same reason they are a fundamental part of the solution (Hawken, 2010). Product design and manufacturing, by creating the artifacts that we use on our daily lives, have a significant share of responsibility for negative impacts. During the design process, important decisions are made that determine products' environmental performance, including durability, materials and manufacturing processes used, and possibilities of treatment at the end of their useful life (Graedel & Allenby, 2010). During the design process most environmental impacts are locked into the product by choosing materials and determining product performance (Lewis & Gertsakis, 2001). It has been acknowledged that for most products around 90 percent of their negative impacts on the natural environment throughout its existence are defined during the design process (Design Council, 1997, as cited in Yang, 2005; Chouinard, 2013).

Coming from fields as diverse as environmental science, product design, engineering, process design, chemistry, and physics, a number of approaches have been developed to create products that are better for the natural environment and human health, as well as methods to measure their environmental impacts. Also, sustainability approaches have been proposed that are relevant for environmentally responsible product design and development and also address how to improve social and economic impacts.

Research problem

This research investigates the use of environmentally responsible design and sustainability approaches by product manufacturing business firms with commitment to become more environmentally responsible. Two research questions are answered:

What are major approaches to environmentally responsible design, and how can they be characterized and compared?

How are environmentally responsible design approaches and assessment methods used in product design and development by a U.S. business firm with commitment to environmental responsibility?

Justification for the research

A number of theoretical approaches to design products exist that aim to minimize environmental impacts. Several sustainability approaches also address areas of intervention to improve how our society manages resources to live on Earth with a long term perspective considering environmental, social and economic aspects. These sustainability approaches address at varying degrees topics that are relevant for product design and development. We need to analyze what these theories propose and how they should be used by manufacturers that want to improve the environmental performance of their products.

On the other hand several studies address the use of environmentally responsible and sustainability approaches in product design by manufacturers, as well as the use of environmental assessment methods, and the needs of designers that work on these topics. Nevertheless, the information that these studies provide is not detailed enough to allow understanding the complexities of the integration of the design theories abovementioned in real product design and development. Furthermore, there is demand for case studies of successful implementation of these theories for products in the marketplace.

Methodology

A method known as content analysis is used to answer the first research question. The units of analysis are texts from several publications about environmentally responsible design and sustainability.

A case study approach is used to answer the second research question. In order to investigate how a company has implemented environmentally responsible design, two projects representing best cases of successful integration and environmental results are studied. Within the case study three sources of data are used. The first source is people who are experts in the projects, environmental assessments, sustainability company-wide, and the owner of the company who initiated their journey to sustainability. The data is collected using interviews. The second source is internal documentation and archival material facilitated by the company. The third source is published literature. The research uses an inductive approach and the data is analyzed using qualitative techniques.

Outline of the dissertation

Chapter 1 introduces the research background, the research problem and justification, and also defines key terms used throughout this dissertation. Chapter 2 presents a literature review structured to include from broader to more specific parent fields of study, immediate fields of study, research problem area, and identifies research gaps. Chapter 3 elaborates about the research methodology and explains in detail how research procedures were conducted. Chapter 4 presents and discusses the research findings without drawing conclusions. Chapter 5 presents the conclusions of this research which are based on relationships between the various kinds of research findings and the literature review.

Definitions

Definitions adopted by different researchers may not be uniform, and the meanings of terms across fields of study often differ. Therefore, key terms are defined in this section to establish positions taken in this dissertation. Also, the use of first person and terms referring to this document and the research it reports are discussed.

The terms this dissertation, or the dissertation refer exclusively to the researcher's report, i.e. the document that you are reading. This is important to avoid confusion with other doctoral theses that have been reviewed. The term this research is used exclusively to refer to the research that is reported in this dissertation.

The terms I and me refer to the researcher and their uses are very limited. They are used when research procedures and results are explained to make clear what was done by the researcher and to avoid confusion that might arise if I referred to the researcher in the third person. Also these terms are used to reflect awareness that the researcher cannot be independent of the field data (Perry, 1995).

The term Product includes material products and services (Baumann & Tillman, 2004; ISO-14044, 2006). Products are what a company sells, and processes are the techniques by which the products are made (Graedel & Allenby, 1996). Of course, machinery and capital goods are products for the companies that make and sell them, but they are still bought and used by their customers as process tools to make their own products (Graedel & Allenby, 1996).

A product's main stream is the stream of materials entering the product, whereas its lateral streams are materials or energy not intended to enter the product but which are required for the process (Wenzel, Hauschild, & Alting, 1997). Residues can be derived from main and lateral streams. These residues are known also as product residues and process residues (Graedel & Allenby, 1996).

Consumable products are purchased to be consumed, i.e. converted by chemical reaction into energy and byproducts, and they are normally put out into the natural environment after only one use (Braungart, 1994). Service products are not consumed; rather they provide some service to the user over and over again (Braungart, 1994).

Service economy is an industrial model in which people obtain the service they want from a product without owning it (Hawken, Lovins, & Lovins, 1999). An example is having the service of cold food at home instead of owning a refrigerator. This meaning of service economy is used in this dissertation, and not the conventional meaning as an economy in which people work more providing services than in the productive sector (Hawken, Lovins, & Lovins, 1999).

The term product system refers collectively to the processes into which a product enters from extraction or raw materials to end of life disposal (Wenzel, et al. 1997).

The consecutive and interlinked stages of a product system, from material acquisition or generation from natural resources to final disposal, are known as a product's life cycle (ISO-14044, 2006). The term life cycle has been applied to both business activities and material balance studies (Keoleian, Menerey & Curran, 1993). In business use, a product life cycle begins with the first phases of design and proceeds through the end of production, including research, marketing, and service to support products (Keoleian, et al., 1993). In contrast, environmental inventory and impact analysis follows the physical system of a product, in which materials and energy flows and transformations are tracked from raw materials acquisition to the ultimate fate of residuals (Keoleian, et al., 1993). This second meaning is used throughout this dissertation.

The United Nations define environmental impact as a "direct effect of socio-economic activities and natural events on the components of the environment." (1997).

This term is used in this dissertation to refer only to the impacts derived from human activities.

Renewability describes the capacity of a material to be replenished by nature quickly enough to meet present and near-term demand (Keoleian, et al., 1993).

Recycling is when the materials of products, at the end of their use life, are processed to be converted into raw materials so they can be used to manufacture new products or parts. Materials can be recycled into the same product several times, in what has been called a closed loop, or used to make other products before eventual discard which is the case of open loop recycling (Keoleian, et al., 1993). When the recycling techniques used lead to a gradual deterioration of the original qualities of a material, the process is called downcycling (Tischner, Schmincke, Rubik & Prosler, 2000).

Throughput has been defined as "... the flow of natural resources from the natural environment, through the economy, and back to the environment as waste" (Daly & Farley, 2011, p. 6).

Summary

This chapter introduced the main elements of this research. The context in which this research takes place was presented. Then the research problem, research questions, their justification and research methodology were briefly described. The dissertation was outlined, and definitions of terms were provided. This dissertation proceeds with a detailed description of the research.

LITERATURE REVIEW

Introduction

Chapter 1 introduced the research reported in this dissertation by outlining a background to the research, the research problem, its justification, and the research methodology. Then an outline of the dissertation was presented and key definitions.

Chapter 2 aims to build a theoretical foundation upon which this research is based. The literature consulted concentrates not only on the area of the specific research problem but also on other areas of knowledge with which it is connected. Figure 1 presents a model that classifies the topics covered by the literature review.

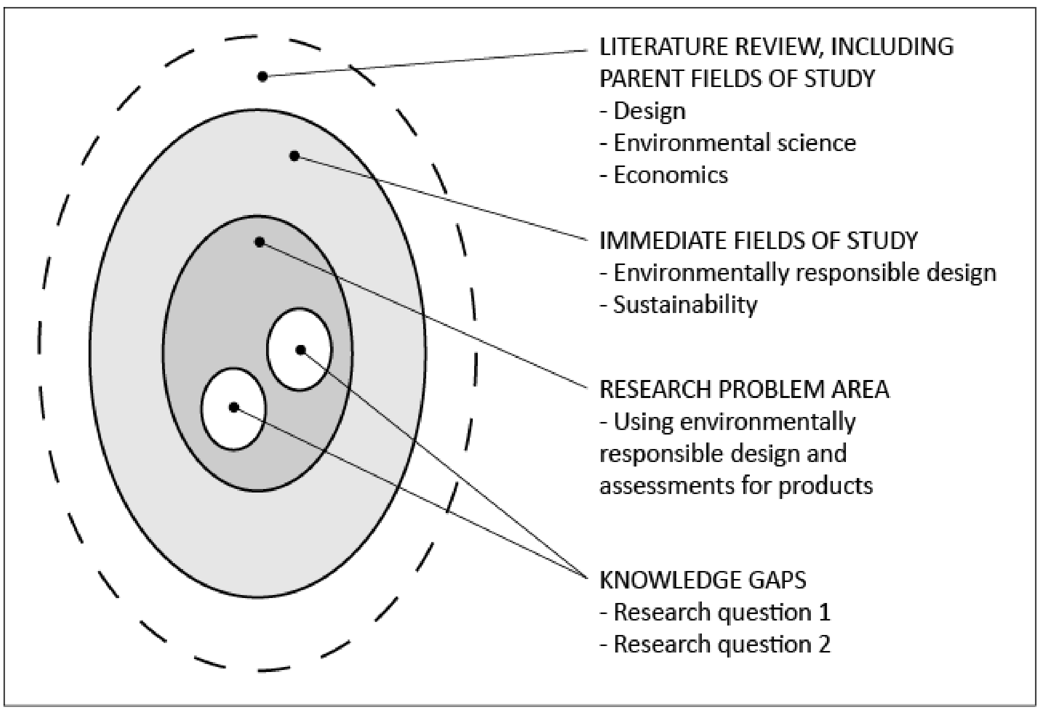

Figure 1. Classification model of the literature reviewed.

The literature review follows a field of study approach, rather than a historical approach. The parent disciplines considered are design, environmental science, and economics, as conventionally conceived. The immediate fields of study reviewed are environmentally responsible design, and sustainability; within them, specific approaches that are relevant to make more environmentally sound products are reviewed, and assessment methods are discussed as well. The research problem area is the implementation of environmentally responsible or sustainability approaches in product design including environmental assessments, within which research studies about their use are reviewed. From reviewing the literature, the research questions of this dissertation emerge, which are explicitly formulated in its last section.

Parent fields of study

Design.

Definitions of design.

In the book *The Sciences of the Artificial* Herbert Simon explained that the scientific disciplines traditionally have been concerned with understanding and explaining how the natural things work, while the professional disciplines have been concerned with the artificial things: how to make artifacts with desired properties and how to design (1996). This distinction puts science and design at opposite ends, being the aim of science to create knowledge about nature, and the aim of design to create the artificial.

Simon also defines design as follows: “Everyone designs who devises courses of action aimed at changing existing situations into preferred ones.” (1996, p. 111). The verb devise according to the *Merriam-Webster’s Collegiate Dictionary* is “to form in the mind by new combinations or applications of ideas or principles” (2008, p. 342), and the adjective preferable is “having greater value or desirability” (2008, p. 979). Therefore, in Simon’s definition design is a verb that refers to creative thought whose outcomes are courses of action to change existing situations into more valuable or desirable ones. Since no one would prefer a new situation that is worse than an existing one then the new situation must be better, which means that design has the role of making things better. Simon’s definitions are important for this dissertation because of the distinction he makes between the objectives of science and design, and because he assigns to design a role of making things better.

Ken Friedman defines design as a process: “Design is first of all a process. The verb design describes a process of thought and planning. This verb takes precedence over all other meanings.” (2000, p. 9). A plan is a detailed formulation of a program of action (*Merriam Webster’s Collegiate Dictionary*, 2008). Both Friedman and Simon define design as a verb, and this characteristic allows the word having the many uses it has: we can hear about designing a car, designing a power plant, and designing a marketing strategy. All creative activities that try to achieve better situations can be included. Reviewing other definitions will help to frame design as a parent discipline for this dissertation.

According to Norman Potter every human being is a designer, and also some people earn their living by design ". . . in every field that warrants pause, and careful consideration, between the conceiving of an action and a fashioning of the means to carry it out, and an estimation of its effects." (2002, p. 10). In this definition, while design is intrinsic to being human, a clear distinction is made for design as a profession where, careful consideration is given to conceive an action, device the means to carry it out, and also estimating its effects. Then, doing design in a thoughtful and systematic way makes the difference between the design professions and any other spontaneous human adaptation of means to ends (Potter, 2002). Potter distinguishes three main categories of design professions according to what they create: "product design (things), environmental design (places) and communication design (messages)." (2002, p. 11). For the purpose of this dissertation the most relevant is product design, which is also often referred to as industrial design.

The Industrial Designers Society of America (IDSA) defines industrial design as ". . . the professional service of creating and developing concepts and specifications that optimize the function, value and appearance of products and services, for the mutual benefit of both user and manufacturer." (2009). Here, the verbs creating and developing indicate that design is a process, in accordance with the previous definitions reviewed, and the nouns concepts and specifications refer to abstract ideas and detailed formal plans, respectively. Within industrial design, product design and process design can be distinguished (Graedel & Allenby, 1996). IDSA's definition mentions user and manufacturer as the recipients of the benefits of design. It is important to consider that in addition to these, other parties exist which benefit from design or suffer their consequences; like society, and the natural environment (Papanek, 1985).

Based on these definitions of design, it can be concluded that the word has meanings as a verb that describes creative processes going from early generation of ideas to detailed planning and specifications, and also as a profession within which processes, products and services are created.

The product system from a life cycle perspective.

A life cycle approach is a holistic way of understanding product systems (Keoleian et al., 1993). By putting information about impacts in the hands of decision makers at the right time, life cycle thinking offers a way to improve them (United Nations Environment Programme/Society of Environmental Toxicology and Chemistry [UNEP/SETAC], 2013). In the public sector, life cycle thinking can help for the development of policies, procurement, and for provision of services; and in the industrial sector it allows going beyond traditional approaches that focus only on specific production sites or manufacturing facilities, to incorporate all relevant actors in a product's value chain (UNEP/SETAC, 2013).

Four broad stages can be identified in a product's life cycle: material acquisition, manufacturing, use, and end of life (Wenzel et al., 1997; Lin & Lin, 2006). These stages include several processes within them. Material acquisition includes extraction of virgin resources from nature and material production (Lin & Lin, 2006; Graedel & Allenby, 2010). Within extraction, mining and harvesting biomass take place (Keoleian, et al., 1993). During material production, bulk materials are processed into base materials following separation and purification steps (Keoleian, et al., 1993). Also, some base materials are combined through physical and chemical means into engineered and specialty materials (Keoleian, et al., 1993).

The second stage is manufacturing, where materials are processed through various fabrication steps and parts are assembled into a final product (Keoleian, et al., 1993; Graedel & Allenby, 2010). Packaging of the product can be included in this stage (Baumann & Tillman, 2004; Lin & Lin, 2006). Packaging can also be included in a separate next stage of distribution or shipping (Keoleian, et al., 1993; Graedel & Allenby, 2010).

Next follows the customer use stage (Graedel & Allenby, 1996; 2010). During this stage the product delivers to the user the functions or services that it was designed for. This stage is influenced by how products are designed and by the degree of continuing manufacturer interaction (Graedel & Allenby, 2010). A product can be either used or consumed (Keoleian, et al., 1993). An example of the former is an automobile, which consumes gasoline to provide the service of transportation; and an example of the latter is gasoline, which is converted into energy and byproducts by the car’s engine. Throughout their use life, service products and processing equipment (capital goods) may be serviced to repair defects or maintain performance (Keoleian, et al., 1993). The use stage ends when the user eventually decides to retire a product (Keoleian, et al., 1993).

After product use the next and final life cycle stage is end of life. During end of life the product or its parts may follow different paths including reuse, remanufacture, recycling or disposal (Rose, 2000). In the case of reuse the product is traded as second hand to be used as originally designed (Rose, Ishii & Masui 1998). Remanufacturing involves disassembling products to recover parts that are cleaned and repaired so they can be used in making new products (Rose, et al., 1999). In the case of recycling the materials are processed to be converted into raw materials so they can be used to manufacture new products or parts. The decisions taken during product design strongly influence whether reuse, remanufacture, or recycling may take place (Keoleian, et al., 1993).

Transportation is used throughout life cycles, within each stage and between stages as well. A specific stage of distribution or shipping can be considered together with packaging after manufacturing (Graedel & Allenby, 2010). Sometimes distribution is included in the use stage (e.g. Saouter & van Hoof, 2001).

Viewing the product system from a life cycle perspective is important to understand its complexity and to identify the different elements that compose it. This is useful for analytical purposes because a complex system is divided into smaller parts that are more manageable for analysis. It is also useful for design because it allows identifying elements of the product system which are not obvious but will be affected by design decisions.

Environmental science.

Definition and brief history.

Environmental science has been defined as the systematic study of our environment and our place in it (Cunningham & Cunningham, 2002). The environment encompasses two worlds: the natural world of soils, air, water, plants and animals; and the world of social institutions, built environment and artifacts that we create for ourselves (Cunningham & Cunningham, 2002). Both worlds are essential to our existence, and their integration causes enduring tensions (Cunningham & Cunningham, 2002). Environmental science integrates knowledge from biology, chemistry, physics, geography, agriculture, engineering and many other fields (Cunningham & Cunningham, 2002). In order for this knowledge to improve how we treat our world, environmental scientists also incorporate knowledge of social organization, politics and the humanities (Cunningham & Cunningham, 2002).

The origins of environmental movement in the United States can be traced to the 19th century when the U.S. Census demonstrated the closing of the frontier, which meant that no area of the country could be considered totally inhabited (Wright & Nebel, 2002). Around that time several conservation groups were formed, including the National Wildlife Foundation and the Sierra Club founded in California by naturalist John Muir (Wright & Nebel, 2002). World War I and World War II brought significant technological achievements, from rocket science to computers and from pesticides to antibiotics, and also an enormous production capacity which was put to work for peacetime applications (Wright & Nebel, 2002). Economic expansion brought increasing material wealth to the people and at the same time environmental problems became obvious, for example smoke in the air from coal burning irritated people’s eyes and respiratory system, rivers were contaminated with sewage and chemicals, and bird populations declined (Wright & Nebel, 2002). In 1962 Rachel Carson published *Silent Spring*, where she exposed several environmental problems derived from the use and later dispersion of toxic pesticides and other chemicals. The publication of this book represents the beginning of the modern environmental movement in the U.S., after which several environmental laws were launched (Carson, 1997; Hawken, 2010).

Environmental impacts.

The environmental impacts of a product are derived from the processes into which it enters (Wenzel, et al., 1997). During these processes substances or energy are exchanged with the surroundings, and only if there is an exchange with the surroundings environmental impacts can occur (Wenzel, et al., 1997). This environmental exchange takes place when there is an input to a process, an output from a process, or an internal interaction with an operator of the process (Wenzel et al., 1997).

Environmental impacts can be categorized into two broad groups: a) depletion categories, which include abiotic resource depletion, biotic resource depletion, land use, and water use; and b) pollution categories, which include ozone depletion, global warming, human toxicology, eco-toxicology, smog formation, acidification, eutrophication, odor, noise, radiation, and waste heat (Bare, Norris, Pennington & McKone, 2003).

Environmental impacts can be derived from chemical or physical actions on the environment. Chemicals or mixtures of chemicals emitted to air, water and ground have effects on the environment depending on their quantity, impact potential, and exposure (Wenzel et al., 1997). Impact potential is a substance's inherent hazardousness, or ability to trigger a given impact; exposure is the degree to which the substance reaches parts of the environment where the impact can be exerted; and quantity is the amount of the substance released (Wenzel et al., 1997). The relationship between these elements can be expressed using the formula:

Impact = quantity x impact potential x exposure (Wenzel et al., 1997).

An example of environmental impacts from chemical action is acidification, where a number of gases emitted to the atmosphere from burning fossil fuels are transformed through oxidation and hydrolysis to acidifying substances that can deposit as dust or acid rain, which then dissolve metals that may cause undesirable effects on terrestrial and aquatic ecosystems like forests and fish habitats, man-made resources, and even human health (Jolliet et al., 2004; Wenzel et al., 2007; White, Belletire & St. Pierre, 2007). An example of impacts derived from physical action is deforestation, one of the first serious physical impacts to which man have subjected the environment (Wenzel et al., 1997).

Environmental impacts of products from a life cycle perspective.

Products impact the natural environment throughout their life cycles. Some residuals generated in all stages are released directly to the environment (Keoleian et al., 1993). Emissions from automobiles, waste water discharges from processes, and oil spills are examples of direct releases (Keoleian et al., 1993). Residuals may also undergo physical, chemical or biological treatments which are usually designed to reduce volume and toxicity of waste (Keoleian et al., 1993). The remaining residuals including those resulting from treatment are then typically disposed in landfills, although the ultimate form of residuals depend on how they degrade after release (Keoleian et al., 1993).

The environmental impacts of products begin with material acquisition. Extraction usually involves the displacement of large quantities of materials, consumes significant amounts of energy, generates plenty of waste, and release hazardous emissions to air, water, and soil causing severe environmental impacts (Lin & Lin, 2006). Production of materials often causes a dominant proportion of the environmental impacts of a product throughout its life cycle (Baumann & Tillman, 2004). For example, to produce one ton of copper in the United States more than 500 tons of inert materials are moved and over 165 tons of ore are processed (Lin & Lin, 2006). The energy used to produce one ton of refined copper is between 100 GJ and 200 GJ, depending on the grade of the ore (Lin & Lin, 2006). Also, as arsenic often exists in copper ore, large amounts of this poisonous element are released in leach liquor from mining and vapor from smelting (Lin & Lin).

The manufacturing of products produces substantial amounts of emissions to the environment which are direct consequences of the manufacturing processes being used (Graedel & Allenby, 1996). Residues from processes are released to the environment reaching air, water, or soil (Graedel & Allenby, 1996). These residues may come from the product's main or lateral streams (Wenzel et al., 1997). Industry is the largest generator of the solid waste discarded in landfills in USA (Graedel & Allenby, 1996). Solid residues can be trace-metals, plastic residues, paper residues, biological residues, radioactive residues, sludge, and mixed residues (Graedel & Allenby, 1996). Liquid residues can contain trace-metals, nutrients, suspended solids, or be solvents and oils, organics, and acids (Graedel & Allenby, 1996). Common gaseous residues of concern include chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), halons, carbon dioxide, methane, nitrous oxide, volatile organic compounds (VOC), nitric oxide, nitrogen dioxide, sulfur dioxide, and trace-metal emissions (Graedel & Allenby, 1996).

During the use stage some products impact the environment more than others. This depends on the degree of their environmental exchange during this stage (Gamage & Boyle, 2006). If a product requires energy during its use stage then this stage usually dominates the environmental profile, as has been shown by many environmental assessment studies (Baumann &Tillman, 2004). Examples of this kind of products are cars, buildings, refrigerators, and washing machines. On the contrary, for products used in a more passive manner, like furniture or packaging, the environmental profile is dominated by production, especially production of materials (Baumann & Tillman, 2004). For example, furniture does not require energy or consumables to function and the only foreseeable need is occasional cleaning, which is expected to have negligible environmental impacts (Gamage & Boyle, 2006).

During end of life the product’s materials or parts can be reused, remanufactured, recycled or disposed of as waste. By giving a product a next use life, reuse allows avoiding all the impacts derived from material acquisition and product manufacturing which would be involved in making a new product. This makes reuse the most environmentally preferable choice at the end of life of products, with the exception of products that need energy or consumables during the use stage which are less efficient than new products (Brezet & van Hemel, 1997). Remanufacturing involves drawing on nonfunctional products by retaining usable parts to make new products, which is frequently cost-effective and almost always environmentally responsible (Graedel & Allenby, 2010).

The ability of a material to be renewable or recyclable accounts largely for the product's environmental impacts (Lin & Lin, 2003). Non-renewable materials can only be replenished at an extremely low rate, if they can be replenished at all (Lin & Lin, 2003). Renewable resources can become non-renewable if the extraction rates are faster than the replenishing rates. Recycling allows using materials of a retired product to make a new one, thus saving the environmental impacts of material acquisition. Within recycling, in general closed loop is preferable than open loop (Graedel & Allenby, 2010).

Eventually every product, product subassembly, or material component is disposed of as waste. Typically a product or its parts will be put in a landfill or incinerated. In a landfill materials degrade and substances can be released to air, soil and water and create negative impacts. In the case of incineration the energy embodied in the product can be recovered (Keoleian, et al., 1993). After incineration substances are released mostly to air and from there find their way to soil and water. In any case the materials finally disperse and substances are released to nature.

Transportation typically produces emissions derived from the use of fossil fuels. The transport sector is one of the most important sources of air pollution and it accounted for 28 percent of CO_2 and 63 percent of NO_x emitted within the European Union (EC, 1999, as cited in Baumann & Tillman, 2004). In the European Union while CO_2 emissions from industry decreased by 12 percent between 1990 and 1999, CO_2 emissions from transport increased by 21 percent during the same period (Baumann & Tillman, 2004). In USA the freight transportation sector has had the fastest growth in energy use compared to all other sectors from 1970 to 1995 (Vanek & Morlok, 2000, as cited in Baumann & Tillman, 2004). Growth in average length of haul for shipments, complexity of supply chains and the increasing importance of imports and exports in the total mix of goods have all contributed to increase this sector’s energy use (Baumann & Tillman, 2004).

Transport emissions may be small for many product groups, but they are considerable for others like food products, wood products and clothing (Vanek & Morlok 2000, as cited in Baumann & Tillman, 2004). For example, a life cycle assessment study focusing on transport systems for bananas showed a total of fossil CO2 emissions of 135g for one banana, which is almost equal to the weight of the banana itself (Bäckström 1999, as cited in Baumann & Tillman, 2004). Another product group with considerable transport emissions is building products (Baumann & Tillman, 2004).

As can be seen, significant environmental impacts are derived of products and the system that surrounds them. Realizing the impacts that our society has had on the environment gave birth to environmental science. It is useful to view the product system with a life cycle approach to understand when and how environmental impacts are produced, and also to design the product system in order to minimize these impacts. Some authors have pointed out that around 90 percent of a product’s environmental impacts are defined during the design process (Yang, 2005; Chouinard, 2013). This means that design has contributed largely to the problem of environmental degradation; it also means that it has an important role in its solution.

Economics

Definition.

Economics has been defined as the study of the allocation of limited resources among alternative, competing ends (Daly & Farley, 2011). It is assumed that these ends, human needs and wants, are constant and unlimited, and that the resources to satisfy them are scarce (Martín, 2003). Within these assumptions the economic problem resides in choosing among limited resources to meet unlimited needs and wants, and people have to deal with this problem from the individual to the societal scales (Martín, 2003).

Relationship between the economy and environmental impacts.

The scale of the human economy is a function of throughput – the flow of materials and energy from the sources in the environment, used by the human economy, and then returned to environmental sinks as waste (Goodland, 1995). Throughput growth is a function of population2growth and consumption, which translates into increased rates of resource extraction and pollution (Goodland, 1995). In today's industrial economy, a higher throughput means economic growth and an increased GNP as well as higher corporate revenues and more jobs; but this also means that the high standard of living in industrialized countries is based on high resource consumption (Stahel, 2010). So far, the scale of throughput has exceeded environmental capacities (Goodland, 1995). Hence, a globalization of the industrial economy's business model is not feasible, nor is the present industrial throughput economy compatible with a global future (Stahel, 2010).

Stahel divides economic history into three stages: Stone Age economy, industrial economy, and performance economy (2010). Today we are living in the industrial economy, which still has many characteristics of the Stone Age economy, and is beginning to have elements of the performance economy (Stahel, 2010). In simple terms, these three stages of economic history represent a gradual uncoupling of wealth creation from resource throughput; going from bulk goods to smart goods (Stahel, 2010). For example, the Stone Age economy means earning cents/kg, like the case of sand and gravel, or steel; in the industrial economy earnings are $/ kg, like what happens with automobiles; and in the performance economy, earnings are millions/g, like for example what happens to a certain extent with memory sticks, and much more with interferon (Stahel, 2010).

Having an economy based on resource throughput is certainly a way of destroying the natural environment. But the main goal of the economy is to provide wellbeing to the people. Does this means that growing the economy will also grow people wellbeing? It is necessary to take a closer look at how the health of the economy is measured to answer this question.

Economic growth is measured as the percent rate of increase in real Gross Domestic Product (GDP) over a period of time (Martín, 2000). The factors that determine economic growth are labor, natural resources, capital, and technological advances (Martín, 2000). GDP represents the monetary value of the aggregated final goods and services produced in a country during a certain period of time (Martín, 2003). Since GDP may increase over time and the population as well, the unit GDP per capita (GDP/population) is also used so that the goods and services available to the inhabitants of a country are reflected (Martín, 2000). While GDP refers to production within the geographical boundaries of a country, Gross National Product (GNP) allocates production based on ownership, i.e. it measures the value of goods and services that a country's citizens produced regardless of their location (Martín, 2000).

Economic progress and national wealth are often expressed in terms of GDP (Schmidt-Bleek et al., 1994). Also, economic growth has been used as a measurement of economic development. Todaro & Smith clustered classic theories of economic development from the 1950s until present into four main groups: linear-stages-of-growth models, theories and patterns of structural change, international-dependence revolution, and neoclassical counterrevolution or market fundamentalism (2009). Although these theories provide different understandings about how economic development should be attained and recommendations to make progress, all of them express it in terms of GDP. Within the present economic system it is assumed that growth in total output, expressed as GDP, maximizes human well-being (Hawken, Lovins & Lovins, 1999).

Although it is widely used in national accounting, GDP has been pointed out as an inadequate metric to express human well-being and ecological health because it measures just the monetarised exchange at the point of sale (Stahel, 2010). For example, traffic accidents have the same short-term impact on GDP and on the bottom line of hospitals as finding a better cure for illnesses (Stahel, 2010). Also, the health and wealth lost in traffic accidents are not deducted from national assets (Stahel, 2010). Similarly, economic wealth measured as GDP does not consider wealth reduction in natural capital, for instance through pollution and loss of biodiversity; indeed, actions to clean-up pollution and to eliminate waste are added to the GDP despite the fact that overall wealth has been lost (Stahel, 2010).

It becomes apparent that the economic system has been based for the most part on resource throughput, and over time this has strongly damaged the natural environment. This also means that to the extent that the natural environment is damaged, it will fail to provide to the human economy what it needs to function. Although the objective of the economy is to provide human wellbeing, by measuring the success of the economy using other metrics there is no way of knowing if human wellbeing is being accomplished. Meanwhile, economic growth continues to be measured in terms of GDP and GNP, which increases resource throughput thus reducing nature's capacity to feed the economy in a vicious circle.

Immediate fields of study and research questions

Environmentally responsible approaches to design.

A number of approaches to design have been proposed so the environmental impacts of products can be minimized. These approaches affect the environmental performance of products although their interventions are not necessarily at the product level. Socio economic aspects are also addressed to varying degrees. Some of these approaches are discussed in this section.

Service economy.

During the 1980s, industry analyst Walter Stahel and chemist Michael Braungart independently proposed a new industrial model, called a service economy, in which people obtain the service that they need from a product without owning it (Hawken et al., 1999). For example, one would have a washing machine to use at home that still belongs to the manufacturer, who is responsible for its maintenance, repair, replacement, and end of life treatment thus liberating the user from these responsibilities (Braungart, 1994). Because products would be returned to the manufacturer, Stahel called the process cradle to cradle (Hawken et al., 1999).

This model, by allowing people to purchase results rather than equipment, can help reduce environmental impacts during use and end of life (Hawken et al., 1999). For example, a refrigerator consumes significant amounts of electricity in use, so the use stage dominates its life cycle environmental impacts. When the consumer owns the refrigerator normally he or she keeps it for many years. When new more efficient refrigerators are made, it is unlikely that the owner of an old refrigerator that still works will replace it. In the service economy model, by means of a take-back program the manufacturer will replace the old refrigerator with a new one that uses less electricity because it has more efficient technology, and then the environmental impacts of its use at home will be reduced. Furthermore, the manufacturer will reuse, refurbish, or remanufacture parts of the old refrigerator; and recycle materials, reducing its environmental impacts at end of life, and also save money and impacts from making new parts from virgin materials.

Braungart's view of a service economy is focused on material cycles. Based on nature's metabolic processes he proposed two alternative cycles into which the materials of a product should be integrated at end of life: a biological cycle where materials degrade and safely return to nature, and an industrial or technical cycle where parts or materials are used to make more products in a closed loop (Hawken et al., 1999). In Braungart's view, consumable products should be biodegradable or abiotically degradable, non-bioaccumulative, non-carcinogenic, non-teratogenic, non-mutagenic, and in used concentration non-toxic to humans, so they can be integrated in biological cycles; and products of service could be less constrained in terms of constituent materials but more constrained in terms of management and disposal, which can be allowed by using a closed technical loop (1994).

Biomimicry.

The term Biomimicry is based on the Greek *bios*, life, and *mimesis*, imitation (Benyus, 1997). Biomimicry is a science that studies nature's models, to imitate or take inspiration from these designs and processes to solve human problems (Benyus, 1997).

Biomimicry uses an ecological standard to judge the "rightness" of our innovations, based on the fact that after 3,800,000,000 years of evolution nature has learned what works, what is appropriate, and what lasts (Benyus, 1997).

Biomimicry is a way of viewing and valuing the natural world, which is different from how current industrial systems do it; it is based not on what we can extract from nature, but on what we can learn from her (Benyus, 1997).

Green Design, Design for Environment, and Industrial Ecology.

Historically, several terms have been used to refer to the design and development of products in ways that consider their environmental impacts. The most well-known names are Cleaner Products, Green Design, Design for Environment, Ecodesign, Sustainable Product Development, and Life Cycle Design (van Hemel, 1998). All of these terms refer to design approaches aspiring to reduce the product's environmental impacts (van Hemel, 1998).

In the 1970s, Green Design started to incorporate research about the environment in design practice (Yang, 2005). In the 1980s, Ecodesign and Design for Environment incorporated the life cycle perspective and consolidated environmentally responsible design approaches in the design and engineering fields (van Hemel, 1998; Yang, 2005). In the 1990s, following the publication of the *Brundtland Report*, some of the literature about environmentally responsible design incorporated to some extent social and economic aspects necessary for sustainable development.

Graedel and Allenby describe three types of systems from the perspective of how materials flow through them (1996). Type I are linear in which resources enter the system, they are processed, and waste comes out; type II are semi cyclical in which limited resources enter plus energy, materials are processed cycling inside the system, and limited waste comes out; and type III are cyclical in which resources and waste are undefined, energy enters the system, and materials are processed and cycle inside the system (Graedel & Allenby, 1996). Considering this, Design for Environment is intended to accomplish the evolution of manufacturing from type I associated to the Industrial Revolution, to type II systems and ideally type III (Graedel & Allenby, 1996).

Design for Environment means that consideration of the environment helps to define the direction of design decisions, just like profit, functionality, aesthetics, ergonomics, or quality, and should ultimately lead to sustainable production and consumption (van Hemel, 1998). Two broad areas of design are considered within Design for Environment, which heavily affect industry-environment interactions: product design, the products and services that a company sells; and process design, the techniques and associated machinery to make products (Graedel & Allenby, 1996).

Frosch and Gallopoulos, of the General Motors Research Laboratories, published a paper in 1989 considered by many as the first publication in the field of Industrial Ecology (Graedel & Allenby, 2010). Industrial Ecology has been defined as ". . . the study of technological organisms, their use of resources, their potential environmental impacts, and the ways in which their interactions with the natural world could be restructured to enable global sustainability." (Graedel & Allenby, 2010, p. 41). It employs a holistic view to study, assess, and improve the utilization of natural resources (materials, energy, and the assimilative capacity of the environment) in an industrial society, (van Berkel, Willems & Lafleur, 1997).

Ecodesign.

Ecodesign introduces environmental considerations side by side with economic and other traditional criteria for product design and development from the very beginning, to make a product that is more environmentally sound in every stage of its lifecycle (Tischner, Schmincke, Rubik, & Prösler, 2000). The German Federal Environmental Agency defines ecodesign as follows:

> Ecodesign means environmentally conscious product development and design. This term describes a systematic manner which aims at including environmental aspects in the product planning, development and design process at the earliest

> possible opportunity. This means that 'environment' is added as a criterion of product development alongside other classical criteria of functionality, profitability, safety, reliability, ergonomics, technical feasibility, and, last but not least, aesthetics. The term eco-design directly expresses the fact that **Eco**logy and **Eco**nomy must be joined inseparably by means of good **design** in eco-design procedures (Tischner, et al., 2000, p. 12).

Ecodesign represents general criteria and procedures to include the environmental performance of the product early in the product developing process. The process of ecodesign itself is not essentially different from conventional product planning processes (Tischner et al., 2000). Its goal though, is to integrate environmental aspects into this process. Some of these aspects include using a minimum of resources, energy, and land area; and minimizing waste and pollutant emissions (Tischner et al., 2000). Ecodesign fits into the concept of sustainable design, addressing environmental responsibility and economic profit (Tischner et al., 2000). This is done through the lens of life cycle thinking, which means a unified view of the entire product life cycle (Tischner et al., 2000).

The document *PROMISE Manual for Environment-Targeted Product Development* published in 1994 by Dutch researchers Brezet, van der Horst & te Riele constitutes seminal work and an important reference for ecodesign. The acronym PROMISE, in Dutch, stands for product development with the environment as innovation strategy (Brezet, et al., 1994, as cited in van Hemel, 1998).

The PROMISE project was started by the Netherlands Rathenau Institute, which advises the Dutch parliament, and was part of the Sustainable Development subprogram of Rathenau (Sterrenberg, Böttcher & Hoo, 1997). The objectives of the project were to continue and bring consistency to existing ecodesign initiatives, develop ecodesign strategies and instruments applicable by companies, and to formulate policy options to promote environmental product development in business (Sterrenberg, Böttcher & Hoo, 1997).

Five sub-projects stemmed from the PROMISE project: eight pilot studies of the implementation of environmental product development in companies, development of an ecodesign manual for companies, an overview of the obstacles and possible solutions for environmental product design in businesses based on the pilot studies, a study about existing government policy regulations and possibilities to stimulate environmental product development through government policy, and finally a report from the Rathenau Institute to the Dutch parliament providing several policy options (Sterrenberg, Böttcher & Hoo, 1997).

The project drew important conclusions about the implementation of ecodesign in businesses: environmental concern can be included in the requirements and criteria already set for product development without radical interference with company operations; ecodesign is important to businesses because it can save costs through reduced use of materials and energy, by having greener products companies gain market potential and become competitive with international companies, and allows companies to deal with an increasingly stricter environmental legislation in a cost-effective way (Sterrenberg, Böttcher & Hoo, 1997).

Three important things happened after the PROMISE project. First, the Dutch Ministry of Economic Affairs, and the Ministry of Environment, Housing and Physical Planning agreed to promote the project’s results and produced information material to make companies acquainted; then, in 1994 the same ministries started an ecodesign demonstration and stimulation project for small and medium sized enterprises which included 95 firms in the first round; and finally, by request of the Dutch Ministry of Environment, Housing and Physical Planning to the United Nations Environment Programme (UNEP), the PROMISE manual was internationally adjusted and translated to English to prepare a publication usable for other countries which was funded by both institutions (Sterrenberg, Böttcher & Hoo, 1997). This UNEP 1997 publication is *Ecodesign: a promising approach for sustainable production and consumption*, by Brezet and Hemel, which became an international reference about ecodesign.

An unexpected outcome of the PROMISE project, which is worth noting, was that the people involved developed an increasing commitment as the project progressed, and the Ministries of Economic Affairs, and of Environment, Housing and Physical Planning, which did not work together prior to the project, at the end of it were convinced that environment and economics working together were much more productive and powerful (Sterrenberg, Böttcher & Hoo, 1997).

Ecodesign strategy wheel.

In 2007, a version of the Ecodesign Strategy Wheel was published by the ecodesign Section of IDSA, based on previous work published in the *PROMISE Manual* by Brezet and colleagues (White, et al., 2007). In this manual, the *MPO ontwerpstrategieën*, or environmental product development design strategies, were presented. The design strategies displayed in a circular arrangement are also known as the

LiDS (Lifecycle Design Strategies) Wheel, term that has been used in several publications.

The Ecodesign Strategy Wheel contributes to the field of Ecodesign, and identifies eight strategies addressing the life cycle stages of a product to design for:

1. Innovation. Conceptualize completely new ways to deliver the product benefit to the user (White, St. Pierre & Belletire, 2013).

2. Reduced Material Impacts. Choose qualities and quantities of materials looking for minimal environmental impacts (White et al., 2013).

3. Manufacturing Innovation. Choose manufacturing processes and optimize their use to reduce energy use, waste, production steps, and eliminate toxic emissions (White et al., 2013).

4. Reduced Distribution Impacts. Optimize packaging volume, weight, and reusability; and plan logistics to reduce impacts (White et al., 2013).

5. Reduced Behavior and Use Impacts. Encourage low consumption behavior, minimize environmental exchange during product use, and seek to eliminate toxic emissions in use (White et al., 2013).

6. System Longevity. Seek for functional, physical and aesthetic durability of products; and for easy maintenance, repair and exchange (White et al., 2013).

7. Transitional Systems. Seek for upgradability of products, second life and function, and reuse of components (White et al., 2013).

8. Optimized End-of-Life. Seek for ease of disassembly and parts recovery, ability to biodegrade, collection systems, and recycling business model, (White et al., 2013).

Within each strategy several improvement options are proposed, which are explained and illustrated by examples. For instance, strategy, design for reduced material impacts; improvement option, avoid materials that damage human or ecological health; example, lithium batteries are much less toxic than lead or cadmium batteries (White et al., 2013, p. 5). The Ecodesign Strategy Wheel constitutes a powerful brainstorming tool to explore areas of product development or improvement to reduce the ecological impacts of products (White et al., 2013).

Cradle to cradle.

McDonough Braungart Design Chemistry (MDBC), LLC, propose a proprietary Cradle to Cradle framework as an alternative design and production concept to eco-efficiency, to incorporate social, economic, and environmental benefits in goods and services (Braungart, McDonough & Bollinger, 2007). In their view, eco-efficiency has various definitions, all of which seek to get more from less with an underlying assumption of a linear cradle-to-grave flow of materials to a landfill or incinerator (Braungart, McDonough & Bollinger, 2007). In contrast, they propose eco-effectiveness as a transformation of products and associated material flows by design, so that at the end of their use life they can be integrated in either technical or biological cycles (Braungart, McDonough & Bollinger, 2007). Assuming that all products emit chemicals, the issue of toxicity is dealt with by replacing known toxic substances with others that have better eco/toxicological profiles (Braungart, McDonough & Bollinger, 2007). In products of service, however, hazardous substances for which there are no viable substitutes may be used if they are managed within a closed loop technical system (McDonough, & Braungart, 2002, p174).

MDBC propose five steps to implement Cradle to Cradle:

1- Free of. Not using materials containing chemicals that are known to be toxic for humans or ecological systems, using great care in selecting replacement substances to ensure they are better than those replaced (Braungart, McDonough, & Bollinger, 2007).

2- Personal preferences. The substances that should be included in the product must be chosen, ideally based on its impacts on human or ecological systems over its life cycle, but if this is not feasible personal preferences based on the best available information should be made (Braungart, McDonough, & Bollinger, 2007).

3- Passive positive list. Assessment of the toxicological and eco-toxicological characteristics of the substances chosen and of their capabilities to flow within the technical or biological metabolisms, to make lists according to their suitability (McDonough & Braungart, 2002; Braungart, McDonough, & Bollinger, 2007).

4- Active positive list. Defined as an optimization of step three (Braungart, McDonough, & Bollinger, 2007). During step four the product is designed from beginning to end so it can be integrated in a biological or technical metabolism (McDonough & Braungart, 2002).

5- Reinvention. Redefine the relationship between the product and the customer from the perspective of the service that the product provides (Braungart, McDonough, & Bollinger, 2007).

Environmental assessment methods for products.

While environmentally responsible approaches to design aim at creating product systems that are more beneficial for the natural environment, environmental impact assessment methods aim at identifying and measuring negative impacts of product systems on the environment based on scientific evidence.

Life cycle assessment.

Life cycle assessment (LCA) is a comprehensive method for analysis of the environmental impacts of products and services over their life cycles (Baumann, & Tillman, 2004). Released substances and use of resources derived from product systems are considered. Life cycle stages include raw material acquisition, supply transportation, product manufacturing, distribution, use, and end-of-life/disposal (Hundal, 2002; International Organization for Standardization [ISO], 2006). LCA was created in the 1970s and re-discovered in the 1990s. Today, several authors consider LCA one of the most important and comprehensive techniques to analyze the environmental impacts of products and services (Baumann, & Tillman, 2004; Bovea & Vidal, 2004; Gamage & Boyle, 2006; White et al., 2007).

The ISO provides requirements and guidelines for the use of LCA through the standard ISO-14044. This standard identifies four phases in an LCA study:

1. Goal and scope definition. The goal of the study is defined as well as its intended use and audience, breadth and depth, system boundaries, level of detail, and the functional unit (ISO, 2006; Baumann, & Tillman, 2004);

2. Life cycle inventory analysis or LCI. Compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO, 2006). It involves the collection of the data required to meet the goals specified (ISO, 2006);

3. Life cycle impact assessment or LCIA. This phase aims at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout its life cycle (ISO, 2006);

4. Interpretation. Phase in which the findings of either LCI and/or LCIA are evaluated in relation to the goal and scope of the study in order to reach conclusions and recommendations (ISO, 2006).

Two other phases may be included in LCA studies. These phases are not required by the ISO standard, but they provide a user-friendly single-figure impact score (White, et al., 2007). These phases are normalization, which expresses impacts according to a reference, for example impacts of an average person in the U.S., or globally; and weighting, which scales impact categories according to priorities of significance (White, et al., 2007).

LCA has been pointed out by several experts as an increasingly important quantitative environmental impact analysis tool for industrial products (Baumann & Tillman, 2004; White et al., 2007; Williams, Weber & Hawkins, 2009). Although research has shown that conducting LCAs may be time consuming, expensive, and difficult to gather data for (Cooper, & Fava, 2006), its use is still increasing.

LCA is a powerful tool to use alongside environmentally responsible approaches to design. Because it is product/process oriented it can be used to understand the environmental impacts of a product and therefore knowing how to modify processes or elements in its supply chain, or to evaluate design alternatives and compare results before and after their implementation.

Ecological rucksack and MIPS.

Ecological rucksack is defined as the total quantity, in kilograms, of natural material (M) that is disturbed in its natural setting and thus considered the total input (I) to generate a product, counted from the cradle to the point when the product is ready for use, minus the weight (in kilograms) of the product itself (Schmidt-Bleek, 2000).

The total mass of materials utilized (in kilograms) to make one kg of technical base materials (raw or starting) available (e.g. wood, iron, aluminum, copper, cement) is expressed as MI, called the "rucksack factor" of base materials (Schmidt-Bleek, 2000).

As examples, typical approximate MI values, or rucksack factors, of base materials are: round wood = 1.2; glass = 2; plastics = 2-7; steel = 7; paper = 15; aluminum = 85; copper = 500; platinum = 550 000 (Schmidt-Bleek, 2000).

MIPS stand for Material Intensity per unit of Service, which is a measure to estimate the ecological stress potential of goods and services from cradle to grave including energy (Schmidt-Bleek, 2000). MIPS includes material inputs per total unit of services delivered by the product over its entire life cycle (resource extraction, manufacturing, transport, packaging, use, reuse, remanufacturing, recycling, and final waste disposal), including the material fluxes associated with energy inputs (Schmidt-Bleek, 2000).

Ecological footprint.

The Ecological Footprint is an analytic tool that accounts for the flows of energy and matter, to and from any defined economy, and converts these into the corresponding land and water area required from nature to support these flows in terms of production and sink capacities (Wackernagel & Rees, 1996). It is motivated by the recognition of the material intensity that our economic activity is based on, current damage done so far to the natural ecosystems that support us, increasing global population, and the fact that measuring economic development in terms of GDP will likely make the actual situation even worse (Wackernagel & Rees, 1996).

In order to calculate ecological footprints a simplified model is built starting from some principles and assumptions: current industrial harvest practices are sustainable, which are often not; only the basic services of nature are included; double counting should be avoided; and a simple taxonomy of ecological productivity is used which includes eight land categories (Wackernagel & Rees, 1996). The steps to calculate the ecological footprint are: first, estimate an average person's annual consumption of particular items from aggregate regional or national data and population; second, estimate the land area appropriated per capita for the production of each major consumption item; then, the total ecological footprint per capita is computed by summing the areas appropriated by all purchased items; finally, the ecological footprint of the whole population is obtained by multiplying the per capita footprint by the population number (Wackernagel & Rees, 1996).

Carbon footprint.

Sunlight comes in to the Earth and is absorbed by matter (Wright & Nebel, 2002). In being absorbed the light energy is converted to heat which is released in the form of infrared radiation (Wright & Nebel, 2002). Carbon dioxide, water vapor, and other gases in the Earth's atmosphere act like glass in a greenhouse thus blocking this heat from leaving the Earth and making its temperature rise (Wright & Nebel, 2002). This insulation is necessary for life as we know it to exist, without which the average surface temperature would be around twenty one Celsius degrees colder (Wright & Nebel, 2002).

The atmospheric average concentration of carbon dioxide is steadily increasing because of human activities, in particular because of burning fossil fuels and deforestation (Wright & Nebel, 2002). Other greenhouse gases derived from human activities are methane, nitrous oxide, chlorofluorocarbons (CFC) and other halocarbons (Wright & Nebel, 2002). Although it is not yet possible to ascertain that increases in greenhouse gases will bring a significant increase in the Earth's temperature, it is clear that global temperatures are rising and this trend coincides with the observed increase in greenhouse gases (Wright & Nebel, 2002). As a consequence of rising global temperatures the climate will undergo major changes, with potential catastrophic effects for humans and ecosystems (Wright & Nebel, 2002). For this reason, measuring carbon footprints and implementing measures to reduce emissions and mitigation have been acknowledged as an urgent priority (United Nations, 2007).

Carbon footprint accounts for the total greenhouse gas emissions caused by an organization, event, product or person (Wright, Kemp & Williams, 2011). This environmental assessment method is increasingly being used by organizations in the public and private sectors (Wright, Kemp & Williams, 2011). Learning about carbon footprints is useful to implement measures to reduce emissions and mitigate negative effects.

Sustainability.

Sustainable development.

Every nation seeks to develop, and even though economic progress is an essential component of it, it is not the only component (Todaro & Smith, 2009). Development encompasses more than the material and financial side of people's lives, so it must be perceived as a multidimensional process involving the reorganization and reorientation of the entire economic and social systems (Todaro & Smith, 2009).

Recognizing human-made damage to ecological systems and growing socio-economic problems on a global scale in 1983 the United Nations created the World Commission on Environment and Development (UNWCED), which was asked to formulate a global agenda for change in order to propose long-term environmental strategies for achieving sustainable development for the future (UNWCED, 1987). A group of scientists and other experts worked for three years and released a report named *Our Common Future*, also known as the *Brundtland Report*, which elaborates on the concept of sustainable development. This concept was defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (UNWCED, 1987). Two key concepts are contained in this definition: needs, which refers to the essential needs of human beings, in particular the needs of the world's poor; and the limitations that the current state of technology and social organization impose on the natural environment's ability to meet human present and future needs (UNWCED, 1987). The need for sustainability arose from recognizing that current patterns of development, when projected into the not-too-distant future, leads to biophysical impossibilities (Goodland, 1995). Achievement of sustainable development involves a progressive transformation of economy and society, so that we can thrive long term without damaging the natural systems (UNWCED, 1987). Since this publication much effort has been made to operationalizing the concept of sustainability (Azar, Holmberg & Lindgren, 1996).

Social, economic, and environmental sustainability.

Sustainable development should integrate social, economic and environmental sustainability (Goodland, 1995). While poverty reduction is considered by some as one of the most important goals of sustainable development, tragically, it is increasing in the world in spite of global and national economic growth (Goodland, 1995). Economic theory historically has focused mostly on economic growth and to a much lesser extent on equity of distribution (Goodland, 1995). This has led to a situation in which 20 per cent of the world population consumes 80 per cent of all resources (Robèrt, 2002; Stahel, 2010). The reduction of poverty ". . . has to come from qualitative development, from redistribution and sharing, from population stability, and from community sodality, rather than from throughput growth." (Goodland, 1995, p. 2).

Economic sustainability has been defined as the maintenance of capital, concept that has been used by accountants since the Middle Ages to allow merchants knowing how much could they consume of their sales receipts without reducing their ability to continue trading (Goodland, 1995). This can be translated as consuming interest rather than capital (Goodland, 1995). Continuous throughput growth has made the scale of the human economy exceed the source and sink capacities that sustain us, thus leading to scarcity of natural capital (Goodland, 1995). Natural capital should be included together with manmade capital in a definition of economic sustainability (Goodland, 1995).

According to economist Herman Daly, former Senior Economist in the Environment Department of the World Bank, the total neglect of the costs of growth may be due to a wrong paradigm that the economy has embraced (Daly & Farley, 2011). In his vision, the natural environment is seen merely as a subsystem of the greater system economy – the extractive and waste disposal sector of the economy – while in physical terms the economy is a subsystem of the natural environment (Daly & Farley, 2011). On the contrary, Ecological economics is an emergent trans-discipline that creates economic models which incorporate ecological systems as part of the calculations when assessing economic performance, as well as ecologic models that incorporate human beings and our economy (Daly & Farley, 2004). As a framework, it may help shape new generations of products and services that do not damage, or are even beneficial for the natural environment, ecosystems, and human beings.

Environmental sustainability is needed by humans. The two fundamental services that the natural environment provides to humans are the source and sink functions: the source function provides material inputs like food, water, air, and energy; and sink functions assimilate our outputs or wastes (Goodland, 1995). The goal of environmental sustainability is the unimpaired maintenance of the human life-support systems that provide these functions (Goodland, 1995). Source and sink capacities are large but finite, and overuse of a capacity impairs its provision of life-support services (Goodland, 1995). The transition to environmental sustainability is urgent because the state of deterioration of global life-support systems imposes a time limit (Goodland, 1995).

Degrees of environmental sustainability.

Economic approaches to sustainability are concerned with human wellbeing or utility; and the capacity to provide utility is embodied in four forms of capital: produced, natural, human and social (Dietz & Neumayer, 2007). The weak sustainability paradigm was founded in the 1970s by extending the neoclassical theory of economic growth to account for non-renewable natural resources as a factor of production (Dietz & Neumayer, 2007). It was realized that non-declining welfare in perpetuity was unlikely when non-renewable resources were a factor of production, so specific rules were established to prevent welfare decline over time based on maintenance of capital stock (Dietz & Neumayer, 2007). Weak sustainability requires that the total net capital wealth does not persistently decrease (Dietz & Neumayer, 2007). This means that the different forms of capital are more or less interchangeable as long as the total amount of capital does not decrease. It entails the assumption that natural capital is similar to produced capital, and could be easily substituted for it (Dietz & Neumayer, 2007). But because human-made and natural capitals are far from being perfect substitutes, weak sustainability is a dangerous goal (Goodland, 1995).

The strong sustainability position is that natural capital cannot be substituted by the other forms of capital (Dietz & Neumayer, 2007). In other words, separate kinds of capital should be maintained, which are complementary and not substitutable as weak sustainability assumes (Goodland, 1995). We have entered an era, in which the limiting factor for development is no longer manmade capital, but the remaining natural capital, e.g. fish catch is limited by fish populations, not fishing boats; crude oil is limited by the accessibility of remaining petroleum deposits, not by pumping and drilling capacities (Costanza, Daly & Bartholomew, 1991). Recognizing the complementarity of different types of capital emphasizes the importance of limiting factors (Costanza, Daly & Bartholomew, 1991).

Absurdly strong environmental sustainability, or superstrong sustainability, means that we would never deplete anything (Goodland, 1995). Nonrenewable resources should not be used at all, thus remain in the ground, and for renewable resources only net annual growth increments could be harvested in the form of over-mature portion of the stock (Goodland, 1995).

Triple bottom line.

In 1994 John Elkington introduced the concept of the triple bottom line (Elkington, 2004). He recognized the need to integrate the economic and social dimensions highlighted by the *Brundtland Report* so that environmental progress could be achieved (Elkington, 2004). Also, and contrary to the anti-industry orientation of early environmentalism, Elkington and colleagues realized that business must have a central role in achieving sustainable development strategies (Elkington, 1994). More than governments or NGOs, businesses would drive change in a transition to a sustainable economy; therefore it became clear the importance of using language that could resonate in business people minds (Elkington, 2004).

The triple bottom line agenda aims to help companies focus not just on the economic value that they add, but also on the environmental and social value they add or destroy (Elkington, 2004). Also, triple bottom line sustainability has been defined as the result of the activities of an organization, voluntary or governed by law, that demonstrate its ability to maintain viable its business operations while not negatively impacting any social or ecological systems (Smith & Sharicz, 2011).

Sustainability approaches relevant for design.

The Carnoules Declaration and Factor X.

In 1994 an international body of senior government, non-government, industry and scientific leaders working out of Germany's Wuppertal Institute for Climate, Environment, and Energy, published the *1994 Declaration of the Factor 10 Club*, also known as the *Carnoules Declaration* (Hawken et al., 1999; Schmidt-Bleek, 2010). This document was intended to advise the European governments and business leaders.

The Carnoules declaration highlights the fact that ecological disruption and natural resource consumption are increasing globally while human welfare is decreasing, and suggests that the world's economic and political crisis is deeply rooted in the way how society manages its ecological resources (Schmidt-Bleek, et al., 1994). Welfare includes several factors such as income, consumption, employment, education, health, freedom from violence, environmental quality, social security, leisure and equity (Schmidt-Bleek, et al., 1994). However, economic progress and national wealth are measured in terms of GDP which is an inadequate measure of human welfare and ecological health (Schmidt-Bleek, et al., 1994). While the economic and resource crises do not show up in GDP, alternative measures of human welfare such as the Index of Economic Welfare (ISEW) and the Genuine Progress Indicator (GPI) do display these crises (Schmidt-Bleek, et al., 1994).

Traditional economic growth is tied tightly to consumptive use of materials and energy, and this has been done with very low resource productivity (Schmidt-Bleek et al., 1994). On average around 90 percent of the biomass harvested and non-renewable materials disturbed by machines in their natural settings are wasted on the way to make products (Schmidt-Bleek, 2000). This means that on average only 10 percent of the materials we mobilize end up in actual products. Human machines move more than twice as much material as geological forces on the Earth's surface, of which a substantial percentage is returned to the environment in a chemically degraded way or mobilized form within a few weeks or months (Schmidt-Bleek et al., 1994). To help stop losing natural capital, it was proposed that industrialized countries increase their resource productivity by an average factor of 10 during the next 30 to 50 years (Schmidt-Bleek et al., 1994). This means, a 90 percent reduction in energy and materials intensity (Hawken et al., 1999).

So far it has made economic sense to exploit raw materials, including water and air, in order to industrialize and several interventions that distort the market have helped to create this situation (Schmidt-Bleek, et al., 1994). The seven areas of interventions that distort the market identified by the Factor 10 club are quoted next:

> 1. Subsidised energy production. Externalising environmental costs of energy production;
>
> 2. Subsidised private transport and the infrastructure it requires, including numerous fuel tax exemptions;
>
> 3. Conferring the burden of risk implicit in "dangerous" technologies onto society as a whole for example in the areas of international ship, air-traffic and atomic energy production;
>
> 4. Providing waste disposal at a "socially affordable rate" thus "socializing" the externalities involved and in effect subsidising a "throughput maximising/throw-away-economy";
>
> 5. Subsidising "sunset" industries in order to keep them alive (for example the Century Contract between the German government and its coal industry and analogous measures in Russia, Belgium and France);
>
> 6. Subsidising certain agricultural systems instead of recognising the energy and environmental costs involved;
>
> 7. Subsidising investments designed to create employment, alongside investments that are designed to eliminate labour. (Schmidt-Bleek et al., 1994, p. 4).

In order to achieve increased resource productivity and move forward toward sustainability the Factor 10 Club proposed several measures, including reassessing the centrality of material, energy and land consumption in our cultures; reorient the fiscal and incentive structures which presently discourage ecologically and humanly sensible behavior; reform the educational systems by integrating the resource preserving concepts at all levels; articulate a fundamentally new vision of development policy, especially with respect to technology transfer; develop measures of real wealth; and encourage research and development in areas of sustainable technology and social change and adaptation (Schmidt-Bleek, et al., 1994).

The Natural Step.

During the 1980s Swedish physician Karl-Henrik Robèrt initiated a process to seek consensus among prominent scientists of his country, about what human beings have done wrong resulting in negative impacts on the natural environment, and how to achieve a greater sustainability (Robèrt, 2002). Using systems thinking to understand how socio-ecological systems work, four system conditions were identified that must be met to allow humans and natural ecosystems coexist long-term (Robèrt et al., 2002).

In a sustainable society, the biosphere it not subject to systematically increasing:

1. Concentrations of substances extracted from the Earth's crust;

2. Concentrations of substances produced by society;

3. Degradation by physical means;

4. And people are not subject to conditions that systematically undermine their capacity to meet their own needs (Robèrt et al., 2010).

Based on these sustainability principles, Robèrt and colleagues proposed a strategic approach to introduce change towards sustainability in organizations at any level. The approach is called Five Level Framework for Planning in Complex Systems (Robèrt et al., 2010). This approach understands the Earth from a systems perspective, and sustainable development as the transition from the current unsustainable society to a sustainable one. The Five Level Framework divides the important information that is needed for planning into five categorical levels focusing on: the system that the planning takes place in, the definition of success, the guidelines that are used to ensure a strategic process and the actions and tools that are used in planning and implementation (Robèrt, et al., 2010). When using the Five Level Framework to plan for sustainability it is referred to as the Framework for Strategic Sustainable Development (Robèrt et al., 2010). This framework is composed of the following levels:

- Systems level, the global socio-ecological system;
- Success level, a society that complies with the sustainability principles;
- Strategic level, define strategies through Backcasting from principles;
- Actions level, define actions that help moving the socio-ecological system towards sustainability; and
- Tools level, which are the tools that support the efforts to reach global sustainability (Robèrt et al., 2010, p 36).

Using the Framework for Strategic Sustainable Development would allow organizations of any kind to move forward in pursuing sustainability (Robèrt et al., 2010).

Natural capitalism.

Natural capitalism recognizes four types of capital in the economy: human capital, financial capital, manufactured capital, and natural capital (Hawken, Lovins, & Lovins, 1999). Human capital represents labor, intelligence, culture and organization; financial capital consists of cash, investments, and monetary instruments; manufactured capital includes infrastructure, machines, tools, and factories; and natural capital is made up of resources, living systems, and ecosystem services (Hawken et al., 1999).

In order to enable countries, companies, and communities value all forms of capital and operate accordingly, Natural Capitalism proposes four central strategies:

1. Radical resource productivity. As we have seen, most resources extracted never end up providing human utility. Increasing resource productivity means obtaining the same amount of utility, or work, from a product or process while using less material and energy (Hawken et al., 1999).

2. Biomimicry. As opposed to human factories, nature's processes cannot take place on the edge of town; they occur where life takes place under life friendly conditions, like life-friendly temperatures, low pressure and without harsh chemicals (Benyus, 1997). For instance, spiders make silk, strong as Kevlar, from digested crickets and flies and without needing boiling sulfuric acid and high temperature extruders (Hawken et al., 1999). Imitating biological and ecosystem processes and methods of production allows saving resources and achieve the qualities desired for products and end users (Hawken et al., 1999).

3. Service and flow economy. In a service economy the leasing and later recovery of a product means that it remains an asset for the manufacturer, while for the user there is an improved experience because of the ease of maintenance, replacement, improved efficiencies in use, and associated costs (Hawken et al., 1999).

4. Investing in natural capital. The natural environment provides resources and ecosystem services that are fundamental for the life on the planet and also for the economy (Hawken et al., 1999). Until recently businesses could ignore these services, but shortages and rising costs are increasingly showing up (Hawken et al., 1999). Investing in natural capital allows reversing the planetary destruction by letting the biosphere produce more ecosystem services and natural resources (Hawken et al., 1999).

Total beauty of sustainable products.

The book *Total Beauty of Sustainable Products* by Edwin Datschefski proposes five basic principles to create products addressing sustainability issues. A typical, attractive, and award-winning product may contain hidden ugliness along its lifecycle; but a true sustainable product is totally beautiful (Datschefski, 2001). Sustainable, in this case, is defined as “. . . good for people, profits and the planet.” (Datschefski, 2001, p. 8).

In order to be sustainable, products should be:

- Cyclic. The product is made either of grown materials that can be composted, or of man-made materials that can be recycled in a close loop (Datschefski, 2001).

- Solar. Renewable energy should be used to make and run the product, and renewable energy is ultimately driven by the sun (Datschefski, 2001).

- Efficient. Increase the efficiency of materials and energy use, reducing them at least to one tenth (Datschefski, 2001).

- Safe. The product should be safe for the manufacturer and the user, which can be achieved by eliminating hazardous materials in products and by-products (Datschefski, 2001).

- Social. Human capital should be valued by avoiding exploitation and maltreatment of workers, and child labor (Datschefski, 2001).

Designers have an enormous power to achieve all of these five basic principles through the design process (Datschefski, 2001).

The sustainability approaches reviewed address environmental, economic and social aspects that are relevant to make products with better environmental profiles. While proposing measures that can be implemented at various levels of decision making, like governments, NGOs, business firms and individuals, all these approaches if implemented would have an influence in a product's environmental performance. It is worth noting that even though these sustainability approaches address environmental, social and economic aspects, much of what they propose target the environmental aspects of sustainability.

Life cycle sustainability assessment.

Using sustainability approaches to design allows doing things in ways that are better for the environment and the people. But knowing what is actually better or worse is no trivial thing. There has to be a definition about what better means. There has to be as well a way to measure the degree to which sustainability is being attained or not. Assessment methods can provide these measures.

UNEP proposed how to use and combine the existing stand-alone methods of environmental LCA, Social Life Cycle Assessment (S-LCA) and Life cycle Costing (LCC) to start an overall life cycle sustainability assessment (LCSA) (UNEP/SETAC, 2011). Environmental LCA has already been discussed on section 3.2.1. S-LCA and LCC will be discussed next.

Social life cycle assessment.

S-LCA is a recently developed method to quantify the impacts of a product system over its life cycle, on persons referred to as stakeholders. Freeman (1984) defined stakeholders as groups and individuals that can affect, or are affected by, the accomplishment of organizational purpose. Social impacts are consequences of positive or negative pressures on social endpoints; this is wellbeing of stakeholders (UNEP/SETAC, 2009).

S-LCA is based on environmental LCA and has a similar structure: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation (UNEP/SETAC, 2009). Subcategories are socially significant themes or attributes, which are classified according to stakeholder and impact categories, and are assessed by the use of impact indicators (UNEP/SETAC, 2009). Subcategories are the socially relevant characteristic or attribute to be assessed, and they have been defined according to international agreements to go beyond personal and cultural subjectivity or political orientation (UNEP/SETAC, 2009). Examples of subcategories are child labor, fair salary, consumer privacy, respect for indigenous rights, corruption, and fair competition (UNEP/SETAC, 2009).

Stakeholder categories define the persons affecting, or affected by corporate activity, which are clustered according to shared interests due to their similar relationship to the investigated product system (UNEP/SETAC, 2009). Five main stakeholder categories are considered: workers/employees, local community, society (national and global), consumers (both end consumers and intermediate within the supply chain), and value chain actors (UNEP/SETAC, 2009).

Inventory indicators are aggregated into subcategories, and subcategories are aggregated into impact categories (UNEP/SETAC, 2009). One impact category can be related to several stakeholder categories, and one stakeholder category can be affected by different impact categories (UNEP/SETAC, 2009). Impact categories represent logical groupings of S-LCA results related to social issues of interest to these stakeholders, and stakeholders may vary from one study to another and also within each step of the supply chain (UNEP/SETAC, 2009). Efforts must be made to define indicators and subcategories adapted to the particular context (UNEP/SETAC, 2009).

The stakeholders involved, subcategories used, choice of impact categories and characterization models depend on the objectives of the study, and should be made in accordance with the goal and scope of the study (UNEP/SETAC, 2009). UNEP makes clear that the stakeholder categories and subcategories are a basis on which to build, and that more experience needs to be gained in order to determine one or a set of generally accepted impact categories (UNEP/SETAC, 2009).

Life cycle costing.

LCC is the oldest of the three life cycle techniques, created in 1933 for financial cost accounting by the United States of America General Accounting Office (GAO) (UNEP/SETAC, 2011). Between 2002 and 2007 a scientific working group on LCC within SETAC was the first to specify a methodology to provide an assessment of the costs of a product over its life cycle consistent to an environmental LCA (UNEP/SETAC, 2011). Following the ISO standard 14040 LCC studies are carried out in four phases: 1. Goal, scope, and functional unit; 2. Inventory costs; 3. Aggregate costs by cost categories; 4. Interpret results (UNEP/SETAC, 2011).

LCC considers the total cost of ownership of machinery and equipment, including the costs of acquisition, operation, maintenance, conversion, and/or decommission (SAE, 1999 as cited in Barringer, 2003). LCC is especially useful to assess the costs of capital goods and products with significant environmental exchange or operation costs while in use.

As can be seen, a wealth of knowledge exists about how products can be designed to minimize their negative impacts on the environment. Sustainability approaches also contribute by addressing broader aspects of socio-ecological systems that, nevertheless, have a strong influence on the product's environmental performance. Any company willing to improve the environmental performance of its product can implement the approaches that have been presented. However, choosing which approach to use may not be a simple task.

For example, a greater environmental performance of a product can be achieved through product design – ecodesign – with implications over the entire life cycle of the product (Tischner et al., 2000). But, even more can be attained if in addition the entire manufacturing system of an operation is improved – Industrial Ecology – to create cleaner and more efficient manufacturing processes (Graedel & Allenby, 2010). Besides these, investing in natural capital – Natural Capitalism – is something that an environmentally responsible company can do to help mitigating damage already done to natural ecosystems (Hawken et al., 2000). Even greater progress can be made if governments provide an economic context to all businesses – Carnoules Declaration – in which their environmental responsibility can be profitable and therefore flourish (Schmidt-Bleek et al., 1994).

While the different approaches appear to display great diversity, many of the topics they address overlap. Each approach is explained from a different point of view and uses its own lexicon, which accents appearing diverse, but maybe they are not so different after all. It becomes apparent that there is a need to take a closer analytical look at these approaches in order to understand in a deeper way what they propose and being able to compare them. This leads to the first research question of this dissertation:

What are major approaches to environmentally responsible product design and development, and how can they be characterized and compared?

Use of environmentally responsible design and assessments.

In the previous section a number of theories about environmentally responsible approaches to design were reviewed, as well as sustainability approaches that can help to make products with a better environmental performance. Several assessment methods were reviewed as well which are useful to measure impacts and monitor progress toward greater sustainability.

This section discusses a number of research studies that have been made with the objective to investigate how environmentally responsible design and assessment methods have been used in product design and development by product manufacturing companies.

Ecodesign empirically explored: design for environment in Dutch SMEs.

Van Hemel studied the use of Design for Environment by Dutch small and medium sized enterprises (SME) during the second half of the 1990s, with the objective of knowing how they dealt with putting this approach in practice (1998). This was a quantitative deductive study that compared 77 SMEs based on empirical data collected by means of a questionnaire delivered by mail and a telephone interview based on fixed questions. The sample were companies participating on the IC EcoDesign project, a government initiative to introduce Ecodesign in small and medium sized business firms (van Hemel, 1998).

The study concluded that the most influential internal stimuli for Design for Environment were innovation opportunities, increase of product quality, and new market opportunities; while the most influential external stimuli were customer demands, government regulation, and industrial sector initiatives (van Hemel, 1998). Among these, internal stimuli were found to be much more influential in the success of the Design for Environment adopted (van Hemel, 1998). Regarding barriers for the use of Design for Environment strategies, the most important were when their implementation was not perceived as a responsibility by the company, no environmental benefit was clear, and when it did not represent a suitable technological alternative to conventional solutions (van Hemel, 1998). The most successful, i.e. actually implemented, Design for Environment strategies were end of life strategies (recycling of materials, remanufacturing/refurbishing), reducing product weight, and using non-hazardous and recycled materials (van Hemel, 1998).

Van Hemel's research findings shed light on important aspects of Ecodesign regarding stimuli, barriers and the Ecodesign strategies most implemented by the participating companies. However, due to the nature of the research approach it is not possible by reading the report to learn in detail the specific characteristics of a company (e.g. size, market sector, products they make) in relation to how ecodesign was used (e.g. stimuli, barriers, actual strategies used).

Managing sustainable product design by integrating corporate product development practice with ISO 14001 environmental management systems.

Yang conducted a single case study about the integration of environmental management systems (EMS) in sustainable product development by office furniture manufacturer Herman Miller, focusing on the Mirra chair (Yang, 2005). This chair was the first product project to implement a sustainable design protocol through collaborative efforts with an internal team of the company named EQAT which is charged with the implementation of their EMS throughout the company (Yang, 2005). MBDC assisted Herman Miller in the development of the Mirra chair by evaluating it in the areas of material chemistry and safety of inputs, ability to disassemble for recycling, and use of recycled and recyclable materials (Herman Miller, 2005, as cited in Yang, 2005).

This research was conducted using interviews about EMS and product design at the corporate level, and at the division and project level (Yang, 2005). The study concluded that in order to integrate sustainable development policies in manufacturing companies effectively from a management perspective, the use of EMS and sustainable product design should occur at four levels: policy integration, organization integration, process integration, and tool integration (Yang, 2005).

Yang’s research allowed understanding how a product manufacturing company with commitment to improve its environmental performance manages to make this happen. Its focus is on the managerial aspects of the integration of sustainability. Although Yang’s research is focused at the product level, it does not address specific environmentally responsible design strategies and manufacturing technical details, as well as descriptions of the use of methods for environmental assessments about the product studied.

Life cycle assessment in business survey.
With the objective of understanding the use of LCA by businesses in Europe, a survey was conducted in Switzerland, Germany, Italy and Sweden (Frankl & Rubik, 1999). The research questions were: Which are the drivers for starting LCA activities in a company? Which are the main applications? Which business departments or functions are involved? And, what is the contribution of LCA to decision-making processes? (Frankl & Rubik, 1999). A total number of 1625 questionnaires were sent to selected companies, of which 382 were returned completed and usable questionnaires belonging to two categories: environmentally oriented companies and largest companies by turnover (Frankl & Rubik, 1999).

Regarding drivers for starting LCA, Frankl and Rubik found that environmental consciousness was a necessary but not sufficient condition, the existence of an environmental management system was another supporting factor, and consumer organizations and environmental groups have a role as well (1999). For all countries costs saving opportunities were important drivers, and a direct influence by the use of LCA by competing companies was not perceived as a driver (Frankl & Rubik, 1999). Swedish companies appeared to be more proactive-oriented, where research and development as well as product specific environmental discussions and problems seemed to be important drivers (Frankl & Rubik, 1999).

Environmental legislations did not seem important, especially in Sweden and Switzerland, but in Germany was ranked near to the most important drivers (Frankl & Rubik, 1999). In Italy many LCA studies were driven by the encouragement of parent companies (Frankl & Rubik, 1999). One of the conclusions was that a long-term and proactive orientation of companies supports the start of LCA use because LCA is able to analyze and describe future problems and risks of products (Frankl & Rubik, 1999).

Concerning applications of LCA, common trends of the four countries are that LCA is used as a tool for research, development, and design; it is used for some but not for all products; it is not only used for green products; and it is used mostly for existing products rather than for new ones (Frankl & Rubik, 1999). Another common result is that LCA is not too much used for marketing because of complex and sometimes disputable results (Frankl & Rubik, 1999). In all countries important uses of LCA are identification of bottlenecks, and external information/education of consumers and stakeholders, with the exception of Italy where LCA results are considered too complicated for the public (Frankl & Rubik, 1999). The use for comparing existing products and possible alternatives suggests a more proactive use of LCA in Switzerland and Sweden (Frankl &

Rubik, 1999). Another conclusion was that LCA is given more a retrospective than a prospective use, it is not used too much for marketing, and it is not used for the strategic applications of radical changes in the product life cycle and shift from product to service (Frankl & Rubik, 1999).

Product innovation is driven by marketing, costs, and competition in most of the companies surveyed, within which the departments involved are marketing, top management, and sales (Frankl & Rubik, 1999). Environmental pressure appears to be the least relevant factor for product innovation, and environmental departments or officers usually do not appear to take part in product innovation processes (Frankl & Rubik, 1999). Companies use a range of environmental management tools of which the most used are risk assessment, energy efficiency analysis, compliance/gap-analysis with legislation, checklists, and LCA (Frankl & Rubik, 1999).

With regard to the LCA technique, it appears that in all countries LCA is increasingly carried out internally, often involving several functions or departments within the company (Frankl & Rubik, 1999). In Sweden this is a major trend, being the case of 77 percent of the companies surveyed (Frankl & Rubik, 1999). Major difficulties of LCA are connected with the environmental inventory, specifically collection and quality of data (Frankl & Rubik, 1999). Assessment and interpretation of results are also seen as sources of problems (Frankl & Rubik, 1999). In Italy the definition of the system boundaries is perceived as a problem (Frankl & Rubik, 1999).

For 40 percent to 60 percent of respondents the main obstacle to a wider use of LCA is that results are disputable; and another topic of general agreement is that communicating LCA results to top management is not considered difficult, which was a surprising result for the researchers (Frankl & Rubik, 1999). Methodological difficulties are considered an obstacle in all countries except for Switzerland (Frankl & Rubik, 1999). Costs of conducting LCA are perceived as an obstacle in Germany and Switzerland but not in Sweden and Italy (Frankl & Rubik, 1999). Costs of implementing measures suggested by LCA results do not appear to be important in any country, which might be explained by the fact that most LCAs have been retrospective and not intended from the beginning as a design tool to introduce changes in production, and that respondents came mostly from environmental departments which are usually far away from accounting and production departments (Frankl & Rubik, 1999). There is general agreement in that LCA results cannot be easily applied immediately, that its benefits are long term, and that LCA use will increase with time (Frankl & Rubik, 1999).

This survey about LCA use in four European countries provides relevant information for this dissertation about drivers, applications, and contributions of LCA to business operations, as well as barriers for its use. Several topics addressed are relevant to the use of LCA in product design, although the depth to which these topics are treated is limited because the survey was not intended specifically for product manufacturing companies. Furthermore, the survey report provides sparse details about the sample of participant businesses, and since the data presented is mostly aggregated by country it is not possible to isolate responses by company type or industry sector which would allow understanding the results that are applicable to product design and manufacturing companies. Nevertheless the survey results allow understanding the topics involved and influencing factors in effective LCA use in a corporate environment.

Life cycle assessment practitioner survey.

A survey for LCA practitioners was conducted by Cooper and Fava to investigate how the assessments are conducted, how results are used, what are the benefits from LCA use, and which barriers exist for its increased application (2006). The study had 65 respondents: 66 percent from North America, 23 percent from Europe, and 11 percent from Brazil, China, India, Japan, and Mexico (Cooper & Fava, 2006). Forty seven percent of respondents categorized their organizations as materials production and manufacturing/construction, 20 percent academia, 11 percent consulting, 11 percent government, and 6 percent NGOs (Cooper & Fava, 2006). The functions they perform within these organizations were 20 percent researchers, 15 percent involved in college or university education and research, 14 percent business managers, 14 percent product and process designers and product stewards, 12 percent involved in environmental health and safety, and between 3 percent and 5 percent in marketing and sales, professional education, primary and secondary education, and public policy (Cooper & Fava, 2006).

The results about how LCA is being conducted fall into six categories: type of LCA used, inventory data collection, analysis and interpretation of data, use of LCA software, impact assessment, and peer review practices (Cooper & Fava, 2006). The most used type of LCA was process chain based on the ISO-14040 standard as declared by 77 percent of respondents, followed by 69 percent who have used economic input-output or streamlined LCA, and 54 percent who have used both (Cooper & Fava, 2006).

Inventory data has been collected from industry by 75 percent of respondents, followed by 58 percent who have used literature or databases not developed for LCA, 52 percent who have used databases developed for LCA costing less than US$10,000, 43 percent who have used models based on science or engineering principles, and 23 percent who have collected data from databases developed for LCA costing more than US$10,000 (Cooper, & Fava, 2006). Inventory data collection was mentioned as the most time consuming phase by 68 percent of respondents, and as the most costly by 63 percent (Cooper & Fava, 2006). Within these, 86 percent have used data sources other than those developed specifically for LCA (Cooper & Fava, 2006). Analysis and interpretation of data was mentioned as the most costly phase by 20 percent of respondents and as the most time consuming by 15 percent (Cooper & Fava, 2006).

Life cycle assessment software is used by 69 percent of respondents within which 58 percent use GaBi, 31 percent SimaPro, and 13 percent TEAM; while spreadsheet software is used by 46 percent of all respondents (Cooper & Fava, 2006). The most used impact assessment method is EcoIndicator followed by CML, TRACI, and self-assembled sets of impact indicators (Cooper & Fava, 2006). Also, a number of respondents declared using multiple methods for comparison (Cooper & Fava, 2006).

Concerning peer review, 45 percent of respondents have conducted or contributed to LCA with no peer review, mostly those involved in research and product or process design (Cooper & Fava, 2006). Of all respondents, 38 percent have used internal company peer review, 33 percent have used an external review by a single person, and 28 percent have used external review by a panel (Cooper & Fava, 2006). A 57 percent of respondents stated that the majority of their peer reviews were completed at the end of the LCA project, 25 percent interactive throughout the project, and 6 percent at the beginning and end (Cooper & Fava, 2006). Four respondents mentioned peer review in the context of cost and impact assessment issues (Cooper & Fava, 2006).

The survey found that practitioners give different uses to the results of LCA and these uses are often combined. A 63 percent of respondents use LCA results in business strategy, 62 percent in research and development, 52 percent as input to product or process design, 46 percent in education, 43 percent in policy development, 37 percent in labeling or product declarations, 26 percent in sales, 20 percent in procurement, and 8 percent in other uses including invitation to tender (Cooper & Fava, 2006). Practitioners saw LCA as a good tool to examine the environmental impacts of products, a quantitative way to estimate the life cycle resources and burdens, and also as a good tool to identify alternatives in product systems (Cooper & Fava, 2006).

The most repeated reasons why LCA is not applied to more products and processes were, time and resources required to collect data, complexity of the LCA method itself, lack of clarity of the relative benefits compared to the costs, and apparent lack of downstream interest or demand (Cooper & Fava, 2006). The main suggestions provided to overcome the barriers to LCA use are greater development and funding for life cycle impact assessment databases, existence of an internal champion for the promotion of LCA within the organization, dissemination of the value that LCA provides, and anything that helps to simplify conducting LCA and reduce the cost and time required to complete a study (Cooper & Fava, 2006).

This survey presents quantitative information expressed as percentages of total respondents about LCA practitioners' profiles, how they conduct the studies, and how results are used; and also qualitative information about the their perception of LCA benefits, reasons why it is not applied to more products and processes, and suggestions to overcome these barriers, all of which are relevant for this dissertation as they help understanding how LCA is used based on practitioners' experience.

However, because the survey results are expressed as shares of total respondents with limited crossed reference among categories it is not possible to understand which kinds of practitioners conduct LCA in what way, and who uses LCA results for what. For example, learning that 63 percent of LCA results are used in business strategy and 52 percent as inputs to product or process design, is useful for this research because both can affect product design and development; but it is unclear how much of the use of LCA in business strategy overlaps with its use in product and process design. Also, details about if LCA use was retrospective for existing products or prospective for new ones, or if they were conducted by practitioners inside the firm or by external consultants are not provided. It is clear though, that significant shares of LCA studies are used in areas that are relevant for environmentally responsible product design, like business strategy, product or process design, labeling or product declaration, sales, and procurement.

Ecodesign information needs: IDSA product designer survey.

In 2004 the Ecodesign section of IDSA organized a survey as part of the partnership between the IDSA and the U.S. Environmental Protection Agency (EPA), with the objective of documenting the need for ecological and sustainable design information by practicing product/industrial designers (White, 2004). All IDSA members were invited to participate, 95 completed surveys were returned, out of which three respondents worked in Canada and the rest in the United States (White, 2004).

In the first section of the survey, a list of ecodesign topics was presented and respondents were asked to rate on a scale from 0 to 4 their need for information about those topics (0 for no need, 4 for extreme need) (White, 2004). The topic most needed was international environmental regulations, which include most prominently the European Union Waste Electric and Electronic Equipment (WEEE), and Reduction of Hazardous Substances (RoHS) directives, increasingly coming into force and relevant to products sold within the European Union (White, 2004). The next most needed topics were comparison of the environmental impacts of processes, and comparison of the environmental impacts of materials (White, 2004). Fifth on the list was life cycle impact assessment, which actually compares environmental impacts of processes and materials (White, 2004). Perhaps the difference between these ratings reflects that many designers are not familiar with LCA, although the need for the information that LCA provides exists (White, 2004). The topic ranked fourth was design for disassembly guidelines which is essential to design products whose materials can be recycled at end of life (White, 2004). Several topics addressed alternatives to potentially toxic substances, of which alternatives to PVC and flame-retardants in plastics were preferred to lead solder alternatives, probably because product designers are more likely to make specifications for plastic housing materials than circuit board solder (White, 2004).

The second section of the survey asked an open question about what other environmentally related design information was needed, which offered the respondents the chance to freely offer topics that were not listed previously (White, 2004). The most frequently offered topic was published case studies of successful eco-designed products, which included wording such as “successful green products that can be used to convince marketing and management” (White, 2004, p 4). The next two groups of topics were economic examples of successful green products using wording such as “short and long-term costs”, “examples where LCA affected the bottom line”, and “where green saves money”; and green material and process economics using wording such as “process costs”, “comparison of recycled and virgin material costs”, and “lead time for green materials” (White, 2004). These answers reflect a need of arguments to support that environmentally responsible design decisions make sense from a financial perspective. Another topic considered important was information about more environmentally sound suppliers, including fabrics, energy efficient components, packaging materials, and Asian manufacturers (White, 2004).

The study concluded that the ecodesign information that designers reported needing most was: international environmental regulations; environmental impact comparison of materials and processes; design guidelines for disassembly and recycling; examples of successful eco-designed products, preferably with economic details; examples of successful green materials, preferably with economic details; and suppliers of green materials and services (White, 2004).

Respondents of IDSA’s ecodesign information needs survey, explicitly demanded information about cases in which ecodesign has been used in real products including economic details. As the study concluded, there seems to be a need of evidence supporting that making products that are better for the environment is profitable and in the end is good business.

Summary

Approaches to environmentally responsible design and sustainability approaches relevant for product design and development have been reviewed, as well as assessment methods to measure the environmental impacts of products and overall sustainability. The apparent diversity in what is proposed by the different approaches, the language they use, and audiences addressed calls for a deeper analysis of them, in order to understand how they should be used by business firms. This leads to the firs research question of this research:

What are major approaches to environmentally responsible design, and how can they be characterized and compared?

On the other hand, several studies have been reviewed about the use of environmentally responsible approaches to design, and assessment methods, in product design and development by business firms. The information they provide is fragmented because no single study addresses both things. Also, the studies reviewed do not provide detailed information about specific products, within specific industries, and the successes, problems and overall experience in using both design approaches and assessment methods. Finally, as IDSA's survey found, designers expressed a need for knowledge about cases where environmentally responsible design has been integrated in real product design and development for successful products in the marketplace. This leads to the second research question of this research:

How are environmentally responsible design approaches and assessment methods used in product design and development by a U.S. business firm with commitment to environmental responsibility?

METHODOLOGY

Introduction

In chapter 2, literature was reviewed to frame the fields of study relevant to this research and to identify knowledge gaps to conduct research about. From broader to more specific, the literature review included parent fields of study, immediate fields of study, research problem area, and knowledge gaps. Chapter 2 concluded with the following research questions:

1. What are major approaches to environmentally responsible design, and how can they be characterized and compared?

2. How are environmentally responsible design approaches and assessment methods used in product design and development by a U.S. business firm with commitment to environmental responsibility?

Chapter 3 discusses the methodological approaches utilized to answer these research questions. The research methodology is justified, and then all the steps followed to conduct the research are explained in enough detail so that another researcher can replicate it.

Justification for paradigms and research methods

Research about environmentally responsible design approaches.

The theories about environmentally responsible approaches to design are embodied in a variety of publications including, but not limited to, journal articles, books, scientific reports, and doctoral theses. These publications constitute recorded human communications, within which the theories exist in written form. Research question 1 can be answered by analyzing these theories.

Content analysis.

The actual data to be analyzed in order to answer research question 1 exists as written text. In any empirical research, data are taken as givens, meaning that the researcher is not in doubt about what they are (Krippendorff, 2013). Nevertheless, different modes of observation require the researcher to intrude to some degree in what they are observing, for example doing experiments or survey research (Babbie, 2010). This inherently alters the data at the moment of collection. Texts as data, on the other hand, were not produced to be analyzed by a researcher, but instead are meant to be read, interpreted and understood by people other than analysts (Krippendorff, 2013). Because these texts as data cannot be affected by the researcher, their systematic study belongs to the family of unobtrusive research (Babbie, 2010).

Content analysis is the study of recorded human communications, which is a type of unobtrusive research (Babbie, 2010). These communications can be written material, such as books, magazines, newspapers, letters, and emails; and can also take non written forms, like paintings, speeches, and songs (Babbie, 2010). Content analysis has been defined more specifically as ". . . a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use." (Krippendorff, 2013).

Although the term content analysis first appeared in English in 1941, the systematic analysis of text can be traced back to the inquisitorial pursuits by the church in the 17^{th} century (Krippendorff, 2013). It was first used in the 19^{th} century to analyze hymns, newspaper and magazine articles, and advertisements (Elo & Kyngas, 2007). One of the most important and large-scale uses of content analysis came during World War II when analysts of the U.S. Federal Communications Commission (FCC) and analysts from Great Britain used this technique to analyze Nazi propaganda, through which they were able to predict their actions (Krippendorff, 2013). Today this research technique has a long history of use in communications, business, journalism, sociology, psychology, psychiatry and public health studies (Elo & Kyngas, 2007).

Content analysis can be used with qualitative and quantitative data, and in an inductive or deductive way (Elo & Kyngas, 2007). According to Lauri & Kyngas, when there is not enough former knowledge about the phenomenon under study, or when this knowledge is fragmented the inductive approach is recommended (as cited in Elo & Kyngas, 2007). An inductive approach moves from the specific to the general, so that specific instances are observed and then combined into a general statement (Chinn & Kramer, 1999, as cited in Elo & Kyngas, 2007).

Initial quantitative newspaper analysis conducted during the 19^{th} century focused on measuring the amount of area devoted to the topics addressed, in order to draw conclusions about the importance of these topics to the newspaper that published them (Krippendorff, 2013). However, a quantitative approach does not necessarily deal properly with meanings. Babbie illustrates this with an example: To determine how erotic a novel is, counting the amount of times that the words love and kiss are used can be used as an indicator, with the advantage of letting know precisely how eroticism was measured; there would be a disadvantage though in terms of validity, because erotic novel conveys a richer and deeper meaning than the amount of times the word love and kiss were used (2010).

Since the theories of approaches to environmentally responsible design exist as recorded human communications, their systematic study is content analysis. There is no pattern that might be logically or theoretically expected about how environmentally responsible design approaches and assessment methods should be implemented in reality, so there is no deductive model within which to test a hypothesis. On the contrary, the expectation is to discover patterns from the analysis of these theories within an inductive approach (Babbie, 2010).

Research about projects of an environmentally responsible business firm.

This research seeks to understand how environmentally responsible approaches to design are used in real product design and development by an American company with commitment to become environmentally responsible. Among American product manufacturing companies there are varying degrees of commitment to responsibility with the natural environment; and for the companies with greater commitment, there might be a range of environmental profiles of their products. It is assumed that the analysis of the design and development processes of projects whose outcomes have better environmental performance made by companies with greater commitment to environmental responsibility can answer research question 2 more effectively that if these characteristics of projects and companies are not met.

Quantitative versus qualitative research.

Quantitative studies have standardized precision, but they have consequences because the same questions are asked in the same order to every respondent, no full reports are obtained, and the information gathered from each person is fragmentary and made of pieces of attitudes, observations, and evaluations (Weiss, 1994). Quantitative data and the use of statistics is an effective way of reducing and summarizing data, but statistics rely on the reduction of meaning to numbers and there is a loss of richness associated with this process (O'Leary, 2010). On the other hand, qualitative research uses thematic analysis instead of statistical analysis (O'Leary, 2010).

The quantitative studies reviewed in Chapter 2 about environmentally responsible design and assessments did not provide enough richness, depth, and detailed information to allow full understanding the complexities of their implementation in product design by business firms. The need to complement the knowledge provided by those studies led to the second research question that this research attempts to answer.

Case study approach.

Sociological case studies, or monographic studies, are investigations of particular cases (Hamel, Dufour & Fortin, 1993). According to Zonabend, these studies are conducted by totalizing in the observation, reconstruction, and analysis of the cases under study (as cited in Hamel, et al., 1993). Consequently, a case study is an in-depth study of the case under consideration, and this depth is a characteristic of case studies (Hamel, et al., 1993).

Case studies are used to contribute to our knowledge about individual, organizational, social and political phenomena; and have been commonly used in psychology, sociology, political science, and business, always with the aim of understanding complex social phenomena (Yin, 2003b). Case studies allow researchers to retain the holistic and meaningful characteristics of real-life events like individual life cycles, organizational processes, and the maturation of industries (Yin, 2003b).

But is the case study a method or an approach? French sociology describes it as a monographic approach (Hamel, et al., 1993). Indeed, case studies can use several methods, such as interviews, participant observation, and field studies; with the goal of reconstructing and analyzing a case (Hamel, et al., 1993).

In general, case studies are the preferred research approach when *how* or *why* research questions are being posed, when the investigator has little control over the events under study, when the focus is on a contemporary phenomenon within a real-life context, and when the phenomenon under study is not readily distinguishable from its context (Yin, 2003a).

Thus, the projects with better environmental performance made by a company with commitment to environmental responsibility are susceptible to be studied comprehensively using a case study approach. The following reasons support this statement. First, the research question asks *How* environmentally responsible design approaches are used in product design and development by an American business firm with commitment to improve its environmental performance. Next, I have actually no control over the events under study because they occurred independently of what I have done. Also, the focus is on a contemporary phenomenon within a real-life context, and this characteristic of happening in real-life is what makes them interesting for this research. Finally, the phenomena under study, the projects, are not readily distinguishable from their immediate context, the company that makes them. Moreover, research about business firms has frequently assumed the form of case studies (Yin, 2003a).

Case studies can be single or multiple (Yin, 2003a). This entails the need of a decision, prior to any data collection, about if a single or multiple case studies are going to be used to answer the research questions (Yin, 2003b). Single case studies are appropriate to five broad circumstances: a critical case in testing a well formulated theory, an extreme or unique case, a case that is representative or typical of a commonplace situation, a revelatory case of a phenomenon previously inaccessible to scientific investigation, and a longitudinal case in which the same case is studied at two different points in time (Yin, 2003b). Two of these circumstances are applicable to a company with strong commitment to become environmentally responsible as a case study: an extreme or unique case that occurs so rarely that scientists have been unable to establish common patterns (Yin, 2003b); and a revelatory case of a phenomenon previously inaccessible to scientific investigation (Yin, 2003b).

A common concern about single case studies is that they provide little basis for scientific generalization, being “How can you generalize from a single case?” a frequently asked question (Yin, 2003a, p 10). The question about generalizing from a single experiment can be asked as well (Yin, 2003a). The short answer for both questions is that “. . . case studies, like experiments, are generalizable to theoretical propositions and not to populations or universes.” (Yin, 2003a, p 10).

Research methods for collection of evidence.

Yin uses an example of a transformed business firm to illustrate the use of multiple sources of evidence as a way of strengthening case studies (2003a). Evidence can come from documentation, archival records, interviews, direct observations, participant observation, and physical artifacts (Yin, 2003a). When findings, interpretations and conclusions are based on multiple sources of evidence, the data is less prone to be inaccurate because of, for example, a biased interview or document (Yin, 2003a). Ideally, if three data sources coincide in a fact it may be considered that it has been established robustly by triangulation (Yin, 2003a).

Interviews.

Interviewing gives us access to the observations of others; through interviewing we can learn about places where we have not been, what happens in families, and how organizations work (Weiss, 1994). Through interviewing we can also learn about people’s interior experiences; we can know what people perceived and how they interpret their perceptions, how events affected their thoughts and feelings, and the meaning to them of their relationships, family and work (Weiss, 1994). Interviewing rescues events that would otherwise be lost; for most people, their triumphs, failures, celebrations and sorrows leave no record except in their memories, and there are no observers of internal thoughts and feelings except those to whom they occur (Weiss, 1994). Interviewing gives us a window to look at the past, and also to look at settings that would be otherwise closed to us, like exclusive organizations, foreign societies, and private lives of families (Weiss, 1994). All of these characteristics of interviewing make it a suitable data collection method to investigate the design and development processes of projects for this research.

Interviewing can provide access to the projects through the observations, experiences and memories of the people who worked on them, for which no other records exist. Also, interviewing people inside a company can allow learning about their internal processes and how they work in ways that are not accessible otherwise from the outside. Furthermore, interviewing allows getting people's subjective experiences and stories in ways far deeper and richer in detail than what can be achieved with surveys and questionnaires (Weiss, 1994).

Although interviewing is a suitable method to collect data, people make mistakes when remembering. Therefore, interviews should not be the only method used for data collection. Other methods should be used as well as sources of evidence in order to have more robust findings.

Documentation.

Documentation is likely to be relevant to any case study, and has an important use to corroborate and augment evidence from other sources (Yin, 2003b). Examples of documentation that can be relevant to this research include letters, memoranda, minutes of meetings, administrative documents, and formal studies or evaluations of the site under study (Yin, 2003b).

Strengths of documentation are: they are stable, or can be reviewed repeatedly; documents are unobtrusive because they were not created as a result of the case study; and they are exact with names, dates, references, and details of events (Yin, 2003b). Main weaknesses are that documents can be difficult to retrieve, the access to them may be blocked, the selection might be biased, and they may have bias from the author (Yin, 2003b).

Archival records.

Archival records include organizational records such as charts and budgets over time, service records like number of clients served over time, lists of names, personal records such as diaries and calendars, and maps and charts of geographical characteristics or layouts of a place (Yin, 2003b). The strengths of archival records are the same as with documentation plus being precise and quantitative; their weaknesses are also the same as with documentation plus less accessibility due to privacy reasons (Yin, 2003b).

Existing documents about the projects under study and about the company that made them, constitute valuable sources of evidence to help answer research question 2. Multiple kinds of documentation can contribute to establish robustness of facts by triangulating among interviews and documents, and also between interviews.

Research procedures

Content analysis of environmentally responsible design approaches.

Sampling and data sources.

The identification of environmentally responsible approaches to design, and sustainability approaches relevant to design was done through the literature review process. All the approaches found were presented in Chapter 2. The first distinction that can be made is that environmentally responsible approaches to design are more directly geared toward product design and development activities, encompassing product and process design and engineering.

Sustainability approaches, on the other hand, are not directly oriented to the product or manufacturing process, but more toward broader political, economic, and societal systems. However, sustainability approaches address environmental and other considerations that are relevant to the product design and development process, within a business firm, and within its broader context. For this reason both kinds of approaches were included in this research.

In order to select a sample of environmentally responsible design approaches, the literature was reviewed and how they referenced each other was considered. These approaches in most cases contain discrete sets of recommendations when intended as design tools, that when followed would improve the environmental performance of the designed products. The specific references to other literature sources cited where these sets of recommendations are presented were mapped and are presented on Figure 2.

Figure 2 shows that several literature sources contributed to the design recommendations consolidated by van Hemel for her Doctoral thesis in 1998. The names used for the approaches in these sources include Green design, Life cycle design, Design for environment, and other names originally in Dutch. These approaches come from literature in the fields of design and engineering, and all this tradition of recommendations finally made up the Design for Environment Typology in van Hemel's thesis (van Hemel, 1998). Then, as Figure 2 shows, in van Hemel's thesis the terms Design for Environment and Ecodesign are used interchangeably.

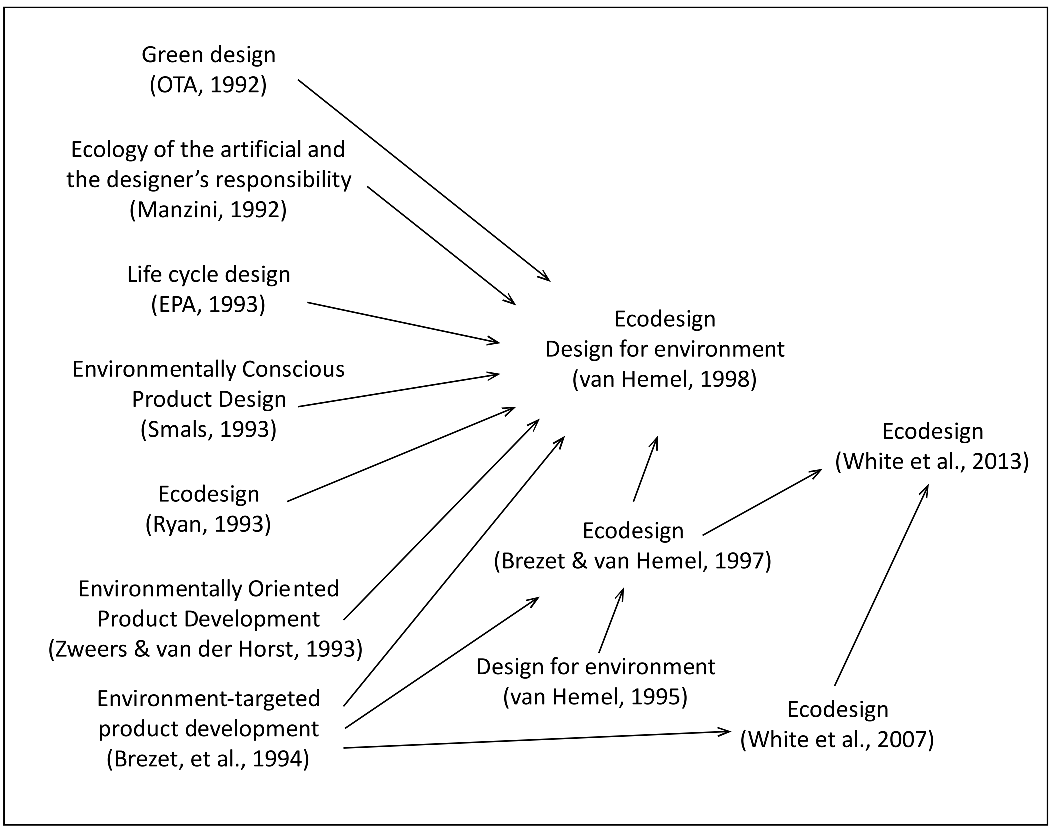

Figure 2. Names used to refer to ecodesign, literature sources, and relations by citations.

An important seminal work is the *PROMISE manual* [Environment-targeted product development] by Brezet and colleagues (1994). It is a reference for van Hemel's thesis, but more importantly for the document *Ecodesign: a promising approach to sustainable production and consumption*, published by the United Nations Environment Programme (UNEP) in 1997, written by Brezet & van Hemel, and which launched Ecodesign and the Ecodesign Strategy Wheel internationally based on the *PROMISE manual*.

A newer version of the Ecodesign Strategy Wheel published by IDSA in 2007 references the *PROMISE manual* as a source (White et al., 2007). Later, the Okala Team published the newest version in 2013 which references UNEP's Ecodesign approach (White, et al., 2013). Both of these versions build on the tradition of previous Dutch experiences and research about Ecodesign.

In order to decide which sets of strategies and improvement options should be selected for analysis, a comparative analysis of all of them was performed. The process followed for this comparative analysis is described in the section Treatment of data and analysis procedures further ahead.

Considering the Dutch literature and the American literature about Ecodesign, and based on the comparative analysis, the most comprehensive set of recommendations in the Ecodesign Strategy Wheels for each literature group were selected to be analyzed for this research. These are the Design for Environment Typology in van Hemel, 1998; and the Ecodesign Strategy Wheel published by the Okala Team in 2013.

Concerning sustainability approaches, although there are discrete sets of recommendations for each of them, there are no sources directly referenced where these recommendations are presented. For this reason it was not possible to create a figure to show the network of relationships and help decide on samples. On the other hand, doing citation analysis for this would not be practical since a complex array of relationships between all the literature sources would surface, with no indication if they directly contribute to the specific recommendations. For these reasons the selection of a sample was done using a different process.

Several topics addressed by the sustainability approaches were identified by reviewing the literature about them. Some topics were shared among various approaches. Then the general literature sources cited in each piece of literature was reviewed as well. This confirmed that shared topics coincided with shared literature sources. Looking for the sustainability approach that presented a more comprehensive set of recommendations, plus that capitalized literature that was referenced by other sustainability approaches or authored by their proponents, The Natural Step was chosen to be included in this research.

Units of analysis.

For the comparative analysis of ecodesign strategies and improvement options between different literature sources, all the sets available were selected. These are found in Brezet et al., 1994; Brezet & van Hemel, 1997; van Hemel, 1998; White et al., 2007; and White et al., 2013.

Within environmentally responsible design approaches, the units of analysis are van Hemel's Design for Environment Typology (van Hemel, 1998); and the Ecodesign Strategy Wheel published by Okala Team in 2013 (White et al., 2013). These were selected because they are discrete sets of recommendations to design products with a better environmental profile outcome.

Within the sustainability approach The Natural Step, several pieces of literature exist that present and explain the different recommendations and methods that this approach proposes. It was decided that a significant portion of Chapter 6 of the book *The Natural Step Story*, by Robèrt, was to be analyzed where the specific recommendations proposed are compiled and explained.

Limitations of the methodology.

Perhaps the greatest limitation of content analysis is the analyst. Content is not inherent to communications and people differ in how they read texts (Krippendorff, 2013). The analyst seeks to answer questions that go outside a text; indeed, the questions that a content analyst wants to answer are the analyst's questions, which are potentially at odds with whether other can answer them or not (Krippendorff, 2013).

Treatment of data and analysis procedures.

Comparative analysis of ecodesign strategies and improvement options.

Each of the texts selected for analysis contain recommendations as sets of sentences. These sentences were listed in columns using MS Excel placing one sentence per cell. To compare two texts, the two columns were placed next to each other, with the newest on the right side, trying to make the recommendations match. When this was not possible, the order of the newer column was preserved and the order of the sentences in the older column was changed to make them match. Then strategies and improvement options were compared according to their meanings. The three Dutch versions were compared, the two American versions were compared, and also one Dutch version was compared with one American version.

Design for Environment Typology.

The texts selected for analysis contain nine categories of improvement options which cluster more than 36 specific recommendations. The first eight categories consist in eight strategies ordered per lifecycle stage, each clustering a number of improvement options. Strategies were defined as ". . . potential routes a company can follow if it wishes to apply the principles of design for environment to one or more of its products." (van Hemel, 1998, p. 29). The improvement options are defined as ". . . potential means of operationalizing or realizing a DFE strategy." (van Hemel, 1998, p. 29).

Strategies and improvement options were written down in a Microsoft Excel file to prepare the data for analysis. The following steps came next:

1. The words used in the typology were listed and counted, being 156 original words;

2. Words were listed in alphabetical order;

3. The amount of times each word was used was counted;

4. Prepositions and conjunctions were removed in order to isolate content words for coding, being 78 content words;

5. Content words were sorted per function: verbs, nouns, adjectives, and adverbs. These functions depend on the context in which the words were used in the typology;

6. The meanings of the content words in their context were looked for in van Hemel's thesis and were written down in the Excel file beside each word;

7. The meanings of the content words were also searched in Merriam Webster's Collegiate Dictionary and their meanings were written down beside van Hemel's meanings.

Next, the text was analyzed qualitatively and quantitatively. For the qualitative analysis, the sentences describing strategies and improvement options were listed in Excel and codes were assigned to the meaning of their content words, taking into consideration the meanings in context by van Hemel, and the meanings as definitions from *Merriam Webster's Collegiate Dictionary*. Then these codes were organized according to categories.

For the quantitative analysis, using an Excel spreadsheet strategies and improvement options were listed. Then from this list, content words were counted and sorted by number of uses. The most frequently used words to describe strategies and improvement options were considered to draw conclusions.

Ecodesign Strategy Wheel.

The newest version of the Ecodesign Strategy Wheel in the form of an app was downloaded from IDSA's website. The sentences were copied and pasted in a column in Excel software, one sentence per cell. The printed version of *Okala Practitioner* was reviewed to correct any differences in the app.

Next, a process of coding was followed in two different ways. One way was writing codes manually on a photocopy of the Ecodesign Strategy Wheel from the Okala guide. Another way was writing codes using the Excel list in adjacent cells to the sentences. Then the codes written manually were copied in the Excel spreadsheet. Finally all the codes in the spreadsheet were classified according to thematic categories.

The Natural Step.

Utilizing a scanner and Optical Character Recognition (OCR) software, the text in Chapter 6 of *The Natural Step Story* was digitalized as live text and imported in Excel. Each sentence was put in its own cell in columns of text. A printout was made to have the text on paper so codes could be assigned manually. The text was read several times. Codes were assigned to the sentences meanings looking for different dimensions that they have, both manually and in Excel. A particular effort was made to identify specific prescriptive sentences that could be analogous to the ones used in the various versions of the Ecodesign Strategy Wheel. The codes were clustered by thematic categories and then conclusions were drawn from the codes and the categories.

Case studies of projects within an environmentally responsible business firm.

Sampling.

Doing case study research about exemplary cases has been cited as an important use of the case study approach (Ginsburg, 1989, as cited in Yin, 2003a). The first selection criterion is that every case has to demonstrate the occurrence of exemplary outcomes prior to their final selection (Yin, 2003a). Following this logic, companies to be selected for this research must have demonstrated the occurrence of exemplary outcomes with regards to environmental responsibility. The specific characteristics of these exemplary outcomes are discussed next.

Companies that enjoy enduring success have core values and purpose that remain unchanged, while their business strategies and practices constantly adapt to their changing context (Collins & Porras, 1996). The dynamic of preserving the core while stimulating progress has made several business firms achieve superior long-term performance, and this ability to manage continuity and change has been shown to be closely linked to the ability to develop a vision (Collins & Porras, 1996). Two major components make a well-conceived vision: core ideology and envisioned future (Collins & Porras, 1996). Core ideology defines what the organization stands for and why it exists; it is a consistent enduring identity (Collins & Porras, 1996). Envisioned future is what the organization aspires to become or to achieve; something that requires significant change and progress to attain (Collins & Porras, 1996).

Accordingly, having environmental responsibility as part of a business firm's vision appears to be a powerful way to help it achieve a superior environmental performance. This is one characteristic that a company should have to be selected for this research.

The second characteristic is that it needs to have experience in using environmentally responsible and/or sustainability approaches to design their products. The need of this characteristic is self-evident, as this research seeks to understand how these approaches are used by business firms. Together with environmentally responsible approaches to design, the company must have also experience in using environmental assessment methods. Otherwise, there would be no way of knowing if progress in environmental performance is being made.

The third characteristic is that the company needs to have several years of experience in using environmentally responsible approaches to design, and assessment methods. This long time experience, in principle, may allow companies to be more knowledgeable about the use of these approaches and methods, and also to be able to witness the outcomes of their implementation. Longer experience may also allow companies to go through several iterations of designing and assessing the results, which would yield richer information for this research. How many years of experience should they have? It is difficult to answer this question. However, considering that the Brundtland report was released in 1987 and that it inspired so many initiatives, it is reasonable to expect a larger number of companies to have begun their efforts to become more environmentally responsible after that year and not before.

An extensive literature and web-based media was consulted, searching for product design/manufacturing companies that met the abovementioned criteria to be potentially included in this research. Particularly, literature about environmentally responsible design and sustainability approaches usually present examples of companies that have used some approach or done some improvements. Also, some cases of companies were presented in sustainability courses at Arizona State University, and professors and colleagues often had suggestions when I told them what my research was about. All of these potential companies were searched for.

The book *Natural capitalism: creating the next industrial revolution*, by Hawken, Lovins & Lovins, published in 1999, covers comprehensively most relevant sustainability-related topics about industry and economics. Important seminal work, this book has an extensive bibliography and presents sustainability theory and actual cases of companies. More specifically, 78 companies that have done environmental improvements of some kind for their operations, facilities or products are mentioned.

The majority of the companies mentioned in this book appear on one or two consecutive pages for one environmental improvement. Some others were mentioned more times throughout the book. Toyota was mentioned in three pages, Xerox in four pages, and Interface in eleven pages where several actions that the company had undertaken were mentioned. More information about these companies was searched for this research. With fewer pages devoted to them but mentioned for direct environmental performance improvements of their products were the apparel manufacturer Patagonia, and furniture manufacturers Steelcase and Herman Miller, for which more information was searched as well.

Several literature sources have identified Patagonia as a company with commitment and experience in improving its environmental performance by using environmental knowledge in product design and development processes (Hartman & Haas, 1995; Chouinard & Brown, 1997; Hawken, Lovins & Lovins, 2000; Meyer, 2001; Reinhardt, Casadesus-Masanell & Freier, 2004; Byrne & Detert, 2006; Chouinard, 2006; Casey, 2007; Casadesus-Masanell, Crooke, Reinhardt & Vasishth, 2009; Chouinard & Stanley, 2012).

During the 1970s, Patagonia took the first big environmental step when the company owners decided to phase out the rock piton business, which was the main product they made, after seeing the degradation of the rocks of the Nose route on El Capitan, Yosemite, due to the repeated use of pitons by many climbers (Chouinard, 2006). Later, in 1994, they produced their first internal environmental assessment report based on Life Cycle Assessment (Chouinard, 2006). Patagonia's mission is "Build the best product, cause no unnecessary harm, use business to inspire and implement solutions to the environmental crisis" (Patagonia, 2014). For all these reasons, it becomes apparent that Patagonia would be an excellent case to study for this research.

Several literature sources have identified Interface Inc. as a company with commitment and experience in improving its environmental performance by using environmental knowledge in product design and development processes (Anderson, 1998; Hawken, Lovins & Lovins, 2000; Doane & MacGillivray, 2001; Robèrt, 2002; TreeHugger, 2004; Dean, 2007; Dunn, 2008; Heimbuch, 2008; TED Talks, 2009; Hawken, 2010).

In 1994 Ray Anderson, Chairman and CEO of Interface Inc., read *The Ecology of Commerce*, which was published the year before, and this book changed his life (Anderson, 1998). After this he started a new journey for his carpet tile manufacturing company to make it sustainable (Anderson, 1998). Immediately after his awakening about the damage that corporations like his cause to natural ecosystems, and recognizing his own responsibility in it, Anderson created a new vision for Interface to change its course toward sustainability (Engineering Enterprise, 2004). Interface's vision is:

> To be the first company that, by its deeds, shows the entire industrial world what sustainability is in all its dimensions: People, process, product, place and profits — by 2020 — and in doing so we will become restorative through the power of influence (Interface, 2008).

Interface has made significant progress toward its sustainability goals, which has been widely acknowledged by the business, the intellectual and the environmental communities. For all these reasons, it is clear that Interface would be an excellent case to study for this research.

Contacts with staff members within both companies were facilitated by members of my doctoral committee, and a process of interacting with the companies began. Several communications with the companies took place by email, phone and in person; in which I explained my research, what I required from them, and answered their questions. Eventually, this research moved forward with Interface.

Data sources and units of analysis.

In order to conduct research within the participating company, it was decided that two projects of the company should be selected for the study. The idea was to demand as little resources and time as possible from the company so that they still participated in this research, but also to investigate more than one project, which was considered a too small sample. If the two projects were properly chosen, then they would be able to inform about more general ways in which the company worked toward its sustainability goal.

The Director of Corporate Life Cycle Assessment Programs pre-selected two projects which, based on her experience, represent the best cases of integration of environmental knowledge in product design and development. She suggested the TacTiles and the Cool Blue projects. Then I searched for information in the company's website and we had a conversation about these and other projects. Finally we were both convinced that the best projects for this research were the ones she suggested.

In order to conduct research about Interface several people were interviewed. Two persons were interviewed who participated in the design and development processes of TacTiles and Cool Blue projects. One person who was interviewed was in charge of the environmental assessments used for these projects, and who was also knowledgeable about their development processes. One person was interviewed about how Interface moves forward toward its sustainability goals from a more general company-wide perspective. Also, a relative of Anderson was interviewed to learn about aspects of his personal life that could shed light about the environmental awareness that he experienced and his personal characteristics that may have contributed to his bold undertakings ever since.

Instruments used to collect data.

The instruments used for data collection were in person semi-structured interviews. These interviews were based on sets of questions that were prepared for each interviewee.

There was a previous process of formulating questions for participant companies. Extensive sets of questions needed to be answered to cover aspects of specific projects and about the company as well. As many questions as possible were answered using sources other than the interviews, in order to ask to the interviewees just what only they could answer with the objective of optimizing the time devoted to each interview.

Interviews were to last no more than one hour; and no more than ten questions should be asked to each interviewee about the topics they were experts in. It was necessary, however, to ask them some questions about themselves in order to have a better feel for the data and clarity about where it was coming from. So, the final questions were of two kinds: a short set of questions about the interviewee, and sets of around ten questions about the topics of the research. The introduction and questions used to guide the interviews are presented next in the order that the interviews were conducted.

1. Interview guide – Stuart Jones, Vice-President of Research and Development at Interface, and John Bradford, Chief Innovations Officer at Interface, both involved in the development of TacTiles and the Recycled Backing/Cool Blue project (they were interviewed separately but using the same interview guide).

- My name is Oscar Huerta; I am a PhD student at Arizona State University. My research topic is the integration of Life Cycle Assessment (LCA) in environmentally responsible product design and development. Also I have been a product/industrial designer for more than 15 years and I am assistant professor at Universidad Católica de Chile.
- As part of my research I am studying cases in which manufacturing companies have integrated LCA with environmentally responsible product design to make products more sustainable.
- Interface is well known for its environmental efforts, and I am studying specifically the projects TacTiles/Use of recycled backing in carpet development. I understand that you worked on both of these projects so I would like to ask you some questions.
- First, may I ask you some introductory questions about yourself?
- What is your business title, and which are your responsibilities in this position?
- Please tell me briefly about your background, and your history in this firm. (studies, past jobs, history here)
- Why did you become interested in working for this company?
- Please walk me through the design and development processes of TacTiles/use of recycled backing.
- How did you know that it would be an environmentally sound project?
- What kind of information was used? Where did it come from?
- Were there specific design methods or tools used? Please explain.

- How were environmental assessments used? Was other kind of environmental knowledge used? In the design processes?
- Were there any tradeoffs that should be made?
- Which departments were involved? Were external organizations involved? Please explain.
- Were there challenges to manage costs versus environmental performance? Please explain.
- Overall, which were the major difficulties and more straightforward things in this project?
- When I process all this information I may need to clarify some things. May I contact you again briefly for this?
- Thank you very much!

2. Interview guide – Erin Meezan, Vice-President of Sustainability at Interface.

- My name is Oscar Huerta; I am a PhD student at Arizona State University. My research topic is the integration of Life Cycle Assessment (LCA) in environmentally responsible product design and development. Also I have been a product/industrial designer for more than 15 years and I am assistant professor at Universidad Católica de Chile.
- As part of my research I am studying cases in which manufacturing companies have integrated LCA with environmentally responsible product design to make products more sustainable.

- Interface is well known for its environmental efforts, and I am studying specifically the projects TacTiles/Use of recycled backing in carpet development. I understand that you worked on both of these projects so I would like to ask you some questions.
- First, may I ask you some introductory questions about yourself?
- What is your business title, and which are your responsibilities in this position?
- Please tell me briefly about your background, and your history in this firm. (studies, past jobs, history here)
- Why did you become interested in working for this company?
- Please explain what Interface does to try to achieve the seven fronts on sustainability?
- How does Interface design and develop products to be more sustainable?
- Please elaborate about how LCA is used in Interface. Are there other assessment methods used?
- Overall, which were the major difficulties in trying to become more sustainable? And the easiest things?
- How being a public company facilitates and makes difficult becoming more sustainable? How are the issues of long term – short term profit, environmental decisions and shareholders managed?
- From a broader management perspective, how the business organizational structure helps in becoming more sustainable? Do any of its aspects make it difficult?

- Do you have in place some management tools that help becoming more sustainable?
- How are core values transmitted to staff members?
- How do you pursue front #6 sensitizing stakeholders, and front #7 redesign commerce?
- When I process all this information I may need to clarify some things. May I contact you again briefly for this? Thank you very much!

3. Interview guide – Connie Hensler, Director of Corporate LCA Programs at Interface.

- First, may I ask you some introductory questions about yourself?
- What is your business title, and which are your responsibilities in this position?
- Please tell me briefly about your background, and your history in this firm. (Studies, past jobs, hist. here)
- Why did you become interested in working for this company?
- Do you have a particular motivation towards sustainability?
- If you do, where do you think this motivation comes from?
- I have some questions about TacTiles and the Recycled backing/Cool blue projects.
- Please walk me through the creation of TacTiles and Cool blue projects.
- Please walk me through the process of conducting LCAs for TacTiles and Cool blue.

- Which internal departments were involved while doing these LCAs?
- Were external organizations involved?
- The LCA reports of these projects suggest that they were conducted after the projects existed. Was LCA or other kind of environmental knowledge used before or during the development of these projects? How did the company know that the projects would actually be environmental improvements?
- How were the results of these LCAs finally used?
- Overall, which were the major difficulties and easiest things while doing these LCAs?
- I have some general questions about the general use of environmental assessments in Interface.
- Is there a general way in which LCA is used in this company? All products or some? How is this decided?
- What resources do you have, internally and externally, to conduct LCAs?
- Do you use other assessment methods? If so, please explain when you use which.
- About Mr. Ray Anderson.
- What sources of environmental information do you know he had?
- When I process all this information I may need to clarify some things. May I contact you briefly again?
- Thank you very much!

4. Interview guide – Mary Anne Anderson Lanier

- My name is Oscar Huerta. I am a PhD candidate at Arizona State University and my research topic is environmentally responsible product design by manufacturing companies, specifically how environmental assessments are integrated in design and development processes.
- Obviously I needed to include Interface in my research, for all the environmental improvements that Mr. Ray Anderson initiated and continue going on in Interface. I have interviewed several people about the specifics of design and assessments, but in order to have a more complete idea about how all this happened I need to learn more about your father.
- Please, would you be so kind to tell me briefly about the history of your father's life?
- How would you describe his personality and character?
- In your opinion, which events or experiences in his life that were important for him and helped forge his personality?
- In 1994 your father had what he describes as an epiphany after reading Paul Hawken's *The Ecology of Commerce.* Do you think this impacted his personal life? If so, how?
- Why do you think that this book made so much sense to him?
- In awakening his environmental awareness, do you think it resonated with something he already had?

- Other than this book, do you know of other books or people that influenced him most?
- What do you think made possible that that book triggered his environmental awareness?
- When I process all this information I may need to clarify some things. May I contact you briefly again?
- Thank you very much!

Besides the interviews, several internal documents and archival material were provided by Interface. These materials were used as data sources complementary to the interviews. They were used as data points to triangulate the information gathered by the interviews. Also, several literature sources in the public domain were consulted to complement the information gathered from interviews, documentation and archival material.

Administration of instruments.

Based on the literature about qualitative research and interviewing, it became clear that the best results of interviews would be obtained in person to encourage trust in the interviewer and build rapport (Weiss, 1994). Therefore, a trip was undertaken to Interface's offices in Georgia, which would also allow for a visit of the manufacturing operations and offices. There was a process of interacting with Connie to plan the visit. An effort was made by her to concentrate the interviews as much as possible for the trip to be both effective and efficient. I flew to Atlanta on Wednesday November 13th 2013 and returned on Friday 15th. On November 14th, separate interviews were conducted in

LaGrange with the Vice President of Research and Development and the Chief Innovations Officer.

All interviewees had received a letter by email in advance explaining briefly my research and the information mandated by the Institution Review Board (IRB) of Arizona State University. All the interviews were conducted as follows. Besides the researcher the interviewee was the only person in the room. First, the researcher introduced himself and explained the research. Although the interviewees were in possession of the information it was considered important to go over it once again briefly. A printed version of the IRB protocol was offered with the request to sign if the interviewee agreed to be quoted by name. All interviewees agreed. The interviewees were then asked if the interview could be recorded for transcription purposes. All agreed. Lastly, the researcher explained that two types of questions would be asked. The first type was a set of questions about the interviewee; the second type was a set of questions that would serve as a guide to the interview.

The interviews were conducted based on the questions, at least to a certain degree. The questions were not necessarily all asked, or asked in the original order in which they were written. The conversations flowed naturally and many times the interviewees answered the questions before asking them. Also some topics emerged that were not planned but which were relevant to this research. Few notes were taken during the interviews to encourage the feeling of conversation by not doing something different than talking and paying attention. These notes were not to register what was said but to remember to ask about other topics that emerged. It was never necessary to re-direct the conversations because the interviewees were always on track with the relevant topics. After finishing with the questions, all interviewees were asked if in the future they would be able to clarify points that remained unclear from the interviews, to which all agreed.

Limitations of the methodology.

As a means for collecting data, interviews have both strength and weaknesses. The source of information is the interviewee's memory, and memory has imperfections. Three kinds of memory flaws can be identified: different kinds of forgetting, wrong memories, and persistence (Schacter, Chiao & Mitchell, 2003). Within forgetting, transience is the decreasing accessibility of memory over time; absent-mindedness are lapses of attention that result in forgetting; and blocking is when the information is present but temporarily unavailable, like the tip-of-the-tongue experience (Schacter, Chiao & Mitchell, 2003). Wrong memories can result from misattribution, when we remember something that happened but we attribute the memory to an incorrect source; suggestibility, or when we have implanted memories about things that never occurred, for example when leading questions produce false memories; or bias, when our current knowledge or beliefs distort our past memories (Schacter, Chiao & Mitchell, 2003). Finally, persistence is when we have unwanted memories that we cannot forget, often resulting from traumatic experiences (Schacter, Chiao & Mitchell, 2003).

For these reasons the data collected from the interviews was compared with what the documents, archival material and published literature said in order to write the findings and conclusions of this research.

Treatment of data before analysis and computer software used.

Early on, it was decided that a company would be hired to transcribe the recordings to text using timestamps. The objectives were saving time and having a native English speaker do it. It would then become possible to read the transcriptions while listening to the recordings and make any corrections needed.

The recordings needed for the transcriptions were prepared by listening to them several times and by editing them using Adobe Audition. Long silences were deleted as well as some talking at the beginning and end of each recording that were not about the topics of interest for this research.

Once the transcriptions were done, they were compared to the original recordings in order to identify mistakes. On average, 37.4 mistakes were found per transcription. Some of these were technical terms, some were names of people and the rest was just normal language that was misunderstood. These mistakes would have affected significantly understanding the interviews if they were not detected.

Next, the transcriptions were printed and read several times. Codes were assigned to their contents which were written on the printouts. The codes were then clustered into broader themes and the results were written down using MS Word. These results were then compared with what the documentation and archival material indicated, and were refined accordingly. After this, the results were read several times and combined into broader thematic categories integrating results of different interviews and documentation.

Ethical considerations

Considering that this research involved the interview of human subjects, it had to be approved by the IRB. All the required forms for exempt status were prepared and submitted to the IRB. Also, information letters for participating business firms, information letter for interviewees which included details about confidentiality and use of recordings, the results of the Collaborative Institutional Training Initiative (CITI) tests for the Principal Investigator (PI) and the researcher, and the guiding questions for interviews were submitted. With all this information, the IRB granted Exempt Status for this research. The information letters for interviewees are presented in Appendix A.

During the process of contacting companies to invite their participation, invitation letters together with information letters for the companies and potential interviewees using the IRB protocols were sent to the companies to be distributed among staff members that had to decide on the company's participation and later to potential interviewees. At the moment of the actual interviews, an additional form was presented to the interviewees to be signed in order to allow them to be quoted by name. All interviewees signed the form.

Summary

Chapter 3 explained the methods utilized in this research, their justification, and provided evidence that they had been applied and followed. Chapter 4 presents the results derived from utilizing the research methodology.

RESEARCH FINDINGS

Introduction

Chapter 3 justified the research methodology and provided evidence of the research procedures followed to collect and analyze data. Chapter 4 presents the results of these analyses and discusses them in relation to the research questions. The findings presented in Chapter 4 are not discussed in relation to the literature review to draw conclusions. This is done in Chapter 5.

Environmentally responsible design and sustainability approaches.

Evolution of the Ecodesign Strategy Wheel.

In order to analyze the evolution of the tool Ecodesign Strategy Wheel, several literature sources were consulted. Table 1 presents these literature sources and assigns a short name for each of them. The short names presented are used to refer to the different versions of the Ecodesign Strategy Wheel in order to facilitate reading this section. Figure 3 presents the different ecodesign strategies tools by short names and their relationships for analyses and comparisons.

Table 1

Sources of ecodesign strategy tools analyzed and short names assigned.

Tool name:	Environment-Targeted Product Development Design Strategies
Authors:	Brezet, van der Horst, & te Riele
Publication name:	PROMISE Manual for Environment-Targeted Product Development
Publication date:	1994
Publisher:	SDU
Short name:	Promise 1994
Tool name:	Ecodesign Strategy wheel
Authors:	Brezet & van Hemel
Publication name:	Ecodesign: a promising approach to sustainable production and consumption
Publication date:	1997
Publisher:	United Nations Environment Programme
Short name:	UNEP 1997
Tool name:	Design for Environment Typology
Authors:	Van Hemel
Publication name:	Ecodesign empirically explored: design for environment in Dutch SMEs
Publication date:	1998
Publisher:	Delft University of Technology
Short name:	TU Delft 1998
Tool name:	Ecodesign Strategy wheel
Authors:	White, Belletire & St. Pierre,
Publication name:	Okala: learning ecological design
Publication date:	2007
Publisher:	Industrial Designers Society of America
Short name:	Okala 2007
Tool name:	Ecodesign Strategy wheel
Authors:	White, St. Pierre & Belletire
Publication name:	Okala practitioner: integrating ecological design
Publication date:	2013
Publisher:	Okala Team
Short name:	Okala 2013

Note : Table prepared based on the literature sources presented in this table.
Full references are presented on the Reference List.

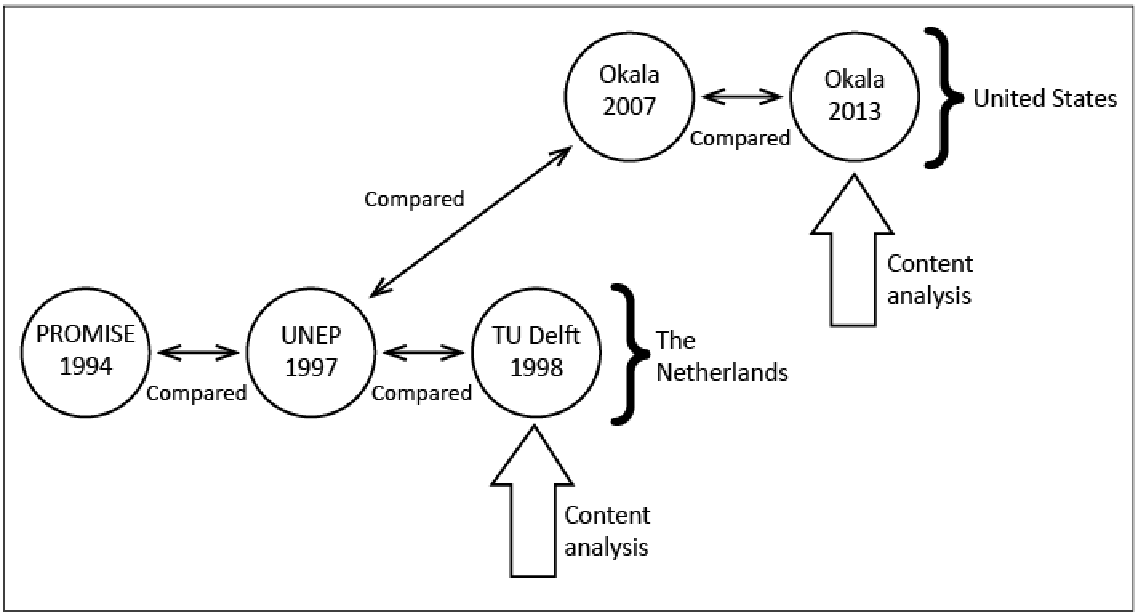

Figure 3. Relationships between ecodesign strategies tools analyzed and compared.

Promise 1994.

Table 2 presents the Environment-Targeted Product Development Design Strategies from the PROMISE manual, with the original terms in Dutch and their translations to English. In this manual, the seven strategies are displayed in a circular arrangement to be used as a tool for product design and development. A clockwise reading starting from the top is consistent with the product's life cycle stages that the strategies address. The strategies in English on Table 2 were numbered, to reflect the order in the original arrangement and make it traceable for future comparisons.

Table 2

Environment-Targeted Product Development Design Strategies from the PROMISE Manual

Original terms in Dutch	Translated terms in English
MPO ontwerpstrategieën:	Environment-Targeted Product Development Design Strategies:
Alternatieve functievervulling	1 Alternative function fulfillment
Ontwerpen voor lange levensduur	2 Design for long life
Materiaalkeuse en-besparing	3 Material choice and reduction
Kringlopen sluiten	4 Close cycles
Energiezuinig ontwerpen	5 Energy efficient design
Schoner produceren	6 Cleaner production
Efficiënte distributie en logistiek	7 Efficient distribution and logistics

Note. Table made based on "Environment-Targeted Product Development Design Strategies", by J. C. Brezet, T. van der Horst, & H. te Riele, 1994, PROMISE Manual for Environment-Targeted Product Development, NOTA/SDU, Den Haag.

The strategies express design considerations with positive environmental profile outcomes for products. Although they are implemented during the design process, their positive outcomes occur during the different life cycle stages of the product. Some strategies address more directly the product: alternative function fulfillment, design for long life, material choice and reduction, and energy efficient design. The strategy of cleaner production is about reducing environmental impacts derived from the manufacturing processes. The strategy of efficient distribution and logistics reduces the product impacts from the factory's gates to the final user. Finally, the concept of close cycles can be applied for product end of life treatments, like recycling, and also within manufacturing processes.

Comparison: Promise 1994 – UNEP 1997.

Table 3 presents the strategies in Promise 1994 side by side with the corresponding strategies in UNEP 1997. The strategies are listed up-down in the order used in UNEP 1997, and the corresponding strategies in Promise 1994 were re-ordered to make them match.

Table 3

Comparison of Promise 1994 with UNEP 1997

Strategies in Promise 1994	Strategies in UNEP 1997
1 Alternative function fulfillment	@ New concept development
3 Material choice and reduction	1 Selection of low-impact materials
	2 Reduction of materials usage
6 Cleaner production	3 Optimization of production techniques
7 Efficient distribution and logistics	4 Optimization of distribution system
5 Energy efficient design	5 Reduction of impact during use
2 Design for long life	6 Optimization of initial lifetime
4 Close cycles	7 Optimization of end-of-life system

Note. Table made based on *Environment-Targeted Product Development Design Strategies* (Brezet, van der Horst & te Riele, 1994), and *Ecodesign Strategy Wheel* (Brezet & van Hemel, 1997).

Strategy 1 Alternative function fulfillment in Promise 1994 corresponds with @ New concept development in UNEP 1997. The sign @ was used to represent the much more innovative strategy compared to the other seven strategies below it, which more clearly represent a product's life cycle stages (Brezet & van Hemel, 1997). The strategy 3 Material choice and reduction was divided into the strategies 1 Selection of low-impact materials, and 2 Reduction of materials usage, thus separating the previous concepts of choice and reduction into two different strategies. For the meanings of the remaining strategies there is a more clear similarity between those proposed in Promise 1994 and in UNEP 1997.

An important difference between the contents of Promise 1994 and UNEP 1997 is the several improvement options per each strategy that the newer version contains. These improvement options are not presented in Table 3 to facilitate comparing strategies one-to-one; they are, however, presented in Tables 4 and 5.

Comparison: UNEP 1997 – TU Delft 1998.

Tables 4 and 5 compare the strategies and improvement options in UNEP 1997 and TU Delft 1998. The strategies and improvement options are presented side by side to facilitate comparisons. The numbers and sign @ are presented in their original form. As can be noted from Table 4, the names of the strategies used in both publications match; the differences are at the improvement option level.

For strategy 1 the improvement option Recyclable materials was deleted. For strategy 2 Reduction in (transport) volume the specification of transport was removed. In both cases, however, the improvement option considers reducing the product volume as well as the packaging volume (Brezet & van Hemel, 1997; van Hemel, 1998). In strategy 3 Optimization of production techniques the word Alternative was replaced with Clean, thus becoming more specific in using cleaner production.

Table 4

Comparison of UNEP 1997 with TU Delft 1998, strategies 1 to 5

Strategies and improvement options in UNEP 1997	Strategies and improvement options inTU Delft 1998
1 Selection of low-impact materials	**1 Selection of low impact materials**
Cleaner materials	Clean materials
Renewable materials	Renewable materials
Lower energy content materials	Low energy content materials
Recycled materials	Recycled materials
Recyclable materials	
2 Reduction of materials usage	**2 Reduction of materials usage**
Reduction in weight	Reduction in weight
Reduction in (transport) volume	Reduction in volume
3 Optimization of production techniques	**3 Optimization of production techniques**
Alternative production techniques	Clean production techniques
Fewer production steps	Fewer production steps
Lower/cleaner energy consumption	Low/clean energy consumption
Less production waste	Less production waste
Fewer/cleaner production consumables	Few/clean production consumables
4 Optimization of distribution system	**4 Optimization of distribution system**
Less/cleaner/reusable packaging	Less/clean/reusable packaging
Energy-efficient transport mode	Energy-efficient transport mode
Energy-efficient logistics	Energy-efficient logistics
5 Reduction of impact during use	**5 Reduction of impact during use**
Lower energy consumption	Low energy consumption
Cleaner energy source	Clean energy source
Fewer consumables needed	Few consumables needed
Cleaner consumables	Clean consumables
No waste of energy/consumables	No waste of energy/consumables

Note. Table made based on *Ecodesign Strategy Wheel* (Brezet & van Hemel, 1997); and *Design for Environment Typology* (van Hemel, 1998).

The adjectives were changed from comparative to positive forms, e.g. cleaner to clean, lower to low, and fewer to few. This was done for two cases of improvement options within strategy 3, several cases within strategies 4 and 5, and one within strategy 6.

Table 5

Comparison of UNEP 1997 with TU Delft 1998, strategies 6 to DFE managerial actions

Strategies and improvement options in UNEP 1997	Strategies and improvement options inTU Delft 1998
6 Optimization of initial lifetime	**6 Optimization of initial lifetime**
Reliability and durability	High reliability and durability
Easy maintenance and repair	Easy maintenance and repair
Modular product structure	Modular/adaptable product structure
Classic design	Classic design
Strong product-user relation	Strong product-user relation
7 Optimization of end-of-life system	**7 Optimization of end-of-life system**
Reuse of product	Reuse of product
Remanufacturing/refurbishing	Remanufacturing/refurbishing
Recycling of materials	Recycling of materials
Safer incineration	Safe incineration (energy recovery)
	Safe disposal of product remains
@ New concept development	**@ New concept development**
Dematerialization	Dematerialization
Shared use of the product	Shared product use
Integration of functions	Integration of functions
Functional optimization of product (components)	Functional optimization
	DfE managerial actions
	Improved management practices
	Development of take-back system
	Industrial ecology

Note. Table made based on *Ecodesign Strategy Wheel* (Brezet & van Hemel, 1997); and *Design for Environment Typology* (van Hemel, 1998).

Within strategy 6, Reliability and durability changed to High reliability and durability, and Modular product structure changed to Modular/adaptable product structure. Within strategy 7, Safer incineration gave place to Safe incineration with energy recovery, and to Safe disposal of product remains. Within strategies labeled @, there are slight rewordings of improvement options to become Shared product use, and Functional optimization.

An important difference between UNEP 1997 and TU Delft 1998 is the addition of the strategy Design for Environment managerial actions. This strategy addresses topics that are not directly related to product, packaging or production, but are managerial actions with positive environmental outcomes (van Hemel, 1998). Improvement options within this strategy are Improved management practices, Development of take-back system, and Industrial ecology.

Comparison: UNEP 1997 – Okala 2007.

Tables 6 and 7 compare the strategies and improvement options in UNEP 1997 and Okala 2007. The strategies and improvement options are presented side by side to facilitate comparisons. The order used in Okala 2007 is preserved and the items in UNEP 1997 were moved to match them. Items were repeated in each list to match corresponding concepts between both lists. An item not having a matching item in the other list means that the concept does not appear in the other list.

With reference to strategies, a one-to-one match between UNEP 1997 and Okala 2007 is apparent from Table 6 and Table 7, with the exception of the contents within strategy 2 Low-impact materials in Okala 2007, which encompass strategies 1 Selection of low-impact materials and 2 Reduction of materials usage in UNEP 1997.

Strategy 1 Innovation in Okala 2007 includes all the improvement options and concepts of strategy @ New concept development in UNEP 1997, plus Modular product structure which is also under 6 Optimization of initial lifetime. Strategy 1 Innovation in Okala 2007 incorporates Design to mimic nature, and Use living organisms in product as improvement options.

Table 6

Comparison of UNEP 1997 with Okala 2007, strategies 1 to 3

Strategies and improvement options in UNEP 1997	Strategies and improvement options in Okala 2007
@ New concept development	**1. Innovation**
Dematerialization	Rethink how to provide the benefit
Integration of functions	Serve needs provided by associated products
Modular product structure	Anticipate technological change and build in flexibility
Dematerialization	Provide product as service
Shared use of the product	Share among more users
	Design to mimic nature
	Use living organisms in product
Functional optimization of product (components)	
1 Selection of low-impact materials	**2. Low-impact materials**
Cleaner materials	Avoid materials that damage human health, ecological health, or deplete resources
Dematerialization	Use minimal materials
Reduction in weight	Use minimal materials
Reduction in (transport) volume	Use minimal materials
Renewable materials	Use renewable resources
	Use waste byproducts
Cleaner materials	Use thoroughly tested materials
Recycled materials	Use recycled or reused materials
Lower energy content materials	
Recyclable materials	
3 Optimization of production techniques	**3. Optimized manufacturing**
	Design for ease of production quality control
Less production waste	Minimize manufacturing waste
Lower/cleaner energy consumption	Minimize energy in production
Fewer production steps	Minimize number of production methods and operations
	Minimize number of components/materials
Alternative production techniques	
Fewer/cleaner production consumables	

Note. Table made based on *Ecodesign Strategy Wheel* (Brezet & van Hemel, 1997); and *Ecodesign Strategy Wheel* (White, Belletire & St. Pierre, 2007).

Within strategy 2 Low-impact materials in Okala 2007, Avoid materials that damage human health, ecological health, or deplete resources and Use thoroughly tested materials add specificity and clarity to improvement option Cleaner materials in UNEP

1997. Use minimal materials encompass improvement options Dematerialization, Reduction in weight, and Reduction in (transport) volume in UNEP 1997. Use waste byproducts is new in Okala 2007, and Lower energy content materials and Recyclable materials formerly in UNEP 1997 were not included.

Within strategy 3 Optimized manufacturing, Design for ease of production quality control, and Minimize number of components/materials were included, whereas Alternative production techniques and Fewer/cleaner production consumables formerly in UNEP 1997 were not included.

Within strategy 4 Efficient distribution, Use local production and assembly is an improvement option that did not exist in UNEP 1997. Reduce product and packaging weight and Use reusable or recyclable packaging provide more detail to the former Less/cleaner/reusable packaging, and Use an efficient transport system resumes what in UNEP 1997 was Energy-efficient transport mode and Energy-efficient logistics.

Strategy 5 Low-impact use in Okala 2007 includes improvement option Minimize emissions / Integrate cleaner or renewable energy sources providing more specificity to formerly Cleaner energy source. Regarding consumables during use, water and materials are specifically mentioned in Okala 2007, while Reduce energy inefficiencies address the concepts of Lower energy consumption and No waste of energy in UNEP 1997. The concept of using Cleaner consumables formerly in UNEP 1997 was not included.

Strategy 6 Optimized product lifetime in Okala 2007 introduces improvement options Design for take-back programs and Design for second life with different function.

The other improvement options in Okala 2007 contain the concepts formerly in UNEP 1997 and add specificity in terms of design actions and goals.

Table 7

Comparison of UNEP 1997 with Okala 2007, strategies 4 to 7

Strategies and improvement options in UNEP 1997	Strategies and improvement options in Okala 2007
4 Optimization of distribution system	**4. Efficient distribution**
Less/cleaner/reusable packaging	Reduce product and packaging weight
Less/cleaner/reusable packaging	Use reusable or recyclable packaging
Energy-efficient transport mode	Use an efficient transport system
Energy-efficient logistics	Use an efficient transport system
	Use local production and assembly
5 Reduction of impact during use	**5. Low-impact use**
Cleaner energy source	Minimize emissions / Integrate cleaner or renewable energy sources
Lower energy consumption	Reduce energy inefficiencies
No waste of energy/consumables	Reduce energy inefficiencies
Fewer consumables needed	Reduce water use inefficiencies
No waste of energy/consumables	Reduce material use inefficiencies
Cleaner consumables	
6 Optimization of initial lifetime	**6. Optimized product lifetime**
Strong product-user relation	Build in user's desire to care for product long term
	Design for take-back programs
Reliability and durability	Build in durability
Easy maintenance and repair	Design for maintenance and easy repair
Modular product structure	Design for upgrades
	Design for second life with different function
Classic design	Create timeless look or fashion
7 Optimization of end-of-life system	**7. Optimized end-of-life**
	Integrate methods for product collection
Remanufacturing/refurbishing	Provide for ease of disassembly
Recycling of materials	Provide for recycling or downcycling
Reuse of product	Design reuse, or "next life of product"
Remanufacturing/refurbishing	Design reuse, or "next life of product"
Remanufacturing/refurbishing	Provide for reuse of components
Cleaner materials	Provide ability to biodegrade
Safer incineration	Provide for safe disposal

Note. Table made based on *Ecodesign Strategy Wheel* (Brezet & van Hemel, 1997); and *Ecodesign Strategy Wheel* (White, Belletire & St. Pierre, 2007).

Finally, strategy 7 Optimized end-of-life includes Integrate methods for product collection which is a necessary improvement at the system level. The other improvement options in Okala 2007 contain the concepts expressed in UNEP 1997 which are rephrased as design activities or goals.

Comparison: Okala 2007 – Okala 2013.

Tables 8 and 9 compare the strategies and improvement options in Okala 2007 and Okala 2013. The strategies and improvement options are presented side by side to facilitate comparisons. The order used in Okala 2013 is preserved and the items in Okala 2007 were moved to match them. Items were repeated in each list to match corresponding concepts between both lists. An item not having a matching item in the other list means that the concept does not appear there.

With reference to strategies, Okala 2013 has the new strategy 7 Transitional systems which improvement options were formerly within strategy 6 Optimized product lifetime in Okala 2007. Most strategies names were changed from Okala 2007 to Okala 2013: 2 Low-impact materials to 2 Reduced impact materials, 3 Optimized manufacturing to 3 Manufacturing innovation, 4 Efficient distribution, to 4 Reduced distribution impacts, 5 Low-impact use, to 5 Reduced behavior and use impacts, and 6 Optimized product lifetime to 6 System longevity. The new names are more explicit in the objective of the design strategies and the environmental goal that it tries to achieve.

Table 8

Comparison of Okala 2007 with Okala 2013, strategies 1 to 4

Strategies and improvement options in Okala 2007	Strategies and improvement options in Okala 2013
1. Innovation	**1 Innovation**
Rethink how to provide the benefit	Rethink how to provide the benefit
Anticipate technological change and build in flexibility	Design flexibility for technological change
Provide product as service	Provide product as service
Serve needs provided by associated products	Serve needs provided by associated products
Share among more users	Share among multiple users
Design to mimic nature	Design to mimic biological systems
Use living organisms in product	Use living organisms in product system
	Create opportunity for local supply chain
2. Low-impact materials	**2 Reduced Material Impacts**
Avoid materials that damage human health, ecological health, or deplete resources	Avoid materials that damage human or ecological health
Avoid materials that damage human health, ecological health, or deplete resources	Avoid materials that deplete natural resources
Use minimal materials	Minimize quantity of materials
Use recycled or reused materials	Use recycled or reclaimed materials
Use renewable resources	Use renewable resources
Use thoroughly tested materials	Use materials from reliable certifiers
Use waste byproducts	Use waste byproducts
3. Optimized manufacturing	**3 Manufacturing Innovation**
Minimize manufacturing waste	Minimize manufacturing waste
Design for ease of production quality control	Design for production quality control
Minimize energy in production	Minimize energy use in production
	Use carbon-neutral or renewable energy sources
Minimize number of production methods and operations	Minimize number of production steps
Minimize number of components/materials	Minimize number of components/materials
	Seek to eliminate toxic emissions
4. Efficient distribution	**4 Reduced Distribution Impacts**
Reduce product and packaging weight	Reduce product and packaging weight
	Reduce Product and packaging volume
Use reusable or recyclable packaging	Develop reusable packaging systems
Use an efficient transport system	Use lowest-impact transport system
Use local production and assembly	Source or use local materials and production

Note. Table made based on *Ecodesign Strategy Wheel* (White, Belletire & St. Pierre, 2007); and *Ecodesign Strategy Wheel* (White, St. Pierre & Belletire, 2013).

Table 9

Comparison of Okala 2007 with Okala 2013, strategies 5 to 8

Strategies and improvement options in Okala 2007	Strategies and improvement options in Okala 2013
5. Low-impact use	**5 Reduced Behavior and Use Impacts**
	Design to encourage low-consumption user behavior
Reduce energy inefficiencies	Reduce energy during use
Reduce material use inefficiencies	Reduce material consumption during use
Reduce water use inefficiencies	Reduce water consumption during use
Minimize emissions / Integrate cleaner or renewable energy sources	Seek to eliminate toxic emissions during use
Minimize emissions / Integrate cleaner or renewable energy sources	Design for carbon-neutral or renewable energy
6. Optimized product lifetime	**6 System Longevity**
Build in durability	Design for durability
Build in user's desire to care for product long term	Foster emotional connection to product
Design for maintenance and easy repair	Design for maintenance and easy repair
Design reuse, or "next life of product"	Design for reuse and exchange of products
Create timeless look or fashion	Create timeless aesthetic appeal
Design for take-back programs	
	7 Transitional Systems
Design for upgrades	Design upgradeable products
Design for second life with different function	Design for second life with different function
Provide for reuse of components	Design for reuse of components
7. Optimized end-of-life	**8 Optimized End-of-Life**
Provide for ease of disassembly	Design for fast manual or automated disassembly
	Design recycling business model
Provide for recycling or downcycling	Use recyclable non-toxic materials
Provide ability to biodegrade	Provide ability to biodegrade
Integrate methods for product collection	Integrate methods for used product collection
Provide for safe disposal	Design for safe disposal

Note. Table made based on *Ecodesign Strategy Wheel* (White, Belletire & St. Pierre, 2007); and *Ecodesign Strategy Wheel* (White, St. Pierre & Belletire, 2013).

With reference to improvement options, most concepts formerly in Okala 2007 remain in Okala 2013 with varying degrees of rewording. Some improvement options were added: within strategy 1, Create opportunity for local supply chain; within strategy 3, Use carbon-neutral or renewable energy sources and Seek to eliminate toxic emissions;

within strategy 4, Reduce Product and packaging volume; within strategy 5, Design to encourage low-consumption user behavior; and within strategy 8, Design recycling business model. These additions either provide specificity on the environmental goals of the design improvements, or expand the scope of the design actions to include other parts of the product system. The only improvement option removed from Okala 2007 was within strategy 6, Design for take-back programs.

Content analysis of Design for Environment Typology.

The Design for Environment Typology proposes nine strategies within which several improvement options are presented (van Hemel, 1998). The ten most used words in the typology including strategies and improvement options are energy (used eight times), clean (used seven times), materials (used seven times), production (used six times), product (used six times), optimization (used five times), consumables (used four times), low (used four times), reduction (used four times), and few (used three times). Then the word system was used three times, followed by 13 words used twice, and the remaining 54 words used only once. The ten most used words make emphasis in production processes, use of energy and materials, and minimizing amounts of inputs used.

The most used words to define strategies are optimization (used four times), impact (used twice), materials (used twice), production (used twice), reduction (used twice), and system (used twice). Then eighteen words are used only once. The strategies are broader categories that cluster improvement options, and they propose mostly optimizing processes and material inputs to reduce impacts. In general, verbs are used to indicate what needs to be done in an ecodesign project, nouns are subjects of verbs, and adjectives indicate qualities of the nouns. The relationships of these word functions as used in the typology are described next.

For the purpose of this analysis adjectives are regarded as single or composed. In a composed adjective there is an adjective and a noun that together function as an adjective. An example of this is low impact materials, in which low impact is the composed adjective and material is the noun. It happens also that a composed adjective functions as an adjective of another noun, and they all together function as an adjective. An example of this is low energy content materials, in which low is adjective of energy, low energy is adjective of content, and low energy content is adjective of materials.

Nouns are the subject of adjectives and verbs. They may be single or composed, the latter made of two or three nouns acting together as a noun. Examples of these are production consumables, and product user relation.

Verbs are used to indicate actions that the design and development team should undertake in order to create more environmentally sound products. They are always used together with nouns, or adjectives and nouns, these being single or composed. The only adverb used is not, which is used to turn a group of words negative.

The general structure of van Hemel's strategies is verb - adjective - noun or verb - noun, with either single or composed adjectives or nouns prescribing what to do. Improvement options are expressed as adjective-noun which can be either single or composed. Since strategies include improvement options the verb is omitted in most improvement options to avoid redundancy.

Looking at the structure of content words functions used in van Hemel's typology and the relationships between them it appears that strategies and principles can be reformatted for a more homogeneous structure and consistency. This means that some principles can be split into two or three. Some can be slightly rephrased.

From the perspective of the meanings of the content words used in the typology it seems that the majority and more detailed improvement options proposed are incremental changes. Only a few improvement options – New concept development, and design for environment actions – really propose more radical changes in the product systems conventionally used. Paradoxically these are the improvements that the author considers with most potential (van Hemel, 1998).

Content analysis of Ecodesign Strategy Wheel version Okala 2013.

Audiences addressed.

The newest version of the Ecodesign Strategy Wheel proposes eight strategies to minimize the environmental impacts of products within which several improvement options are contained (White et al., 2013). The analysis of the Ecodesign Strategy Wheel reveals that the strategies and improvement options presented can be used by many actors, including designers, engineers, supply chain managers, and business managers. The majority of the strategies and improvement options are addressed, explicitly or implicitly, toward product design and development activities within business environments. This means that they can be performed either by manufacturing companies, or by product design companies and consultants.

Some of these activities can be performed by designers alone, but the majority would be better attained by designers and engineers working in teams or collaborating. For example within strategy 6 Design for System Longevity, improvement options Foster Emotional Connection to Product and Create a Timeless Aesthetic Appeal belong specifically to the designers' domain. On the other hand, within strategy 5 Design for Reduced Behavior and Use Impacts, improvement options Reduce material consumption during use and Reduce water consumption during use require a substantial involvement of engineers.

Some improvement options can be attained by supply chain management rather than by design and engineering. Examples of these within strategy 4 Design for Reduced Distribution Impacts are improvement options Use lowest-impact transport system and Source or use local materials and production, and also within strategy 1 Design for Innovation improvement option Create opportunity for local supply chain.

For the improvement option Share among multiple users within strategy 1 Design for Innovation the audience is users or communities. This seems to be the only improvement option addressed solely to users or people outside a manufacturing or design company.

Action-ability dimension.

Besides design and engineering activities several strategies and improvement options are also actionable by other business departments or disciplines. Top management can put in action improvement options that are not as close to the product level and are more part of a company's strategy. For example within strategy 1 Design for Innovation, implementing improvement option Provide product as service would require a company to set up a new business model rather than a new product or service by itself.

Actions at the management level would be required for any improvement option that involves bringing materials or products back to the company. Examples of these are Develop reusable packaging systems, Design recycling business model, and Integrate methods for used product collection.

In order to put in practice some of the improvement options, a step of assessment would be required to inform design decisions. These assessments may need the involvement of other specialists, or at least consulting information generated by other specialists. For example within strategy 3 Design for Manufacturing Innovation, improvement option Seek to eliminate toxic emissions requires measuring emissions during manufacturing processes in order to plan for improvements. This can be done by environmental scientists, chemists, and materials experts. Another example is Seek to eliminate toxic emissions during use within strategy 5 Design for Reduced Behavior and Use Impacts.

Finally some improvements are designed to be ultimately performed by entities outside the company that makes the product or provides the service. This can follow two different paths. The first is to design for example for end of life disposal which happens in a landfill or incineration facility. Knowing the conditions under which these treatments take place is important to design the product and specify their material components. The second is taking a path where the product manufacturing company expands its business areas to include other responsibilities along the product's life cycle.

What-to-design dimension.

Most improvement options can be applied at the product level to design products and services, including components, assemblies and direct information about the product for the user. Other improvement options can be applied at the process level, which can include manufacturing processes or disassembly or recycling processes. Also, some improvement options can be applied at the systems level, with varying degrees of involvement of entities that are external to a manufacturing company which need to be involved for the improvement option to be effective. Some improvement options take place at the business level, which includes opening new business units. Finally some improvement options are geared toward packaging design.

The Natural Step.

In order to conduct a content analysis of The Natural Step theory, several texts were selected for analysis. The Natural Step identifies four system conditions that the socio-ecological system imposes if sustainable development is to be achieved (Robèrt, 2002). The system conditions derive from the identification of the four basic mechanisms by which human society has damaged natural ecosystems and interfered with its own sustainable development (Robèrt, 2002).

The system conditions are:

1. In the sustainable society, nature is not subject to systematically increasing concentrations of substances extracted from the Earth's crust;

2. In the sustainable society, nature is not subject to systematically increasing concentrations of substances produced by society;

3. In the sustainable society, nature is not subject to systematically increasing degradation by physical means; and

4. In the sustainable society, human needs are met worldwide (Robèrt, 2002, p. 65).

Within each system condition, several "suggested practices" (Robèrt, 2002, p 65) are proposed that help human society move forward to achieve sustainability within the ecological constraints of natural ecosystems. In the texts analyzed, the practices are suggested but not as discrete sets of improvement options. Instead, they are introduced within the narrative about the system conditions by means of statements, explanations and examples which range from more general to specific. This method of presenting the suggested practices helps to understand how they are linked to the system conditions and make sense. On the other hand, it is not always easy to clearly identify the suggested practices for improvements; re-reading the text and taking notes would be necessary for an interested reader to identify them more clearly.

The process followed was the analysis of the contents of The Natural Step, which was explained on Chapter 3. The findings of this analysis are discussed below.

Contents and meaning.

The first system condition, or System condition 1, calls for not systematically increasing concentrations of substances extracted from the Earth's crust in the biosphere. The main topic is materials, of which two broad activities are addressed: materials extraction, and materials handling.

Figure 4 shows the themes covered within the first system condition. The headings in gray boxes encompass the topics under them, both in vertical and horizontal readings.

<table>
<tr><td colspan="4"></td><td colspan="3">MATERIALS HANDLING</td></tr>
<tr><td colspan="2"></td><td colspan="2">MATERIALS</td><td colspan="2">USE</td><td>Establish sophisticated</td></tr>
<tr><td rowspan="4">MINING</td><td rowspan="4">Not for short term dispersal</td><td rowspan="4">From Earth's crust
- Metals
- Minerals
- Fossil fuels</td><td rowspan="2">Common</td><td>Prefer</td><td rowspan="4">Efficiently</td><td rowspan="4">Recycle properly</td></tr>
<tr><td>More freely</td></tr>
<tr><td rowspan="2">Scarce</td><td>Gradual phase out</td></tr>
<tr><td>If long term benefits</td></tr>
<tr><td colspan="2"></td><td colspan="2">Renewables</td><td>Switch to these</td><td colspan="2"></td></tr>
</table>

Figure 4. Content analysis results of The Natural Step's system condition 1: recommendations for materials from the Earth's crust extraction and handling.

Materials extracted from the Earth's crust are metals, minerals and fossil fuels (Robèrt, 2002). Extraction of these substances must not be for short term use and dispersal (Robèrt, 2002). Substances extracted from the Earth's crust can be divided into two types: ones that are commonly found in the biosphere and others that are scarce (Robèrt, 2002). Commonly found substances should be preferred, and they can be used more freely than scarce ones (Robèrt, 2002). Substances that are scarce in the biosphere are widely used right now. They should be gradually phased out from societal use in order to attain sustainability (Robèrt, 2002). Moreover, their use should be restricted to limited applications with long-term benefits (Robèrt, 2002). All materials extracted from the Earth's crust should be used efficiently; they should also be recycled properly in closed loops (Robèrt, 2002). To ensure that the recycling processes are effective and beneficial, sophisticated recycling systems should be established (Robèrt, 2002). Renewable materials should be preferred to those extracted from the Earth's crust (Robèrt, 2002). Switching to these materials is part of the transition to a sustainable human society (Robèrt, 2002).

System condition 2 focuses on substances produced by society. Figures 5 and 6 display the themes covered under system condition 2. Figure 5 shows production of substances, conditions for production, and final destiny.

SUBSTANCE PRODUCTION	CONDITION FOR PRODUCTION	FINAL DESTINY
Intentional	Not faster than they can be:	Broken down and integrated into natural cycles
Unintentional		Returned to the Earth's crust

Figure 5. Content analysis results of The Natural Step's system condition 2: recommendations for production of substances created by society.

Production of man-made substances can be intentional such as manufacturing chemicals; or unintentional such as by-products of incineration (Robèrt, 2002). In either case their production should not be at a faster rate than they can be broken down and integrated into natural cycles, or returned to the Earth's crust (Robèrt, 2002).

Figure 6 shows substances created by society by types and how these should be handled.

SUBSTANCE TYPE	RECOMMENDATION	CONDITIONS FOR USE			ESTABLISH SOPHISTICATED	
					Leakage prevention methods	Recycling systems
Non-existent	Phase out	Occasional, only if no safe alternatives exist	Ability to break down quickly into existing substances	Use efficiently	Prevent leakage	Recycle properly
Scarce						
Non-biodegradable						
Biodegradable	Control highly used					

Figure 6. Content analysis results of The Natural Step's system condition 2: recommendations for handling substances created by society.

Substances produced by society can be classified into two types: ones that do not exist in the biosphere and those that exist but are scarce (Robèrt, 2002). They can also be classified according to their ability to bio-degrade (Robèrt, 2002).

Non-existent, scarce and in general non-biodegradable substances must be phased out from societal use (Robèrt, 2002). They can be used occasionally only if there are no safe alternatives, and if they have the ability to break down quickly into substances that exist in the biosphere (Robèrt, 2002). Biodegradable substances can be used more freely, but their use should be controlled and monitored (Robèrt, 2002). This is because some of them are building up in the biosphere due to the excessively high volumes used (Robèrt, 2002). All substances produced by society must be used efficiently (Robèrt, 2002). Additionally, sophisticated methods should be established to prevent them from leaking into the biosphere, as well as to recycle them (Robèrt, 2002).

System condition 3 deals with physical degradation of the biosphere. Ecosystems should not be affected physically in ways that impede their production capacities or diminish biodiversity (Robèrt, 2002). Agriculture, forestry and fishing should be practiced in ways that do not lead to extinction of species, loss of soil nutrients, or sub-soil water depletion (Robèrt, 2002). Enough space should be allowed for animals and plants to live unaffected by human activity (Robèrt, 2002). Examples of problems that displace ecosystems and their processes are construction, clear cutting forests, over-fishing, and mass tourism in pristine natural areas (Robèrt, 2002). Examples of good practices include obtaining raw materials from environmentally managed forestry plantations, and sourcing food from farms that grow crops sustainably. Furthermore, new factories should be located on the foundations of old ones and all construction should be planned with respect for natural ecosystems (Robèrt, 2002). Logistics should be planned strategically to reduce long distance transportation and become more efficient as a way of reducing demand for roads and infrastructure (Robèrt, 2002).

System condition 4 is about meeting human needs worldwide. In order to achieve this, human values should be respected, and measures should be taken to inject human values into everyday business activities (Robèrt, 2002). One human value of special importance is fairness. Fairness is a shared value, and should be pursued at a global level to fulfill at least the most basic human needs worldwide (Robèrt, 2002). To achieve this, resources should be saved in the developed world by means of efficiencies and better technology, in order to re-distribute them fairly and efficiently to meet the needs of people in the developing world (Robèrt, 2002).

Just as efficiency is an important way of meeting system conditions 1, 2 and 3, it is equally important for system condition 4. In this case, efficiency means creating as much human benefit as possible from each thing taken from or released into nature (Robèrt, 2002). Specific measures are needed to decrease the amount of metals, chemicals and renewable resources used for the same human utility achieved (Robèrt, 2002). This approach is called dematerialization. But dematerialization has another measure besides a gain in efficiency. By finding new and subtler ways to satisfy human needs, services can be used rather than products or commodities thereby reducing the amounts of material things in circulation (Robèrt, 2002).

In Robèrt's theory, meeting human needs worldwide should be pursued within the constraints of system conditions 1, 2 and 3; at the same time meeting human needs worldwide is a pre-requisite to meet system conditions 1, 2 and 3 (2002).

Audiences addressed.

The analysis of The Natural Step theory reveals some audiences addressed. These audiences can implement what the theory prescribes. In this sense, audiences are explicitly and implicitly addressed. When audiences are explicitly addressed, society is the audience most mentioned in the texts analyzed. This is not expressed as what needs to be done by a society to become sustainable; instead, it is described how a sustainable society is. For example: "Even in a sustainable society, it may be necessary to increase the mining of particular substances in the short term – for example, certain rare metals needed in solar cells (to be recycled later, of course)." (Robèrt, 2002, p. 69). Although in the end it is the society at large who should implement sustainable measures, it is unclear who should do this within society.

Businesses are also mentioned as audiences that can implement the practices suggested for sustainability. Businesses are addressed three times in the texts analyzed. The first time is: “Another sustainable option is to become more efficient – for example, companies can plan strategically to reduce the need for land-consuming, long distance transportation.” (Robèrt, 2002, p. 72). In this case, two ideas are presented: efficiency in terms of transportation can be attained by not transporting goods long distances; and by moving materials locally thereby reducing the need to build more infrastructures for transportation. The first can be leveraged by companies, but the second, building transportation infrastructure, involves government decisions. Although corporate activities can demand transportation infrastructure, it is the government who really decides and contracts the building of infrastructures.

The second time that companies are explicitly addressed follows next:

> [System condition 4] . . . recognizes people’s constant striving to improve the ways in which we satisfy both our own needs and those of other people. For companies, this is largely a matter of getting better at giving customers what they want, while using fewer resources (Robèrt, 2002, p. 72).

Increasing efficiency to give customers what they want, while using fewer resources, is something that companies can do by themselves. The third time that companies are directly mentioned is:

> For instance, allocate the fuels no longer being used in the rich world as a result of smarter ways of doing business to the developing world to meet their justifiable demands to be recruited into the world’s economy. The rationale is simple for any firm with global interests - the developing world has tomorrow’s neighbors,

> markets, and partners. Fairness will be an increasingly important component of sustainable businesses. (Robèrt, 2002, p. 73).

Fairness certainly can be addressed by companies, both locally and internationally. There is a role that governments and NGOs play as well, especially to make fairness possible at an international level.

The action-ability of The Natural Step's proposals can be exerted by a much wider audience than what the texts analyzed directly mention. This is precisely one of its strengths, which is discussed next.

Action-ability dimension.

There is a specific audience for very few of the suggested practices in the texts analyzed. All of these have been discussed. For the majority of the practices suggested, however, there is not an explicit audience. Indeed, this is a characteristic of The Natural Step Framework, which is intended to help organizations to move forward toward sustainable development (Robèrt et al., 2010).

However, from an action-ability perspective several audiences can be identified that are able to implement the practices that The Natural Step suggests. These audiences include governments, non-governmental organizations (NGOs), business firms, corporate departments, communities, and end-users or individuals.

From the texts analyzed, 67 prescriptions-in-context were identified. In context means that if a prescription is used in two different contexts meaning two different things then two prescriptions are considered. An example would be efficiency: the concept of efficiency would count twice if used as efficiency of materials used, and efficiency of transportation planning.

Business firms can put into practice 88 percent of the prescriptions-in-context in the text. Governments can put in practice 76 percent of these prescriptions; corporate departments 39 percent; end users or individuals can put in practice 14 percent; and NGOs 10 percent. Most of the prescriptions-in-context are actionable by several of these entities. Governments and business firms have power to leverage the majority of the practices suggested by The Natural Step to move toward sustainable development.

Temporal dimension.

The text analyzed about The Natural Step has a structure. Each system condition is described at the beginning, followed by an explanation. Each explanation about the system conditions begins with a sentence that describes how a sustainable society is when this state has been reached. From there, a narrative unfolds presenting the suggested practices, explaining and illustrating them with examples. This pattern is repeated for each of the system conditions. The following is an example of these initial sentences: “In a sustainable society, all materials taken from the Earth’s crust are handled in such a way that concentrations of metals, minerals, and fossil fuel fumes do not build up in nature.” (Robèrt, 2002, p. 68). By being explicit at the beginning of the discussion of each system condition about the desired future to be achieved, these sentences allow the reader to understand where the rest of the text leads.

Sentences describing how a sustainable society is when it has been reached are used throughout the text and not only at the beginning. The use of end-situation descriptions is likely to come from a method called backcasting. Robèrt recommends using backcasting for planning in complex systems. In backcasting, a desired situation in the future is envisioned. From that point in the future, the thinking process works back until the present, which allows for the identification of the actions required to achieve the original goal (Robèrt, 2002). This is different from forecasting, in which the present is projected into the future to speculate what will happen (Robèrt, 2002).

Throughout the texts analyzed about The Natural Step, slightly more than half of the sentences that suggest a temporal dimension refer to an envisioned sustainable future. The remaining sentences with a temporal dimension address managing the transition to a sustainable society. By these means the present situation is connected with an envisioned sustainable future. Two examples of the transition to a sustainable society are quoted below:

> Some metals – the scarce metals that normally occur in very low concentrations in nature – are gradually phased out from large-scale societal use since the probability of rising concentrations of such metals in nature is extremely high. . . .
>
> Sustainable options are to switch to renewable fuels and materials, such as wood, fibers, ceramics, glass, and so forth (Robèrt, 2002, p 68-69).

Research findings: Case studies of projects within Interface Inc.

Company information

Interface, Inc. is the world's leading producer of modular carpet (Interface Global, 2008). The company is based in Atlanta and was created in 1973 (Anderson, 1998). Table 10 shows Interface's financial information for fiscal year 2012.

Table 10.

Financial information about Interface, Inc. for fiscal year 2012

Item	Year 2012	Percent
Net sales	$ 932,020,000	100%
Cost of sales	$ 614,841,000	66%
Operating income	$ 64,841,000	7%

As Table 10 shows, Interface sells about a billion dollars per year (Interface, 2013). Table 11 shows Interface's markets per region. Of Interface's sales, around 61 percent correspond to corporate offices, and 39 percent correspond to non-corporate offices (Interface, 2013). Fifty-five percent of Interface's sales take place in the Americas, 30 percent in Europe, and fifteen percent in the Asia-Pacific region (Interface, 2013).

Table 11.

Interface's markets per region for fiscal year 2012

		Markets	
Region	% sales	% Corp. of.	% Non-corp. of.
Americas	55%	47%	53%
Europe	30%	-	-
Asia-Pacific	15%	-	-
Company-wide	100%	61%	39%

Table 12 shows the amount of Interface's employees worldwide and their functions. The company had 3,146 employees worldwide during fiscal year 2012 (Interface, 2013). Forty-four percent of total Interface's personnel work on manufacturing (Interface, 2013).

Table 12

Amounts of Interface's personnel and their functions for fiscal year 2012

Personnel functions	# people	Percent
Sales and marketing	630	20%
Clerical, staff, supervisory and management	1,118	36%
Manufacturing personnel	1,398	44%
Total employees worldwide	3,146	100%

Figure 7 shows information about Interface's manufacturing plants and headquarters offices. The company has eight manufacturing plants worldwide (Interface, 2013). Three of these plants are located in Georgia, USA, representing 56 percent of the total manufacturing plants area (Interface, 2013). All manufacturing plants are certified by ISO 14001 Environmental Management System, with the exception of the Taicang plant in China (Interface, 2013).

	Headquarters offices	Sq. ft.	Sq. m.	
	Atlanta, Georgia*	20,000	1,858	
	Manufacturing plants	Sq. ft.	Sq. m.	% area
ISO 14001 certified	LaGrange, Georgia	539,545	50,125	
ISO 14001 certified	LaGrange, Georgia*	209,337	19,448	56%
ISO 14001 certified	West Point, Georgia	250,000	23,226	
ISO 14001 certified	Craigavon, North Ireland*	80,986	7,524	5%
ISO 14001 certified	Scherpenzeel, the Netherlands	245,420	22,800	20%
ISO 14001 certified	Scherpenzeel, the Netherlands*	121,515	11,289	
ISO 14001 certified	Bangkok, Thailand	275,946	25,636	15%
	Taicang, China*	71,375	6,631	4%
	Total manufacturing area:	1,794,124	166,679	100%
	ISO 14001 certified area:	1,722,749	160,048	
	ISO 14001 certified % area:	96%	96%	
	ISO 14001 certified per location:	88%	88%	
	* Leased property			

Figure 7. Interface's manufacturing plants and headquarters offices.

Research participants

Five persons were interviewed for this research in order to collect data about projects of Interface Inc. Four of them work for Interface, and one person, Ray Anderson's daughter, works for the Ray C. Anderson foundation. Tables 13 and 14 present briefly the interviewees' profiles.

Table 13

Interviewees for research about Interface Inc., female participants

Name:	Mary Anne Anderson Lanier, Ray's first-born daughter.
Position:	Trustee, The Ray C. Anderson Foundation
Responsibilities at The Ray C. Anderson Foundation:	Create focus for the foundation to inspire change and inspiration, and to educate the public as a resource center.
Positon prior to The Ray C. Anderson Foundation:	Worked for 12 years in Interface's Sustainable Operations team, managing projects like Environmental Education Grants, SocioMetrics, and the Cool Carpet program.
Name:	Connie Hensler
Business title:	Director of Corporate Life Cycle Assessment Programs.
Time at Interface:	21 years
Responsibilities at Interface:	All the Life Cycle Assessment work for the operations of Interface globally. Advises business units in chemistry issues, and represents the company at conferences.
Past responsibilities at Interface:	Technical director at a plant for five years, and then Director
Background:	BS in Biology with a minor in chemistry, MA in Applied Environmental Microbiology.
Position prior to Interface:	Worked as Technical Director for a textile ink manufacturer, responsible for product development, quality control, and color matching laboratories.
Name:	Erin Meezan
Business title:	Vice-President of Sustainability for the global business.
Time at Interface:	10 years
Responsibilities at Interface:	Make progress towards the company's sustainability vision, including employees participation, technical assistance on technologies, and monitoring progress.
Past responsibilities at Interface:	Basic research analyst.
Background:	Lawyer with focus on environmental law. Juris Doctor and Master in Environmental Policy.
Position prior to Interface:	Worked for the Federal Government to help States and local governments understand the economics of renewable energy and deploying technologies.

Note . The information about Connie Hensler and Erin Meezan was provided by themselves during the interviews. The information about Mary Anne Anderson Lanier was obtained from "Foundation leadership" by The Ray C. Anderson Foundation, 2012, Retrieved from http://www.raycandersonfoundation.org/leadership.

Table 14

Interviewees for research about Interface Inc., male participants

Name:	John Bradford
Business title:	Chief Innovations Officer, Interface Americas.
Time at Interface:	17 years
Responsibilities at Interface:	Launch new business units to get revenue from innovations, direction of future innovations.
Past responsibilities at Interface:	Process development and improvement, product development, General Manager in CA, innovation.
Background:	Mechanical engineer with focus on machine design, and energy in power systems.
Position prior to Interface:	Worked as a process engineer for seven years at Milliken & Company.
Name:	Stuart Jones
Business title:	Vice-President of research and development (R&D), Interface Americas.
Time at Interface:	18 years
Responsibilities at Interface:	All R&D activities, including new product development and manufacturing support. Their laboratories support all businesses around the world.
Past responsibilities at Interface:	Development chemist.
Background:	Engineer with a special emphasis in chemistry.
Position prior to Interface:	Worked 10 years as a chemist for a textile ink manufacturer, and then he was a Safety and Environmental Engineer.

Note . The information about John Bradford and Stuart Jones was provided by themselves during the interviews.

Next follow more extensive explanations about who the participants are and what they do, to help the reader understand where the data comes from, and thus have a “good feel” for the data (Perry, 1995, p. 19).

Connie Hensler.

Connie Hensler is Director of Corporate LCA Programs for Interface, Inc. She does all the LCA work for the global operations. In addition to this, she advises the business units on chemistry issues, represents the company at conferences, and does customer presentations. Her core responsibility is LCA, which she conducts to support research and development, help drive product design and process development, and also to do environmental product declarations (EPD). Interface has a program named Cool Carpet, where they purchase carbon offsets for all products to make them climate-neutral, which is supported by LCA as well.

Hensler graduated from Georgia State University in 1979, with a Bachelor's Degree in Biology and a minor in Chemistry. In 2001 she completed her Master's Degree in Applied Environmental Microbiology, also at Georgia State University. When she finished her bachelor’s degree, she worked in a chemistry laboratory, which launched her career in chemistry. She worked in that field for 25 years. Before coming to Interface, she was technical director at a textile ink manufacturer where she was responsible for product development, quality control, and color matching laboratories.

Hensler joined Interface in 1993, the year before Ray Anderson’s epiphany. She was not attracted by the company’s environmental mission because Interface did not have one yet. For her, Interface was just a carpet company, and she sought a job where she could expand her knowledge of textiles. She was also looking for a company that was local because she lived in the area. She began working at one of the manufacturing plants as a technical director. After doing this for five years, she became director of manufacturing at that plant for two years. She then went into corporate research and development from 2000 to 2006. In 2007 she began working on corporate LCA and has been working on this since then. Her chemistry background has been an asset for her

LCA specialization. In LCA knowing all of the product chemistry is important, as well as knowing the toxicological and ecological side of the impact characterizations.

Erin Meezan.

Erin Meezan is the Vice-President of Sustainability at Interface for the global business. She is responsible for helping to make progress towards the company's vision in all aspects of the business including that employees understand the sustainability focus of the company, and their opportunities to participate. Her team provides technical assistance to the business units on technologies, gives advice about potential environmental impacts of the decisions they make, and monitor how the company makes progress in achieving the sustainability goals. They play a role in talking about the mission of the company publicly and dedicate efforts to actively promote what they do to try to get other companies on a similar path.

Meezan is a lawyer by training with focus on environmental law. She has a Juris Doctorate and a Master's in Environmental Policy. Prior to joining Interface, she worked for the Federal government actively helping states and local governments understand the economics of renewable energy, and deploying technologies.

Meezan began working for Interface ten years ago as a basic research analyst. She came to Interface because she had heard of Anderson and his company's mission. She knew that Interface was hiring and she wanted to work for a company that had this kind of bold vision.

John Bradford.

John Bradford is Chief Innovations Officer for Interface Americas. His responsibility is to launch new business units inside Interface to capitalize the innovations they produce. He also strongly influences the direction of innovation inside the company. Before his current position, he was responsible for all of the innovations and innovation processes within Interface. The company used their own innovations, but then it was realized that there was revenue to be gained by either sharing those innovations for royalties or by selling materials outside the company, like recycled materials, and other products. Using their innovation capabilities to grow the business, instead of just exploiting their own innovations, is his responsibility.

Bradford is a mechanical engineer and a graduate of Auburn University (1990). He has two degree emphases: an energy focus in power systems and machine design. After graduating from engineering he worked for Milliken & Company, also a textile company, for about seven years within their process engineering group.

Bradford began working for Interface in 1997. When he interviewed with Interface, he learned of its aspirations to become a sustainable company. He became intrigued by this interest. Since he grew up on a farm, he understood well the cycles of nature from his farming experience, and saw a way for machine design and farming to co-exist which, for him, had separated. At that time, Interface was contemplating what to do about this new sustainability vision. Bradford was a member of a team that embraced this change of responsibility in the company. For a short period of time he worked on process development and improvement, then moving on to product development before moving to California to become general manager. Bradford returned to Georgia and took over innovation responsibilities for the next ten years. He now works in the entrepreneurial side of the business.

Stuart Jones.

Stuart Jones is Vice-President of research and development for Interface Americas, and responsible for all the research and development activities, which includes new product development and manufacturing support. Interface's laboratories support all of their businesses around the world and do analytical work in evaluation, troubleshooting for customer complaints, supporting new product design and development, manufacturing and process improvement initiatives, and new equipment and process installations.

Jones is an engineer with a special emphasis in chemistry. He started working on research and development as a technical services technician almost twenty years ago. This he did for a company that supplied OEM polyurethane systems and formulated industrial vinyl screen printing inks. He worked as a chemist in the vinyl division for about ten years. He then worked as a safety and environmental engineer for the same company.

Jones began working for Interface in1996 as a development chemist. He joined Interface because he knew that it was a Fortune 500 company; he was also intrigued by the environmental initiatives that the company had begun. These were the early years in Interface's journey to sustainability and Jones did not know clearly how the company was going to get there. Nevertheless, the commitment came from the top via Ray

Anderson, and this attracted Jones. He was also attracted by the culture of the company when he met some of its employees, most of whom had been in the company for more than fifteen years.

Main topics.

The TacTiles project.

The TacTiles project came from the understanding that when Interface sells a product, it also sells the burden associated with the installation process. Interface began to observe what occurred downstream. What they saw was big men carrying large amounts of carpet and four-gallon buckets of glue, who spread the glue on the floor, who had to wait for the glue to dry until it became tacky before putting the carpet tile down and, when the job was finished, who threw the paint rolls, buckets and any leftover in the garbage (J. Bradford, personal communication, November 14, 2013). The process was messy, took a long time, produced massive waste, and required that people who worked at the office leave. Interface decided to incorporate the installation process into the design domain to make it more elegant. This new installation process led to TacTiles (J. Bradford, personal communication, November 14, 2013).

It started with biomimicry. Jones describes what happened like this:

> We were sitting around brainstorming, we were offsite, it was a hot summer day and everybody was bored and running out of ideas. Then somebody was leaning back in their chair and saw a fly and said, “A fly can land upside down on the ceiling and we glue carpet to the floor, that’s stupid.” We left that day with an assignment for our biologists, Connie was one of them. We said, “Go back and study how nature connects things together” . . . . Go back and study all that and come back and teach us all. In three months, teach us everything that nature has to teach us about sticking stuff together. They came back after studying all of this

and looking at gecko feet, and fly's feet, and even layers of earth and stratified rock, how does nature put things together. They . . . realized nature doesn't really stick things together, nature doesn't really use glue, nature uses gravity and surface tension (S. Jones, personal communication, November 14, 2013).

For carpet tiles, connecting a number of them together requires gravity; it keeps them in place (S. Jones, personal communication, November 14, 2013). Then they tried to fix tiles without interacting with the floor underneath, which gave birth to TacTiles as a solution (S. Jones, personal communication, November 14, 2013).

The TacTile is a 2.5 by 2.5 inch square sticker that is placed underneath the corners of four carpet tiles when putting them together (J. Bradford, personal communication, November 14, 2013). Figure 8 shows a TacTile putting attaching four carpet tiles from the corners.

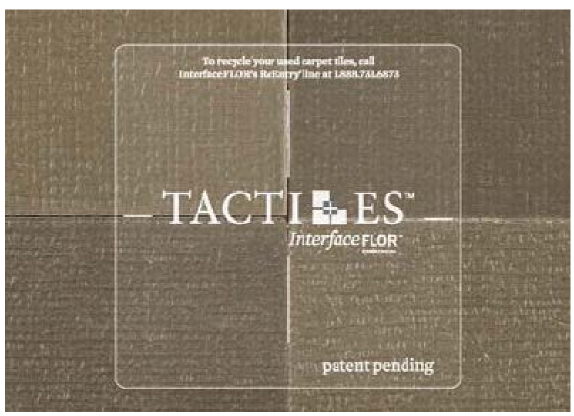

Figure 8. Photograph of a TacTile holding four carpet tiles by the corners from underneath. Adapted from "The Next Generation of Installation", by Interface, Inc., 2006, *TacTiles Intro Product Overview and How to Sell Presentations final*, Copyright 2006 by Interface, Inc.

A roll that weighs less than a pound takes the place of a thirty pound bucket of glue; thus its footprint is tiny because it has much less material (J. Bradford, personal communication, November 14, 2013). Workers are no longer transporting water, or throwing plastic buckets and paint rollers into the garbage (J. Bradford, personal communication, November 14, 2013). The only waste is the liner, which is recyclable (J. Bradford, personal communication, November 14, 2013).

This elegant solution opened several opportunities for innovation. Before TacTiles, Interface could not make an area rug with carpet tiles (J. Bradford, personal communication, November 14, 2013). With TacTiles, a person can now make a scalable area rug that fits the dimension of the room, either all the way to the walls or not (J. Bradford, personal communication, November 14, 2013).

In addition, Interface is making the TacTiles smart by putting sensors on them. By doing so, it allows for the measurement of vibrations from footfalls in order to know the type of activity in the room, where it is occurring, and the time of occurrence (J. Bradford, personal communication, November 14, 2013). These sensors can also track traffic, humidity, frequency of cleaning, and many other things (S. Jones, personal communication, November 14, 2013).

When using TacTiles, the recycling process of carpet tiles using the Cool Blue line is cleaner and more efficient. The Cool Blue line is a recycling system that Interface has in place to make backing from used carpet tiles. When TacTiles are used, the tiles are easier to reclaim, they remain clean, without glue and without concrete debris or pieces of material stuck to them, which would otherwise contaminate the recycling process (S. Jones, personal communication, November 14, 2013). The TacTiles themselves can be recycled with the backing with no problem. (S. Jones, personal communication, November 14, 2013). TacTiles complement the recycling process of the backing done in the Cool Blue line.

TacTiles go through the Carpet and Rug Institute Green Label Plus, a certification program for volatile organic compounds (VOC) emissions, which has accepted standards to be met for both carpet and carpet adhesives (C. Hensler, personal communication, November 15, 2013). When using TacTiles emissions of VOCs during the installation and use stage of carpet tiles dropped more than ninety percent (Interface, 2011). Adhesives emit much more VOCs than TacTiles, but the emissions of VOCs from adhesives are quite low compared to other items in the building causing indoor air quality issues, such as paints, furniture and other materials (C. Hensler, personal communication, November 15, 2013). For this reason Interface does not use the low emissions of VOCs from TacTiles as a sales or marketing argument (C. Hensler, personal communication, November 15, 2013).

Recycled backing and the Cool Blue project.

Interface's carpet tiles are made of several layers of materials. Figure 9 shows these layers.

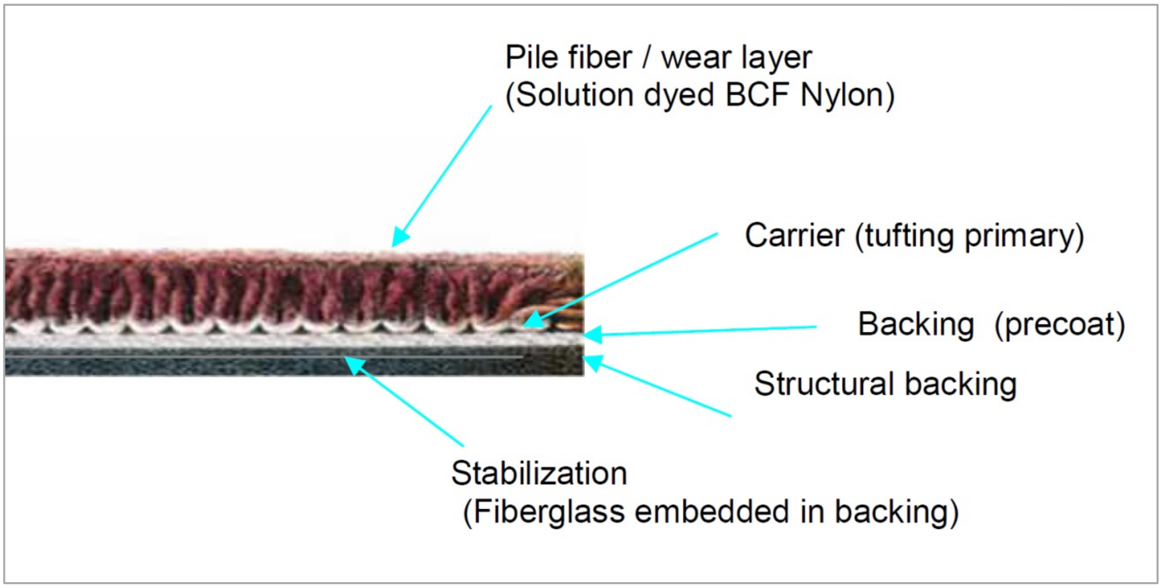

Figure 9. Diagram of product construction. Adapted from "Life Cycle Assessment of Modular Carpet – Comparison of Material Choices", by C. Hensler, 2012, *Interface Sustainable Strategies,* Copyright 2012 by Interface, Inc.

Early on at Interface, the company began to measure the environmental footprint of all the different materials that they used, and used a matrix to make decisions in order to reduce them (J. Bradford, personal communication, November 14, 2013). This direction resulted in two projects.

One was a dematerialization project, which placed a focus on achieving either the same or higher performance levels of finished products but using less material (J. Bradford, personal communication, November 14, 2013). Interface was able to remove material from the backing, change some chemistry yet, provide similar properties, and achieve higher levels of performance (J. Bradford, personal communication, November 14, 2013). Interface was also able to remove weight from the face; since nylon had the highest footprint of raw materials used, removing one ounce of nylon made a significant reduction on the product's footprint (J. Bradford, personal communication, November 14, 2013). Interface also played with many kinds of tufting methods to achieve the same performance and the same look at lower levels of face weights (J. Bradford, personal communication, November 14, 2013).

Dematerialization was only the first step. The second step transitioned materials from virgin to recycled. This is where the Cool Blue line eventually came in to play (J. Bradford, personal communication, November 14, 2013). When Ray Anderson first developed his Seven Fronts of Sustainability, front #4 closing the loop – use recycled materials, which came from his exposure to The Natural Step – meant that Interface wanted to disconnect from the lithosphere and find a way to recycle their product rather than continuing to extract resources (C. Hensler, personal communication, November 15, 2013). Because of this, recycling was already in their list of priorities. Interface began understanding that if it did not have to go to the petroleum well-head then the footprint would become smaller (J. Bradford, personal communication, November 14, 2013). It also kept material out of the landfill, which was a double benefit (J. Bradford, personal communication, November 14, 2013).

Interface's first carpet tiles with recycled backing appeared around year 2000. These were made by an external company that ground used tiles, turned them into crumb and extruded these into a sheet that could be laminated (S. Jones, personal communication, November 14, 2013). This process took a long time, it was expensive, and wasteful. Nevertheless, this is exactly what was done to make carpet tiles using recycled materials (C. Hensler, personal communication, November 15, 2013). Moreover, the product was difficult to make, below the expected quality, and most customers at that point did not value the fact that the carpet was made of recycled material (S. Jones, personal communication, November 14, 2013). Interface charged a premium for it because the process was so expensive, and by doing so they discouraged people from buying recycled content (C. Hensler, personal communication, November 15, 2013). For two years Interface dedicated ten cents of every square yard, called the re-entry fund, to fund the take-back program (S. Jones, personal communication, November 14, 2013).

Pressure was building to try to find a way to recycle more efficiently and more economically (C. Hensler, personal communication, November 15, 2013). In the end, it was decided to bring the recycling process in and structure it like a business (S. Jones, personal communication, November 14, 2013). This is when the Cool Blue project started; however it was not called Cool Blue until a few years later (C. Hensler, personal communication, November 15, 2013).

Interface intended to build an internal backing line that would handle non-virgin material in a pellet form (C. Hensler, personal communication, November 15, 2013). The current process for virgin material uses a liquid polymer (C. Hensler, personal communication, November 15, 2013). The company wanted to make a production line that could be fed with any kind of polymeric recycled material that could be melted because no one knew what the future of carpet-backing would be (C. Hensler, personal communication, November 15, 2013). One of the key premises behind building the Cool Blue Line was to make it flexible enough to use more than one kind of polymer as raw material feed (C. Hensler, personal communication, November 15, 2013).

Carpet tiles have a nylon face and a vinyl backing (J. Bradford, personal communication, November 14, 2013). The initial thought was to find an elegant solution to the heaviest material that was used in their process, which is the backing (J. Bradford, personal communication, November 14, 2013). Different machines were considered for making sheets of vinyl out of irregular materials (J. Bradford, personal communication, November 14, 2013). Interface began taking carpet back, purifying it to a degree, turning it into pellets, and then remaking sheets of material (J. Bradford, personal communication, November 14, 2013). Material was cryogenically ground into powder; the powder was then placed into an extruder in order to extrude a sheet (J. Bradford, personal communication, November 14, 2013). This process turned out to be too expensive, but the experiment proved that it could be done (J. Bradford, personal communication, November 14, 2013). Trials were conducted then with a Banbury mixer (J. Bradford, personal communication, November 14, 2013). These early trials experimented with ways to recycle backing internally.

The next step was to move to the Cool Blue technology, which is sintering (J. Bradford, personal communication, November 14, 2013). Hard pellets of recycled materials are scattered onto a table in a uniform way (J. Bradford, personal communication, November 14, 2013). These are then pressed together so that the solid material turns to a liquid in just a few seconds, just enough to fuse together and become a sheet (J. Bradford, personal communication, November 14, 2013). Trials were undertaken in different countries where different parts of machines were available (J. Bradford, personal communication, November 14, 2013). During this period Interface worked with machinery manufacturers outside of the textile industry but that already had a similar process for making sheet using a double belt manufacturing line (C. Hensler, personal communication, November 15, 2013). Interface customized these machines to fit its product allowing for the lamination of the face cloth – the soft part of the carpet – to be attached to the backing (C. Hensler, personal communication, November 15, 2013).

A small single tile pilot process was then built in Interface's laboratories (C. Hensler, personal communication, November 15, 2013). Equipment had to be found to process the material in order to prepare it to feed that machine (C. Hensler, personal communication, November 15, 2013). Two or three different kinds of chopping and agglomeration were identified, where the chopped backing was semi-melted and extruded through a small noodle-making piece of equipment (C. Hensler, personal communication, November 15, 2013). Eventually, carpet tiles were processed into crumbs to be used as raw material for the Cool Blue equipment (C. Hensler, personal communication, November 15, 2013). One of the big challenges was the scattering equipment, in which finally rollers with pins were used to scatter an even layer of irregular crumb to be pressed later (C. Hensler, personal communication, November 15, 2013).

Once it was proven that the process could be done one single tile at a time albeit on a lab pilot scale, the next challenge was securing the finance to build the full-scale machine. Bradford was instrumental in selling the idea to the board of directors as a sound investment (C. Hensler, personal communication, November 15, 2013). A larger machine was designed based on the small machine. In 2004 Interface purchased and commissioned the Cool Blue line, which now runs in LaGrange (J. Bradford, personal communication, November 14, 2013). This machine takes 100 percent recycled raw material and turns it into backing (J. Bradford, personal communication, November 14, 2013). It is the only machine of its kind in the world, and plans are afoot to build the same machine in Interface's other factories all over the world (J. Bradford, personal communication, November 14, 2013). The small version of the machine still exists in the machinery laboratory (J. Bradford, personal communication, November 14, 2013).

LCA was used when Interface first began the recycled backing process (C. Hensler, personal communication, November 15, 2013). The latter was performed by an external company and, as new developments and changes arose, Interface continued using it in order to verify how these new developments would affect the impacts and to know if they were going in the right direction (C. Hensler, personal communication, November 15, 2013). LCAs of all products are now updated every year, including the ones that have recycled backing as part of the Cool Blue line (C. Hensler, personal communication, November 15, 2013).

The recycling center.

In order to feed the recycling processes of the backing and the yarn Interface had to build a recycling center. This involved the creation of new machines (J. Bradford, personal communication, November 14, 2013). While Interface recycles the backing of the carpet they have a partner who recycles the yarn, which is used to make the upper face (J. Bradford, personal communication, November 14, 2013). In the recycling center the yarn is pre-prepared and a supplier in Europe takes it, turns it into new yarn, and sells it back to Interface (J. Bradford, personal communication, November 14, 2013).

In the past, the recycling of yarn made by Interface's suppliers was based on chemical processes that depolymerized or dissolved nylon 6 or 6.6 (S. Jones, personal communication, November 14, 2013). These processes used chemicals, water and energy; were extremely costly; produced a great deal of waste; and had low yields (S. Jones, personal communication, November 14, 2013). This profusion of waste came from the need to clean microscopic contamination in used fiber, which would otherwise ruin the yarn spinning process (S. Jones, personal communication, November 14, 2013). The main problem was the removal of fibers from carpet tiles that had first been ground (S. Jones, personal communication, November 14, 2013). The external suppliers had large plants, which changed hands several times and which eventually went out of business (S. Jones, personal communication, November 14, 2013).

Interface found a solution to separate the face from the backing that was mechanical and simple (S. Jones, personal communication, November 14, 2013). The solution came from technology that is used in the leather industry. This was done by modifying a leather splitting machine (S. Jones, personal communication, November 14, 2013). Such machines are designed to cut thin layers in increments of 0.1 mm (S. Jones, personal communication, November 14, 2013). With just minor modification to the incoming feed system, Interface could adapt these machines for their needs (S. Jones, personal communication, November 14, 2013). By doing so, Interface was able to remove 90 percent of the fiber from used carpet tiles without the usual contamination from the adhesives or other components of the carpet tile (S. Jones, personal communication, November 14, 2013).

Use of life cycle assessment in Interface.

Brief history of the measurement systems and life cycle assessment in Interface.

After Ray Anderson's epiphany, Interface began to implement measurement systems to monitor their progress. Having a clear vision, goals were set up and systems were put in place to measure progress (J. Bradford, personal communication, November 14, 2013). Because Interface's vision was to become a sustainable company and to have no impact, then impact had to be measured (J. Bradford, personal communication, November 14, 2013).

QUEST and Ecometrics were among the first measuring systems that they used (C. Hensler, personal communication, November 15, 2013). QUEST is an acronym for Quality Utilizing Employee Suggestions and Teamwork, which was a global waste elimination initiative (Interface, 2006). Interface measured how much waste was produced in every part of the production process; for example, how much waste there was in the tufting process and in the yarn winding (C. Hensler, personal communication, November 15, 2013). Once measured, Interface tried to reduce these numbers (C. Hensler, personal communication, November 15, 2013). Once the waste was identified the company came up with actions to reduce it. These actions were called QUEST projects, and were accompanied with QUEST trainings (C. Hensler, personal communication, November 15, 2013).

The second measurement system was Ecometrics. It measures several factors that are connected to environmental impact, such as energy used per square meter of carpet produced, or water used, or materials at the landfill, or pounds of material purchased versus square meters produced, or recycled content of materials purchased (C. Hensler, personal communication, November 15, 2013). It took Interface some time to implement Ecometrics. It began in 1995 but no reliable data was available until 1996 (C. Hensler, personal communication, November 15, 2013).

Ecometrics measures processes conducted inside the company (C. Hensler, personal communication, November 15, 2013). Only non-renewable energy was taken into account, as a way to encourage the business units to convert to renewable energy (C. Hensler, personal communication, November 15, 2013). Energy was measured per square yard production instead of direct energy use (C. Hensler, personal communication, November 15, 2013). This was done because Interface wanted to grow as a business and therefore produce more square yards (C. Hensler, personal communication, November 15, 2013). If direct energy use had been measured, it would have gone up regardless of efficiencies achieved (C. Hensler, personal communication, November 15, 2013). Significant energy reductions were achieved over the years (C. Hensler, personal communication, November 15, 2013). For water Interface did a per-square-yard reduction as well, although the company does not use much water in its plants because it does not dye material (C. Hensler, personal communication, November 15, 2013).

Ecometrics continues to be used today. The results are published on their website and updated annually (C. Hensler, personal communication, November 15, 2013).

LCA has been used at Interface since 2000 (C. Hensler, personal communication, November 15, 2013). Starting with QUEST and Ecometrics, Interface always sought ways to measure progress (C. Hensler, personal communication, November 15, 2013). The company learned about LCA; it considered purchasing LCA software in order to see if it was useful (C. Hensler, personal communication, November 15, 2013). Because Interface did not know which LCA software to buy, a graduate student from Georgia Tech was hired as an intern (C. Hensler, personal communication, November 15, 2013). He was asked to evaluate all available LCA software (C. Hensler, personal communication, November 15, 2013). He analyzed the competing programs that existed. By using this analysis, Interface identified GaBi Software from PE International as the appropriate tool (C. Hensler, personal communication, November 15, 2013). Interface then acquired a license for the software and began training people to use it including Hensler (C. Hensler, personal communication, November 15, 2013). A recent graduate was also hired full time to start conducting LCAs for the company (C. Hensler, personal communication, November 15, 2013). The first LCAs conducted in Interface assessed the company's existing products in general to identify where the largest environmental impacts were produced. The company then began using LCA to measure environmental impacts in product development projects (C. Hensler, personal communication, November 15, 2013).

When LCA was first introduced it was used together with Ecometrics (C. Hensler, personal communication, November 15, 2013). LCA gave Interface another lens through which to look at their environmental performance (C. Hensler, personal communication, November 15, 2013). The company's environmental perspective was no longer internal; instead, it was looking at the complete life cycle (C. Hensler, personal communication, November 15, 2013). For example, Interface was already reducing the energy use per square yard inside the plant; with the new approach using LCA for its products, however, the company realized that, although it should reduce its energy use, this was a small contributor to their total footprint from a life cycle perspective (C. Hensler, personal communication, November 15, 2013). Seventy-five percent of the company's footprint was in its yarns and backings (C. Hensler, personal communication, November 15, 2013). While recycling was on the list of future improvements, it suddenly became one of the most important processes to focus on after looking at it from a life cycle perspective (C. Hensler, personal communication, November 15, 2013).

How life cycle assessments are conducted in Interface today.

Every year, LCAs are conducted on all the products that the company makes. This process occurs in every plant across the world, and includes updating and redoing studies (C. Hensler, personal communication, November 15, 2013). One of the programs is the Cool Carpet program, aimed at carbon neutrality through the purchase and retirement of carbon offsets, for which they calculate the average carbon footprint for all the products made by Interface (C. Hensler, personal communication, November 15, 2013). These LCAs include the installation method, therefore the TacTiles, and the recycled backing for those that use Cool Blue backing C. Hensler, personal communication, November 15, 2013).

The Cool Blue line has three components: a material component, an energy component, and a labor component (J. Bradford, personal communication, November 14, 2013). The labor component does not fall into the LCAs (J. Bradford, personal communication, November 14, 2013). Interface assesses materials and energy for the most part (J. Bradford, personal communication, November 14, 2013).

Besides the annual updates, new LCAs often support diverse projects and new product development (C. Hensler, personal communication, November 15, 2013). What follows is a random example of doing an LCA. In LaGrange, the engineering group considered changing a product by eliminating one layer and using a different material to reduce the environmental impacts. Hensler was contacted and was asked: “We’re doing this project. We need to know how it affects the old way and this possible new way. Is it good? What are the LCA results?” The engineer gave her basic inventory data about the new material. Sometimes Hensler had to contact the supplier, sometimes not. This depended on how much information the engineering group had. Hensler collected all the new data from the engineer, and then she reported back to him: “Here are the results, this time it turns out that it’s not better, it’s not worse, it looks like it’s about five percent better, but with the uncertainty in my study it’s not better or worse from a lifecycle assessment perspective.” On this occasion the engineer was disappointed; he wanted to be able to say that it was a tremendous environmental improvement (C. Hensler, personal communication, November 15, 2013).

With regards to resources to conduct an LCA, it has already been mentioned that GaBi is the software platform used by Interface. Other data collection programs are also used to collect the Ecometrics data. Ecometrics itself is a data source for LCA (C. Hensler, personal communication, November 15, 2013). For the Cool Carpet program, for example, all the energy consumed is included, and not just process energy (C. Hensler, personal communication, November 15, 2013). Both the amount and the kind of energy used at a plant are considered (C. Hensler, personal communication, November 15, 2013). Ecometrics is a data source for this (C. Hensler, personal communication, November 15, 2013). Besides the use of GaBi by Hensler to conduct LCAs, a simpler version named GaBi Reader is used in research and development to make rough comparisons of the environmental impacts of materials considered in projects (S. Jones, personal communication, November 14, 2013). GaBi reader is used for verifications and most often to determine which alternatives not to pursue (S. Jones, personal communication, November 14, 2013). More thorough and complex LCAs are undertaken by Hensler when needed (S. Jones, personal communication, November 14, 2013).

In 2006 Interface had plans to place an LCA practitioner at each plant. This would allow an onsite person to do the LCA work (C. Hensler, personal communication, November 15, 2013). The recession hit just at the time when Interface was about to launch the initiative; in the end, no one was hired (C. Hensler, personal communication, November 15, 2013). In fact, the majority of the staff who worked on LCA at the corporate office was laid-off except for Hensler (C. Hensler, personal communication, November 15, 2013). She is currently the only person that conducts LCAs at Interface (C. Hensler, personal communication, November 15, 2013).

When conducting LCA, Hensler must interact with several people inside the company (personal communication, November 15, 2013). Other than software, her relationship with the people in each business unit allows her to perform the LCAs (C. Hensler, personal communication, November 15, 2013). For the extensive annual updates, Hensler has discussions with engineering, purchasing and quality control to collect correct specifications for weights and the different parts of the product (C. Hensler, personal communication, November 15, 2013). For instance, discussions with purchasing provide information about where the raw material comes from, the shipping distances, and the methods of transport (C. Hensler, personal communication, November 15, 2013). From engineering, Hensler learns about the energy consumption for the different processes and also cost accounting for waste factors (C. Hensler, personal communication, November 15, 2013). Every year waste factors are updated. By doing so, Interface learns how much carpet is wasted when they die-cut the tiles and what percentage the scrap represents (C. Hensler, personal communication, November 15, 2013). For individual projects, Hensler collects specific data from whoever is working on them (C. Hensler, personal communication, November 15, 2013).

The company PE International, which makes GaBi and creates LCA databases, is sometimes involved when Interface conducts LCAs (C. Hensler, personal communication, November 15, 2013). For instance, Interface did not have access to the sources of electricity in China’s grid when it opened a plant there (C. Hensler, personal communication, November 15, 2013). Interface had to buy a data set, which they acquired from PE International (C. Hensler, personal communication, November 15, 2013). If Interface is looking at a new bio-based material, the company may not be able to conduct the LCA of this material (C. Hensler, personal communication, November 15, 2013). Interface may work with PE International, either hiring them to create the database or buying an LCI data set if PE International has something similar (C. Hensler, personal communication, November 15, 2013).

In order to visualize the life cycle impacts of their products, Interface uses what it calls a spider diagram as a chart to display the aggregated footprint (J. Bradford, personal communication, November 14, 2013). The company makes decisions to improve its environmental performance. Progress increases as the spider diagram becomes smaller. LCA is used to measure this footprint (J. Bradford, personal communication, November 14, 2013). The topics of each part of the web are the impact categories derived of the impact characterization methods used.

How life cycle assessment results are used in Interface.

Interface uses LCA results in several ways. One of these is for decisions in product development. For example, Hensler will be asked if a new raw material is better or worse than their current material; or if a new packaging has a lower environmental footprint or not. It is her responsibility to answer questions such as these (C. Hensler, personal communication, November 15, 2013). LCA also supports the Cool Carpet program as a means of calculating the footprint of its products for climate neutrality (C. Hensler, personal communication, November 15, 2013). LCA is also used for environmental product declarations (EPD) where impacts are publicly disclosed (C. Hensler, personal communication, November 15, 2013). Recently, past LCA studies that were conducted in the development process of several projects were compiled into one single document. The objective of the exercise was to do a critical review in order to use the information for comparative claims (C. Hensler, personal communication, November 15, 2013). Recently as well, Interface sent the TacTiles project to a Europe competition where backup data based on LCA was provided in order to support information for the competition (C. Hensler, personal communication, November 15, 2013). Finally, Interface uses the LCA to educate its costumers (C. Hensler, personal communication, November 15, 2013).

Life cycle assessment and suppliers.

For years, Interface requested LCA data from its suppliers. Such a request is significant for a supplier, and Interface has had varying degrees of success (C. Hensler, personal communication, November 15, 2013). At times, suppliers do not understand what is being requested (C. Hensler, personal communication, November 15, 2013). These suppliers often do not always understand what an LCA is (C. Hensler, personal communication, November 15, 2013). At other times, the suppliers know what the LCA is but feel overwhelmed by the request (C. Hensler, personal communication, November 15, 2013). At yet other times, some suppliers do not want to share more information than is necessary about their products (C. Hensler, personal communication, November 15, 2013). In general, however, asking suppliers for inventory data has not been successful. Some reports showing characterized data have been collected (C. Hensler, personal communication, April 10, 2014). Two examples (below) provide details about Interface's experience in collecting data from suppliers.

One supplier, when requested for LCA data was exceptionally cooperative and helpful. The company hired an LCA consultant to assess the recycled fiber they were selling to Interface (C. Hensler, personal communication, November 15, 2013). With another supplier, a contract was signed specifying that it be required to provide Interface with LCA data on the product that it sold to Interface. If such data were not provided, the supplier would be penalized a certain dollar amount every month as a kind of fine (C. Hensler, personal communication, November 15, 2013). The supplier has not provided the LCA data for an entire year, and has paid Interface for providing the data (C. Hensler, personal communication, November 15, 2013). At the end of that year the supplier and Interface met. It was told: "Look, for the money that you've paid us you could have paid somebody else to do an LCA study." (C. Hensler, personal communication, November 15, 2013). As a result, Interface connected the supplier with a consultant who agreed to help them compile the LCA data and to stop paying the fine to Interface (C. Hensler, personal communication, November 15, 2013). Interface is attempting to assist suppliers by reducing what appears to be an overwhelming obligation of doing an LCA. Interface wants to make the LCA clear and simple, and to direct suppliers to resources that could help them provide what Interface needs (C. Hensler, personal communication, November 15, 2013).

Based on previous experiences in engaging suppliers with LCA, Interface now has a better plan. At a large upcoming supply chain meeting interface will request specific LCA information, almost like product category rules (PCR), about how it wants suppliers to deliver the LCA results, have these verified, and how to report the data (C. Hensler, personal communication, November 15, 2013). This new program includes all Interface suppliers. Furthermore the data will be proprietary (C. Hensler, personal communication, November 15, 2013). A system will be set up so that this proprietary information cannot be accessed by Interface (C. Hensler, personal communication, November 15, 2013). For instance, the inventory data can be converted into a GaBi data set that is locked so that Interface cannot see their proprietary information, but still can plug it into their models to use the impacts of their product (C. Hensler, personal communication, November 15, 2013). Hopefully the project will be successful in creating a new supply chain LCA model for Interface (C. Hensler, personal communication, November 15, 2013).

Ray Anderson.

Brief history of Ray Anderson's life and beginnings of Interface.

Ray Anderson was born in 1934 and died 2011. He was a child of the Great Depression (M. A. Anderson Lanier, personal communication, November 15, 2013). His mother was one of seven children and his father was one of seven children as well (M. A. Anderson Lanier, personal communication, November 15, 2013). Anderson's father never finished high school because he had to work to help provide for his family (M. A. Anderson Lanier, personal communication, November 15, 2013). His mother went to college and became a school teacher (M. A. Anderson Lanier, personal communication, November 15, 2013).

Anderson’s parents got married in the 1920s. In those days the costume was that married women could not teach in a classroom. Anderson’s mother was therefore forced to leave teaching (M. A. Anderson Lanier, personal communication, November 15, 2013). She had three children, Ray and his two older brothers, which she taught at home. The children also attended school (M. A. Anderson Lanier, personal communication, November 15, 2013). All three ended in one profession or another. Ray’s older brother became a doctor; the middle brother became a science teacher and a Baptist minister; and Ray became an engineer (M. A. Anderson Lanier, personal communication, November 15, 2013).

Anderson used to say that he grew up with a book in one hand and a ball in the other (M. A. Anderson Lanier, personal communication, November 15, 2013). “He was a very gifted athlete, a star on the football team, the baseball team, the basketball team.” as his daughter said (M. A. Anderson Lanier, personal communication, November 15, 2013). He earned a football scholarship to Georgia Institute of Technology in Atlanta and graduated in 1956 with a degree in industrial engineering (M. A. Anderson Lanier, personal communication, November 15, 2013). He married his first wife in 1954 when he was still in college (M. A. Anderson Lanier, personal communication, November 15, 2013).

Anderson was from an area in Georgia that is a center of the textile industry, where cotton was grown and made into products of one kind or another. To no one’s surprise, Anderson started working in the textile industry (M. A. Anderson Lanier, personal communication, November 15, 2013). In 1959, he began working for Callaway

Mills, a large textile manufacturing company in LaGrange (M. A. Anderson Lanier, personal communication, November 15, 2013). Eventually the company was sold to Milliken, another textile manufacturer. Anderson worked for Milliken for several years and became Vice-President (M. A. Anderson Lanier, personal communication, November 15, 2013).

During the late 1960s and early 1970s, Anderson would travel to Europe looking for products, ideas, innovations and other things that Milliken might want to adopt (M. A. Anderson Lanier, personal communication, November 15, 2013). This is how he discovered the concept of carpet tiles (M. A. Anderson Lanier, personal communication, November 15, 2013). Milliken showed no interest, but Anderson was interested. At this point, he decided to start his own company together with four other men, who were friends he had known in the textile manufacturing world (M. A. Anderson Lanier, personal communication, November 15, 2013). He partnered with Carpets International, which was the largest carpet manufacturer outside the United States at that time, and which wanted to have a presence in the U.S. A. (M. A. Anderson Lanier, personal communication, November 15, 2013). In 1973, Anderson and his friends formed a subchapter S corporation with 50 percent of the capital invested by Ray Anderson and 50 percent by Carpets International (M. A. Anderson Lanier, personal communication, November 15, 2013). Years went by and eventually Interface purchased the remaining interest from Carpets International; this is how Interface came to have a presence in Europe (M. A. Anderson Lanier, personal communication, November 15, 2013).

The epiphany.

Anderson was invited by Ed Terry, who was in charge of the Interface Research Corporation, to attend the Global Resource Conservation Kick-off meeting and give a vision statement on what Interface should be doing about the environment (C. Hensler, personal communication, November 15, 2013). Anderson did not yet have an environmental vision, other than to comply with the law. The thought that being in compliance with the law might also mean that Interface was nevertheless damaging the environment never occurred to Anderson (Anderson, 1998). Ray Anderson's words describe what happened next:

> Then, through what seemed to be pure serendipity, somebody sent me a book: Paul Hawken's *The Ecology of Commerce*. I read it, and it changed my life. It hit me right between the eyes. It was an epiphany. . . I had the vision I was looking for, not only for that speech but for my company, *and* a powerful sense of urgency to do something to begin to correct the mistakes of the first industrial revolution. Hawken's message was a spear in my chest that is still there (1998, p 39-40).

Ray's keynote remarks for the Global Resource Conservation Kick-off.

Hensler began working for Interface one year before she attended the Global Resource Conservation Kick-off meeting. She did not know much about the company at that point (C. Hensler, personal communication, November 15, 2013). For this meeting, representatives from the research and development groups from each manufacturing plant were coming together. They were asked to discuss environmental issues at their plants (C. Hensler, personal communication, November 15, 2013).

Anderson attended the meeting and gave Interface's vision statement (C. Hensler, personal communication, November 15, 2013). This vision statement was to begin the company's journey on its new path of sustainability (C. Hensler, personal communication, November 15, 2013). Hensler's words express eloquently her feelings about what happened in and after that meeting:

> It brought tears to my eyes. It was just so poignant. . . . I was coming to work every day, and I was doing my formulation work. I was working on a new product, and I was trying to get this product to do what the customer wanted it to do. I was trying to make it work in the manufacturing process and trying to get the costs down. That was business as usual, doing research and development. Now, after that [meeting], I was looking at the bigger picture at Interface instead of focusing on this little piece of the work that I'm doing so that the company can make a sale and get some money. Now I was suddenly looking at the whole plant and what were all the things that would have an environmental impact in context to this new product I was going to develop. It just inspired a lot of people, I think. It gave the people the concept that now, we're not just going to be here working to put more money in Mr. Anderson's pocket. We're here working to make a difference, to improve the world. It definitely was an inspirational change (C. Hensler, personal communication, November 15, 2013).

Hensler feels fortunate for having been at that meeting and hearing directly what Ray Anderson said (C. Hensler, personal communication, November 15, 2013). The attendees from Interface were a small group of people; Hensler is the only person still at Interface from the group who attended this meeting (C. Hensler, personal communication, November 15, 2013).

What exactly impressed Hensler so deeply? She remembers that it was Anderson sharing one of the examples from *The Ecology of Commerce* about reindeers exceeding the carrying capacity of an island (C. Hensler, personal communication, November 15, 2013):

> [St. Matthew] Island in the Bering Sea was a deserted island until 1944, when 29 reindeer were imported. Scientists calculated that the island had a carrying capacity of . . . 1600-2300 reindeer. By 1957, the population had grown to 1350, with no natural control, no predators. By 1963 there were 6000 (they thought the calculations were not correct). But, the calculations were correct! By 1966, the population had dropped to 42. Not just the "extra" died. The "overshoot" produced a catastrophic effect (Interface, 1994).

For Hensler, the story was a good metaphor to look at the Earth and ask if humans are consuming more resources than it can sustain much like those reindeer were doing. Is collapse inevitable because we have over consumed? (C. Hensler, personal communication, November 15, 2013). During that meeting Anderson recognized the damage that Interface was doing as a company with its consumption of resources. He wanted to change that situation (C. Hensler, personal communication, November 15, 2013).

The Global Resource Conservation Kick-off meeting was truly inspiring. It was not at all what they expected to hear. They expected the meeting to be a basic development working group, but after Ray's speech and the conversation during the meeting everybody who attended left inspired (C. Hensler, personal communication, November 15, 2013). This meeting generated a great deal of internal work on projects to reduce their environmental footprint (C. Hensler, personal communication, November 15, 2013).

Afterwards, attendees started offering many training classes at all of Interface's facilities in order to share the new vision of the company, and to setup QUEST teams to begin working on projects (C. Hensler, personal communication, November 15, 2013). These teams would identify what should be worked on, and what could be done in each department (C. Hensler, personal communication, November 15, 2013). Training classes involved going to departments in plants, explaining what needed to be accomplished, how the team could contribute, and generating project ideas to start generating the Ecometrics numbers (C. Hensler, personal communication, November 15, 2013).

Memories of interviewees about Ray Anderson.

Specific questions about Ray Anderson were asked only to his daughter. Some questions related to him were asked to Hensler about the Global Resource Conservation Kick-Off meeting. Nevertheless, all the other interviewees spontaneously talked about Anderson without being asked.

Besides knowing about Interface's intention to becoming sustainable, one of the attractions for Jones to work for the company was the fact that the commitment for sustainability came from the top:

> . . . the commitment was there from the very top, from Ray Anderson down. Unlike . . . [other companies, where there is] customer-facing commitment to a lot of environmental initiatives, but when it [comes] time to implementing them in-house and making an actual investment or changing the infrastructure in order to accomplish that goal, the support really . . . [is not] there (S. Jones, personal communication, November 14, 2013).

On the contrary, Interface was "willing to put their money where their mouth is" and this was one thing that attracted Jones (personal communication, November 14, 2013).

When Bradford and his team worked on the Cool Blue line, they became anxious when they received the money to build this machine; it was a huge responsibility to make this new invention work. Bradford remembers that Anderson believed in him and his team more than they believed in themselves. In his own words:

> . . . when somebody believes in you $10.8 million that they don't have . . . that puts in different kind of self-pressure in play, because you would run through that wall for that guy, because he believes in you. . . . To me, when somebody really believes in you, more than you believe in yourself, that's edifying (J. Bradford, personal communication, November 14, 2013).

Anderson was effective in explaining to his people what the company was trying to do. Certain things resonated more or less with each individual. Jones does not consider himself an idealistic environmentalist, but this was not an impediment for him to understand Interface's environmental responsibility. He remembers talking about this with Anderson:

> . . . all of these take, make, and waste processes that we did. When Ray Anderson explained this to me, the light came on, I got it immediately. It's not about saving the world or anything, it's about being responsible. Just because you can, doesn't mean you should. And just because we can use all virgin chemicals and we can use toxic chemicals as long as we comply with the law, and we can do all of these things, as long as we market it correctly, we can use the cheap materials and the cheap processes and do things the easy way and be very competitive. It's much, much harder to do it the right way and still be the leader (S. Jones, personal communication, November 14, 2013).

Ray Anderson's personal characteristics.

Ray Anderson's daughter describes him like this:

> He had so much charisma. He just had this gift of making everyone feel like they were the only person in the room when he was talking to them, a cheerful, wonderful, big smile. . . . Vivacious, very warm. He's the epitome of a southern

> gentleman. . . . That’s not to say he wasn’t a fierce competitor. He was a fierce competitor. . . .
>
> Everybody loved him. He was an amazing storyteller. There was something, when he was in the room, you wanted to listen to him. He was on stage. It never seemed terribly orchestrated. It was just natural. He was a very natural, kind, warm, giving, enthusiastic person (M. A. Anderson Lanier, personal communication, November 15, 2013).

All these characteristics may have been very helpful for Anderson when he began redirecting the course of Interface to make it more sustainable by inspiring people and explaining the new vision and mission.

Some of Anderson’s personal characteristics appear to have influenced how he started looking for advice and eventually assembling the Eco Dream Team. According to his daughter, Anderson never assumed that he had the answers. He knew that he needed to find thought leaders from outside Interface, people who knew well what was going on and who could help them (M. A. Anderson Lanier, personal communication, November 15, 2013). He called Paul Hawken and said “I’ve read your book, and I’ve got to do something.” (M. A. Anderson Lanier, personal communication, November 15, 2013). Anderson Lanier also shared the following insight:

> Paul put him in touch with other people that he knew were working in the field. He assembled what he called the Dream Team to come and work with Interface, and help them.
>
> It was as simple as, Amory Lovins came and toured the facility in LaGrange, the manufacturing facility. He just stood there and he looked up, he

> said "Uh-huh, you've got little pipes and big motors. What if you switch those to big pipes and little motors? Think how much energy you could save." That was basic engineering design. You don't need as much power to move stuff through a bigger pipe (M. A. Anderson Lanier, personal communication, November 15, 2013).

Anderson had a passion for reading which certainly contributed to his learning process after the epiphany. Anderson Lanier shared some stories about this as well:

> He read voraciously. All of my life I remember that he always had a stack of books like this. His reading just changed from novels, maybe, to reading what had been published on the environmental side. . . .
>
> His office was over there. The bookcases, I think there are cases and cases of his books in storage down in LaGrange right now. We gave half of them to LaGrange College [laughs]. He read everything he could get his hands on (M. A. Anderson Lanier, personal communication, November 15, 2013).

Besides being a good reader, he enjoyed talking with people:

> He talked to everybody he could find to talk to. I'm sure that's how he met Michael Crow. He would go from one speaking engagement to another. People would introduce him to people. He always assumed that he could learn something from someone else (M. A. Anderson Lanier, personal communication, November 15, 2013).

Some changes in Ray Anderson's personal life after the epiphany.

Anderson Lanier remembers when her father told the family of his intention to make Interface a sustainable company:

> The first time he told us, we lived in Atlanta and we had very small children, and he said, "You know what? We're going to figure out how to not waste anymore. We're going to figure out how to make our carpet and not strip the earth of its natural resources." I looked at him and I laughed. I said, "You don't even recycle the newspapers. You're going to have to learn a thing or two. You're going to have to be able to put this in practice at home. [laughs] If you're going to take on the world, you need to start at home." (M. A. Anderson Lanier, personal communication, November 15, 2013).

Anderson did make changes at home. At that time he was driving a Bentley because another person convinced him that the car gave him the image he needed (M. A. Anderson Lanier, personal communication, November 15, 2013). After the epiphany he was so uncomfortable using that car that he said "I'm going to put my money where my mouth is. I'm going to get rid of that Bentley. I'm going to drive the most environmentally responsible car that's available." (M. A. Anderson Lanier, personal communication, November 15, 2013). He owned the very first Toyota Prius [hybrid car] in the state of Georgia (M. A. Anderson Lanier, personal communication, November 15, 2013).

At a certain point Ray Anderson was giving many speeches around the world. When he returned to Atlanta he needed to get away and rest (M. A. Anderson Lanier, personal communication, November 15, 2013). With his second wife, they decided to build a mountain house in the North Carolina Mountains, a couple of hours north of Atlanta (M. A. Anderson Lanier, personal communication, November 15, 2013). In order to do it correctly they worked with an organization that helps contractors to build in the most environmentally friendly way (M. A. Anderson Lanier, personal communication, November 15, 2013). It was a small house that was built with wood from standing dead trees, was solar powered and completely off the grid, had a propane generator for backup, and was supplied with water from a well (M. A. Anderson Lanier, personal communication, November 15, 2013).

Factors that may have contributed to Ray Anderson's environmental awareness.

Not every person decides to change the direction of a company and personal life by just reading a book about the environmental impacts of industry. Perhaps a person needed to have something inside with which a book resonates in order for such a change to occur. Anderson Lanier had an opinion:

> He [Anderson] had grown up in a time where people really knew the value, what was important and what was valuable. I think part of him was maybe a little bit overcome by that. He was disenchanted with all the stuff. He was a man of faith. He was a deep Christian. I think he couldn't say it in the business world, but I really think it was a conviction of the Holy Spirit. He was so convicted that this was something that he had to do, that he didn't care if the world thought he was a crazy old man. . . .
>
> I'll say, too, that there were a lot of times when a lot of us thought he was working too hard on this mission. He was neglecting his own health to pursue spreading this message. He was an evangelist in a lot of ways. I said, "Daddy, practice this word. You can say no." He said, "I can't. I cannot say no to my calling. This is what I'm called to do." That's what drove him (M. A. Anderson Lanier, personal communication, November 15, 2013).

When asked if Anderson had been exposed to the natural environment in ways that might have contributed to his awareness Anderson Lanier said that her father grew up in the small town of West Point on the banks of the Chattahoochee river, and during his lifetime the river began to have series of floods (M. A. Anderson Lanier, personal communication, November 15, 2013). Anderson said "The engineers, all they would do was they just would build dams further and further up the river to control the water, without ever looking at the cause of the flooding." (M. A. Anderson Lanier, personal communication, November 15, 2013). "It was clearly caused by clear-cutting everything that controlled the water that ran off into the river, all the way upstream." (M. A. Anderson Lanier, personal communication, November 15, 2013). She remembers as a child that they had to go to West Point to help her grandparents move out of the house because there were two feet of water inside the house (M. A. Anderson Lanier, personal communication, November 15, 2013). There is an organization in Atlanta called the Chattahoochee River keepers, and Anderson Lanier thinks that it was able to give Anderson that perspective of what was happening to his river when he was a child (M. A. Anderson Lanier, personal communication, November 15, 2013).

Anderson Lanier also shared these two insights:

> When he was a young boy, there were channel catfish in that river that were this big. He said, “During the Depression, if you could catch one of those, your family could eat from that for a week.” They’re not there anymore. The pollution has driven all of them away.
>
> I’ll tell you another thing. Both of my parents died of pancreatic cancer, my mother and my father. The town where we lived, LaGrange, which is 15 miles from West Point, where my dad grew up, it’s south of Atlanta. It draws its drinking water from a river that has been through all of this industrial mess. There’s no telling what’s in that water that we don’t know about. The incidence of cancer south of Atlanta is, I think, significantly higher (M. A. Anderson Lanier, personal communication, November 15, 2013).

Transversal related themes.

Cycling and recycling.

Closing cycles is one of the central strategies of Interface to reduce their impacts on the environment. The company has achieved significant progress in recycling. About half of the yarn that goes into the tufting plant is 100 percent recycled (J. Bradford, personal communication, November 14, 2013). Half of the recycled yarn comes from post-consumer carpet, and the other half comes from post-industrial waste (J. Bradford, personal communication, November 14, 2013). For Bradford there is a timeline from oil coming from the lithosphere of the Earth to the time that plastic gets in the landfill, and it is getting shorter and shorter because we have become a disposable society (personal communication, November 14, 2013). The only way we can make the timeline longer again is to recycle; the recycle loop keeps the longevity running (J. Bradford, personal communication, November 14, 2013).

Stuart Jones, the Vice-President of Research and Development discusses recycling in the context of corporate responsibility:

> I do realize we have a huge responsibility. The volumes of materials that we use, multiple truckloads, for instance, of inorganic filler every day. If we were mining that material like we used to, there would be a hole halfway to China over here in Alabama that we'd be responsible for, because we'd be digging up and crushing three to five truckloads of limestone a day to feed our plant. We got away from those kinds of materials as much as possible. That's what intrigued me about putting recycled content back into our products. It makes our process more cyclical . . . (S. Jones, personal communication, November 14, 2013).

This quotation reveals that using virgin materials is considered an undesirable choice because of the need to mine these materials. It is assumed that mining is bad for the natural environmental. On the other hand, using recycled materials represents responsibility towards the environment by not being part of the problems associated with the mining that others do.

Recycling represents a technical cycle that Interface has been working on for years. The company is also working on closing the loop for biological cycles:

> What we're nurturing now is the biological cycle, rapidly renewable energy sources, rapidly renewable polymer and chemical sources like switchgrass and algae, and these other sources. We have little fingers in all of these activities in various fields where we're working with companies that are developing cutting-edge new technologies in raw-material sourcing, mostly in the bio field

> and bio sources. That's as interesting now as recycling was before (S. Jones, personal communication, November 14, 2013).

Besides treating materials in cycles within Interface, the company has established relationships with other companies that recycle materials for them. This has led to a cyclical relationship with other companies:

> Let's say, you're the chemical company and I'm Interface. Instead of an arm's length linear transaction, I give you cash and cash flows that way from my business and chemicals flow this way from your business. These are just two linear processes that happen to cross somewhere. We took the approach of more cyclical processes to more mimic nature . . . . for instance, our yarn vendors; we have a cyclical relationship with them. They ship us fiber. When our fiber is done, we harvest that fiber from used carpet. We bale it up and we ship it back to them. They make more fiber for us. We supply them. They supply us. We have a great relationship with our yarn suppliers that way (S. Jones, personal communication, November 14, 2013).

By mentioning that Interface attempts to mimic nature's cyclical processes, Jones makes a direct reference to biomimicry. The previous comment expresses a cyclical interaction with companies upstream. Interface also has established cyclical relationships with their customers, or downstream: "For backing we do it [recycling] in-house, and our customers have become our suppliers." (S. Jones, personal communication, November 14, 2013).

Renewability.

Bradford thinks that the chances that energy will become renewable over time are greater than the chances that raw materials will become renewable (J. Bradford, personal communication, November 14, 2013). He envisions an important role of recycling in switching to use renewable materials, to the point that if raw materials are not recycled there is no chance that renewables will take the place of virgin raw materials (J. Bradford, personal communication, November 14, 2013).

As a company Interface thinks that shifting to renewable materials will not happen such as, for example, using one day polyester and the next day poly-lactic acid (PLA) (J. Bradford, personal communication, November 14, 2013). Interface thinks that one day polyester is used, then it gets recycled, then materials blend four percent PLA, 96 percent recycled polyester, and then over a 20 year period the renewable plastic goes from four percent to 100 percent (J. Bradford, personal communication, November 14, 2013). The same would happen with nylon and vinyl (J. Bradford, personal communication, November 14, 2013).

For example, Solvay is a large company with operations in South America. It knows how to make vinyl using sugar cane (J. Bradford, personal communication, November 14, 2013). The company is having difficulties getting it into the market because it is too expensive be used instead of standard vinyl from petroleum. As an additive, however, it is probably not too expensive and, over time, it could make sense (J. Bradford, personal communication, November 14, 2013). This is how Interface thinks that the shift to renewables will occur.

Costs.

The dematerialization concept that was implemented early on to achieve good product performance by using less material produced cost savings despite the original objective to reduce environmental impacts (J. Bradford, personal communication, November 14, 2013). It should be noted that initial undertakings in implementing recycling systems were not cost effective. Such was the case when Interface began using recycled backing made by external suppliers:

> That was an expensive process. The product was very expensive . . . people would not pay extra for that . . . . We took the hit on it. We dedicated 10 cents of every square yard that we sold into what we called the re-entry fund. That was all to fund the take-back program. For two years, we dedicated 10 cents of every sale to go into this slush fund. That's how we paid for the shipping and processing to get all of this material back and put back into new product. . . . But as we just kept working at it . . . . We worked with other companies. They would start-up and go out of business when the economy would take a downturn (S. Jones, personal communication, November 14, 2013).

Interface finally brought the process in-house and established it like a business (S. Jones, personal communication, November 14, 2013). The take-back system was expected to create a significant cost, but it ended up being affordable:

> The first year, it was going to cost us a million dollars just in freight to bring all the material back. We actually got more material than our goal, for a third of what we thought it would cost us in freight. Once we started with this new business model, and we got into operation working with our dealers in various parts of the country that would help bring the material back, the economy scale just started to grow, and it became less and less expensive (S. Jones, personal communication, November 14, 2013).

As can be seen, collaboration with external entities such as suppliers, service providers, and customers became necessary to make the enterprise of recycling possible and affordable.

An early attempt of take back program was called the Evergreen Lease, in which carpets were offered as a product of service that was leased instead of sold (Interface Global, 1996). This system did not work. According to Anderson, the market was not ready for such a service (Engineering Enterprise, 2004). The system Interface has in place now is called the Re-Entry program, in which the sale of new carpet includes taking back used carpet to be recycled (C. Hensler, personal communication, April 10, 2014). Arrangements are made with installers to collect the used carpets which are then brought to Interface by a network of transport suppliers (C. Hensler, personal communication, April 10, 2014).

When Interface first brought the recycling of the backing inside the company, the recycling processes that they tried were also expensive. For example, the process of cryogenically grinding the backing into powder and then extruding that into a sheet was too expensive to be used (J. Bradford, personal communication, November 14, 2013).

As the recycled backing evolved into the Cool Blue line, the recycling process became significantly less expensive (J. Bradford, personal communication, November 14, 2013). Interface realized that by using recycled raw materials it was able to cut off the oil well and the aromatics plant (J. Bradford, personal communication, November 14, 2013). Consequently, about 70 percent of the life cycle cost was diminished (J. Bradford, personal communication, November 14, 2013). By refining the recycling process Interface managed to make recycled material cheaper than virgin material until recycling ended up paying for itself (S. Jones, personal communication, November 14, 2013).

In the Cool Blue line the cost driver of manufacturing was converted from oil to labor (J. Bradford, personal communication, November 14, 2013). The cost of virgin material is driven by the cost of oil, but the cost of recycling is driven by the cost of labor (J. Bradford, personal communication, November 14, 2013). Over the next thirty years, Interface expects to have a more stable foundation in the cost drivers of the business, because, in Bradford's opinion, the cost of labor is going to be more stable than the cost of oil (personal communication, November 14, 2013). In addition, the price of raw materials remains constant because the prices of oil can vary so much (S. Jones, personal communication, November 14, 2013).

Machine design.

While working on the Cool Blue line, Interface realized that the processes that had been put in place over the past twenty years were actually anchors to their improvements (J. Bradford, personal communication, November 14, 2013). The company felt that these processes had made it captive and that it could not change (J. Bradford, personal communication, November 14, 2013). Changing these processes required a new machine design, which intrigued Bradford. He began to explore new ways of taking raw materials from recycled streams instead of from virgin streams (personal communication, November 14, 2013).

Bradford shared the following story:

> When I went to school, every problem statement in school started with a set of givens. One of the assumptions that always came into play in a machine design was assume that raw materials are abundant and consistent. So, much, many of machinery designers coming out of school even today take that assumption for granted. They design these machines that can only run virgin materials. If they don't have virgin material inputs, they can’t make an acceptable output. . . . We have to wash that . . . educational foundation away and assume that raw materials aren’t going to be abundant and consistent going forward. They’re not. They’re going to be inconsistent and they’re going to be recycled, because we can’t continue to take oil from the Earth and put back waste in our landfills at the rate that we’re going (personal communication, November 14, 2013).

At the beginning Interface was trying to fit an irregular raw material into an extruder which requires a pure raw material. Then came the Cool Blue Line, which does not need a pure raw material (J. Bradford, personal communication, November 14, 2013).

Influencing factors for environmentally responsible design and development.

Influential literature and people.

Literature and people that influenced Ray Anderson.

After reading *The Ecology of Commerce,* Anderson's life changed forever. He began redirecting his company to become sustainable. He also began reading voraciously (Engineering Enterprise, 2004). Several books are worthy of note. They are *Ishmael, The Story of B*, *My Ishmael*, *Natural Capitalism*, *Silent Spring*, *Earth in the Balance, Beyond the Limits, Vital Signs*, *State of the World*, *Lean and Clean Management*, and *For the Common Good* (Anderson, 1998).

Besides reading, Anderson began searching for people who could bring expertise to Interface in order to make progress on its journey toward sustainability. Eventually, he assembled a group of thought leaders who helped with this task. He called the group his Eco Dream Team. The Eco Dream Team included Janine Benyus, Paul Hawken, Amory Lovins, Daniel Quinn, John Picard, Dr. Karl Henrik Robèrt, William Browning, Jonathon Porritt, Hunter Lovins, and Walter Stahel (Interface, 2014). Other people he met that helped in the sustainability journey were William McDonough (Anderson, 1998); Donella Meadows, and Lester Brown (Engineering Enterprise, 2004).

Ray Anderson's vision and influence.

For Interface, Anderson has been the most influential person in the change of course towards sustainability. As one of his team members acknowledged, having top management with a clear vision of what the company wants to become, believing in this vision, believing in its people, and have courage to move forward are key elements to making progress toward sustainability (J. Bradford, personal communication, November 14, 2013). Once most of people within the company truly engage with the vision, it becomes unstoppable. This engagement is what made the progress possible (J. Bradford, personal communication, November 14, 2013).

Anderson's inputs were inspirational and visionary. He was talking about the vision and what he wanted Interface to become. It was then that each individual discovered how to fit (J. Bradford, personal communication, November 14, 2013). Bradford remembers that Anderson used to say that the vision has to be so clear that it takes your breath away (personal communication, November 14, 2013). For example, there were obstacles all along the way at the time when Interface was working on the Cool Blue project (J. Bradford, personal communication, November 14, 2013). But having a clear vision kept the company charging through difficult times (J. Bradford, personal communication, November 14, 2013). This vision also fueled the courage of Interface's personnel. This is how they were able to move forward with the change (J. Bradford, personal communication, November 14, 2013).

Anderson also was committed to exercising his influence. To make progress toward sustainability several external companies needed to be engaged. These companies were outside of Interface's direct control but not without its realm of influence (J. Bradford, personal communication, November 14, 2013). Exerting influence takes time. Unfortunately, leaders that wish to exert influence must invest time, with is something that few leaders wish to do (J. Bradford, personal communication, November 14, 2013). Anderson was a leader who was willing to invest time.

Influencing factors for the creative process.

Biomimicry.

During the interviews, the topic of biomimicry arose many times. Jones explicitly mentioned biomimicry several times when he was explaining the creative processes Interface has followed in research and development when working on its projects.

TacTiles was an example or this:

> . . . to do something like that, that everybody else ran away from because they said it couldn't be done and it was too hard. Cool Blue is a good example of that, and TacTiles are as well, because we took a completely different approach. It started with biomimicry. . . . How does nature connect things? The ideation process was really kind of bizarre in our group (S. Jones, personal communication, November 14, 2013).

David Oakey is an independent contractor who runs a design office that designs carpets for Interface (Engineering Enterprise, 2004). Jones remembers that it was Oakey who introduced them to Janine Benyus, author of *Biomimicry: Innovation Inspired by Nature*:

> She [Benyus] was introduced to us by David Oakey, who's a designer for us. He's a contract designer. He does all the carpet pattern designs. He was looking to introduce biomimicry into his design team for pattern design and style design. That's where Entropy came from . . . [and] so many of these products you see . . . . We went over there, and we met with Janine. She and Dayna introduced us to

> the concept of Biomimicry, and then we all went out in the woods and walked around, just looking at things, how does nature do stuff (S. Jones, personal communication, November 14, 2013).

Jones also describes how Oakey's team used biomimicry for the Entropy project:

> David Oakey and his team did their woods walk and discussed, how would nature make a floor? That's where the design concept for Entropy started. It's all random. It's always random. No two square feet look identical. Then they said about trying to figure out how to design a product when the whole world in carpet design has built around repeating patterns. How do you do that? Nobody knew how to do that. . . . It took a whole team of people to figure out how to do that. It was an industry-changing product by far. It changed the whole industry as far as modular carpet (S. Jones, personal communication, November 14, 2013).

Biomimicry has been useful for Interface, not only for product design, but for process design as well:

> We have found biomimicry to be very helpful to us in redesigning our processes and converting this take, make and waste manufacturing model that's been in place since the first Industrial Revolution, and turning that into a cyclical process that more mimics nature, to move into the second Industrial Revolution (S. Jones, personal communication, November 14, 2013).

After being introduced to Benyus, people at Interface began meeting periodically with her and other people from the Biomimicry Guild to work on projects for a few years (S. Jones, personal communication, November 14, 2013). Besides reading Benyus' book about biomimicry, the same people also read Vogel's *Cats' Paws and Catapults* (S. Jones, personal communication, November 14, 2013). Interface also engaged an intern with the task of preparing a course about biomimicry and biomimetic design for the company (S. Jones, personal communication, November 14, 2013).

Interface's approach to innovation.

During Interface's journey to sustainability, the company developed several innovations, two of which, TacTiles and Cool Blue, are perhaps the most notorious.

According to Bradford, there are two approaches to innovation. One approach, the mindset of scarcity, is about believing in looking for the next great “Aha!” which is scarce, and only a few people can find it if they are lucky (personal communication, November 14, 2013). The other is the approach of abundance (J. Bradford, personal communication, November 14, 2013). Innovations can be produced in abundance by combining different species with attributes (J. Bradford, personal communication, November 14, 2013). The results are innovations, which can be combined once again to produce a tree of explosive innovations (J. Bradford, personal communication, November 14, 2013).

At times, existing innovations can be married with things that do not make sense at first sight, but do so afterwards (J. Bradford, personal communication, November 14, 2013). This is the innovative approach of abundance, and is the thought process that exists at in Interface (J. Bradford, personal communication, November 14, 2013). Bradford is of the opinion that innovations can come in abundance when people interact and share. He explains using the following example:

> The Renaissance happened in the coffee houses. Not one guy saying, “Aha! There’s gravity” or “Aha! Here’s a new way to paint” It was not that. It started in a conversation, and someone had the courage to try something new (J. Bradford, personal communication, November 14, 2013).

Gaining and sharing knowledge together was an integral part of the innovation process in his team. First, Anderson offered inspiration and vision; this was followed by team members inspiring each other by asking non-obvious questions and imagining (J. Bradford, personal communication, November 14, 2013). They explored, became curious, became children again, and enjoyed the journey (J. Bradford, personal communication, November 14, 2013). The team brainstormed and filtered their ideas; then asked themselves where they fit into this journey and what their strengths were (J. Bradford, personal communication, November 14, 2013). They envisioned the future (J. Bradford, personal communication, November 14, 2013). Everyone started to grow personally and gained the courage to share with the others what each could offer (J. Bradford, personal communication, November 14, 2013). Finally, change happened (J. Bradford, personal communication, November 14, 2013).

With courage the team could commit (J. Bradford, personal communication, November 14, 2013). The team needed to try new things to know what was wrong before knowing what was right (J. Bradford, personal communication, November 14, 201). With this, they became confident (J. Bradford, personal communication, November 14, 2013). Creating this innovation culture is what Bradford thinks made things happen at Interface (J. Bradford, personal communication, November 14, 2013). No one person can drive innovation; everyone on the team has to be an innovator and feel that he or she is a part of the movement (J. Bradford, personal communication, November 14, 2013).

Courage seems to play an important role in innovation. People need courage to offer their ideas and to commit to them. They also need courage to persist when things go wrong (J. Bradford, personal communication, November 14, 2013). The good thing is that “courage is contagious” as Bradford said, much like the time when Anderson believed in them more than they believed in themselves (personal communication, November 14, 2013).

Besides innovation and other activities that have been introduced in projects, it is important to recognize that normal project management is an important part of any development process (J. Bradford, personal communication, November 14, 2013).

The importance of conversation.

Bradford thinks that gaining and sharing knowledge with his team was essential to move toward the company's environmental achievements. An important part of gaining and sharing knowledge is conversations:

> It's a constant conversation and a constant ability to open up problems, talk about problems so that you can find . . . elegant solutions, for them. It's the ability to keep the conversation going for a long time. We started the conversation in 1998. We didn't build the machine [Cool Blue] until 2004. Most companies give up before that (J. Bradford, personal communication, November 14, 2013).

Reading was also an important part of the process:

> All of us were reading different books at different times . . . We were reading them together. We all read *The Ecology of Commerce*; we all read *Biomimicry*; we all read different influencers in our thought process. We were in one accord, but we were having conversations from many different perspectives, and everyone had a voice (J. Bradford, personal communication, November 14, 2013).

Creative process.

The creative process also occurred in research and development. Working on products and processes usually involves searching for relevant literature, including patents (S. Jones, personal communication, November 14, 2013). This is done because other people's ideas can be a spring-board for new concepts (S. Jones, personal communication, November 14, 2013). That said, there is care taken not to focus on this too much because it can be limiting at the same time (S. Jones, personal communication, November 14, 2013). The approach is to "think outside of the box"; for example, this can occur by saying "if we were going to reinvent this completely, how we would do it?" Throwing away traditional concepts can usually lead to some interesting conversations (S. Jones, personal communication, November 14, 2013). Sometimes a tiny part of the product or the process has to be changed in an elegant way in order to make it brilliant (S. Jones, personal communication, November 14, 2013). For example, Interface found a mechanical solution to separate different materials of carpet tiles for recycling (S. Jones, personal communication, November 14, 2013). They accomplished this by modifying a leather splitting machine to slice used carpets in layers (S. Jones, personal communication, November 14, 2013). This solution emerged through a slightly different way of thinking (S. Jones, personal communication, November 14, 2013).

Besides literature and patents directly related to the topics of specific projects, the team also read books that provided more general knowledge, understanding and inspiration. Some of these sources are *Biomimicry: Innovation Inspired by Nature*; *Cats' Paws and Catapults: Mechanical Worlds of Nature and People*; *Wabi-Sabi for Artists, Designers, Poets & Philosophers*; *First, Break all the Rules*; and, *Now, Discover Your Strengths* (Bradford, 2006).

Influencing factors external to the company.

Partners and supply chain.

Partners are necessary to become a sustainable company. The Cool Blue line recycles around forty million pounds of reclaimed carpet tiles which need to be taken back from the user to the recycling facility (J. Bradford, personal communication, November 14, 2013). Usually this is done, not by large companies, but small entrepreneurs who transport used carpets back to Interface (J. Bradford, personal communication, November 14, 2013). Interface had to build a network of those companies and all of them became their partners (J. Bradford, personal communication, November 14, 2013). This is part of the enterprise of recycling. In order to expand the Cool Blue line worldwide, Interface is building a supply chain for it (J. Bradford, personal communication, November 14, 2013).

Being able to engage other companies outside Interface is critical to succeed in its environmental endeavors. Bradford illustrates this with the following example. At Interface they know how to be 91 percent of the way to sustainability but the company has reached only about 63 percent (J. Bradford, personal communication, November 14, 2013). The gap between 63 and 91 percent is not knowledge; it is supply chain development; it is that customers need to me sensitized and understand why sustainability is a good idea; it is capital; and it is that the marketplace needs to be ready (J. Bradford, personal communication, November 14, 2013).

The architecture and design community as customers.

In 1998 and 1999 few of Interface's customers valued that its carpets were made with recycled content (S. Jones, personal communication, November 14, 2013). However, when the architecture and design community began specifying more environmentally sound products for their buildings, Interface, which already had the products, benefitted from this change. Jones explains:

> It was only a few years before the entire industry was chasing Interface, because the design and architecture community were starting to take up on sustainable design. Once that really took hold in the design and architecture community, we

> were by far the leader. We were immediately recognized, and everybody else had started playing catch up and started chasing the sustainability and all of that, most of them just in their marketing, not in real practice (S. Jones, personal communication, November 14, 2013).

Meezan, the Vice President of Sustainability, also acknowledges that the architecture and design community has played a strong role in Interface's success in the marketplace:

> . . . over the last 10 years, our customers became tremendously focused on this, and it became a huge market advantage: green building standards, architects and designers asking for more sustainable products; we were right in the sweet spot of what a big part of our market was asking for (E. Meezan, personal communication, November 14, 2013).

By specifying products and materials used in buildings, interiors, and finishes, architects and designers have an enormous influence in what is finally purchased. Two interviewees observed that the architecture and design community have a particular interest in the environmental performance of the products that they specify and therefore in Interface's products:

> We're having a conversation right now with the architect and design community who's been very involved in asking for health information, on certain health hazards of things that go into our products. . . . Two years ago, it was . . . a red-list approach where they would say, "Just tell us if any of your products use any of these chemicals. If they do, they're on a list and we're not going to spec them" . . . now they're asking us, "Disclose every material or chemical that's used in your product. If it at all has a hazard associated with any part of its lifecycle, whether or not we would be exposed to it in your product, we want to know about it" That's incredibly forward-thinking. That's way beyond anything the federal government is asking. It's way beyond anything we're seeing in the consumer sphere. It's driven by this group of highly sensitive architects and designers (E. Meezan, personal communication, November 14, 2013).

In Meezan's opinion, the architecture and design communities are more forward-thinking than other disciplines. This might explain in part their interest in the environmental impacts of products:

> . . . as a group, for whatever reason, architects and designers are further ahead in their thinking than other disciplines. I don't really know why that is. Maybe, it's fundamentally because the discipline that they have in creating environments and building a building requires them to think a little bit differently about creating that environment. I don't know. I'm surprised at how forward thinking they are (E. Meezan, personal communication, November 14, 2013).

Negative influencing factors.

External negative influencing factors.

In the beginning when Interface tried to make progress toward sustainability, some people expressed disbelief in the success of what they were trying to do. Suppliers expressed resistance and disbelief, as this example shows:

> I remember when Ray Anderson, back in 1995 or 96 called in Exxon. They were a big supplier of ours to the tune of about 22 million pounds a year, just in this facility. They supplied us worldwide. He told them that we're getting out of oil, and we will not have a relationship with them [Exxon] at some point in the future unless they get on board with us and help us get to this sustainability goal. They laughed him out of the room. They literally laughed at him. "You'll never do it" . . . they said he was crazy. . . . It took a few years, but they eventually saw the brilliance in what he was doing. It led the entire industry (S. Jones, personal communication, November 14, 2013).

In the mid-nineties some shareholders thought that their money would be at risk if they continued investing in a company that decided to become sustainable:

> A couple of years into sustainability they were in New York, Ray and our CEO, and they were giving a presentation to shareholders and Ray said, "I actually don't want to give the shareholder presentation. I want to talk to them about sustainability. I've got a whole new idea about what our vision is, what we're focused on." Our CEO said, 'I don't really know if that's a great idea.' Ray did it anyway. The next day, one of our large shareholders sold all of our shares . . . it

> freaked him out so much. He thought that we were just off the wall. . . . I think it was something like 11 years after that happened, Dan [CEO] bumped into that same guy who dumped our stock, and the guy said to him, essentially, something like, “I made a mistake” It was like a moment for them [Dan and Ray], I think, when they realized that at some time in that decade opinions had changed (E. Meezan, personal communication, November 14, 2013).

Challenging standard practice was seen with incredulity by competing companies, as this reflection expresses:

> . . . while others are throwing up their hands saying, “You can’t do that. You can’t make the carpet stop burning without putting flame retardants in it. You can’t pass the fire codes without putting flame retardants in it,” back when everybody was using halogenated compounds. Well, we found a way to do that. We haven’t used flame retardants in 15 years (S. Jones, personal communication, November 14, 2013).

Also, competing companies had difficulties understanding the need of moving away from the convenience of readily available petroleum-based virgin raw materials:

> PLA, when it came out, bio-sourced plastics, that was silly to everybody, “Why would you do that? The economy of scale for petroleum-based chemicals is so big, and they’re so cheap, and they’re so good, and they’re perfect every time. Why would you want to get away from that?” (S. Jones, personal communication, November 14, 2013).

Having few partners outside the company was an obstacle as well. Partners are necessary. Not having partners with the company makes it difficult, if not impossible, to become more sustainable. The customer in the marketplace has to be onboard as well; engaging them by exerting influence is necessary (J. Bradford, personal communication, November 14, 2013). This takes commitment and time (J. Bradford, personal communication, November 14, 2013).

Despite negative influencing factors, Interface has been able to phase out virgin raw materials for their products gradually. Increasingly, it has replaced them with recycled materials in a cost effective manner that has allowed shareholders to earn good profits. Competitors have seen Interface's success in challenging standard practices, and many of them have made progress toward sustainability as well.

Internal negative influencing factors.

Despite the company's commitment and vision in the early years after Anderson's epiphany, the absence of a road map towards sustainability was a great obstacle (E. Meezan, J. Bradford, personal communications, November 14, 2013). Interface had to create its own road map to progress toward sustainability. In Bradford's words: "We were walking through the jungle with a machete, cutting our own path. That's how we did." (J. Bradford, personal communication, November 14, 2013). The lack of a clear road map and knowing what to do was one of the difficulties faced by Interface.

Another difficulty was people inside the company. Businesses are composed of people, and it is with people that the biggest changes need to occur (E. Meezan, personal communication, November 14, 2013). One person cannot make another person have an epiphany (J. Bradford, personal communication, November 14, 2013).. Everyone grows at a different rate; and everyone engages at different levels (J. Bradford, personal communication, November 14, 2013). For Bradford changing people has probably been the most difficult part of the process.

In the end, there are times when things just go wrong. This can happen to every company that makes products (J. Bradford, personal communication, November 14, 2013). In its journey, Interface met obstacles all along the way: people inside the company who did not believe that they could get there; not having a measurement system; and once the company had a measurement system having to deal with people outside the company who did not acknowledge it or questioned it (J. Bradford, personal communication, November 14, 2013).

By means of interviewing people and reviewing internal documentation, archival material, and published literature a deeper understanding was gained about Interface's journey toward achieving greater sustainability. Inquiring about two projects, TacTiles and Cool Blue, allowed several themes to emerge that informed the design and development processes, the implementation of environmentally responsible approaches, and the learning process about how the organization as a whole contributes to the end result.

Conclusion

The case studies of TacTiles and Cool Blue revealed specific details about these projects, as well as general ways in which Interface undertakes design and development processes. The use of LCA is consistent in these two projects and also in every product that Interface makes. LCA is used in all existing products and also to develop new projects.

The literature consulted and the interviews revealed the involvement of The Natural Step early on Interface's changing course toward sustainability. The case studies revealed details about the implementation of The Natural Step's theory in the projects analyzed as well as in Interface's approach to projects in general. Interface's design processes and operations utilize elements from the four system conditions of The Natural Step, following several practices suggested within them. Some of The Natural Step's suggested practices are not used by Interface, but these are practices that do not apply to Interface's activities.

Comparisons between ecodesign theories and findings from the case studies within Interface reveal that all ecodesign strategies are used by Interface. Although ecodesign was not mentioned by any of the interviewees and literature consulted about Interface, the case studies revealed a consistent use of all ecodesign strategies. Most of the improvement options within ecodesign strategies are used by Interface as well, either in the projects studied or in other activities that the company undertakes. The use of ecodesign strategies by Interface reveals a focus on every stage of its products' life cycle. Some of the improvement options within ecodesign strategies are not used by Interface, but these are not applicable to Interface's products or industry sector.

Summary

Chapter 4 presented the research findings for the case studies about Interface Inc., and the analysis of environmentally responsible and sustainability approaches relevant to product design and development. Chapter 5 draws conclusions about these findings by relating them to each other and to the literature review discussed on Chapter 2.

CONCLUSIONS AND IMPLICATIONS

Introduction

Chapter 4 presented the findings for the research questions of this research. Chapter 5 draws conclusions by discussing the research findings across research questions and also in the context of the literature reviewed.

Conclusions about the research questions

Environmentally responsible design theory.

The analysis of ecodesign theories revealed several strategies, and improvement options within them, to design products with sound environmental performance. These strategies address all of a product's life cycle stages. This is an important characteristic of all the versions of ecodesign strategy wheels. The ecodesign strategies are applicable to a wide range of products and services, and can be used by many actors, including designers, engineers, and business managers.

The analysis of The Natural Step theory revealed several specific practices that are suggested for society to become sustainable. These practices are organized according to four system conditions that should be met in order for the human society to coexist with the natural ecosystems long term. The recommendations of The Natural Step can be applied at different scales, ranging from the product component scale to the business and government scale. These recommendations can be used by many actors including businesses, governments, and NGOs.

Ecodesign theory and The Natural Step theory are consistent with each other. Although they are intended for different audiences and with different levels of detail, the recommendations provided to improve the environmental performance of products and industrial activities are never contradictory and always consistent.

Environmentally responsible design in Interface.

Comparing what ecodesign theory prescribes and what Interface actually does shows that all eight ecodesign strategies are used. For some strategies more improvement options are used than for others, but it is the case that, since the ecodesign strategy wheel is a tool intended for a broader use than the products that Interface makes, several improvement options do not apply.

For Innovation, the improvement options used are: Rethink how to Provide the Benefit, by eliminating the use of glue when TacTiles was designed; Design to Mimic Biological Systems, by the use of biomimicry for TacTiles, the Cool Blue line and other projects; and, Create Opportunity for Local Supply Chain, by assembling a supply chain of entrepreneurs that work to bring used carpet tiles back for recycling. Within the strategy Reduced Material Impacts, the improvement options that were used are: Avoid Materials that Deplete Natural Resources; Use Recycled or Reclaimed Materials; and, Use Waste Byproducts, which are accomplished by the recycling systems Interface has implemented in its plants. The option Minimize Quantity of Materials has been accomplished by the dematerialization project. The option Use Renewable Resources, i.e. to switch to renewable materials, is in progress at the moment. Within strategy 3, Manufacturing Innovation: Minimize Manufacturing Waste, Minimize Energy use in

Production, and Use Carbon-neutral or Renewable Energy are used by Interface in the two cases studied and in general for all of Interface's processes. Also, reducing waste and energy use were adopted early as a result of the use of QUEST and Ecometrics. Within Reduced Distribution Impacts, Interface has been reducing product weight and volume through the dematerialization projects. Within System longevity, Design for Durability and Design for Maintenance and Easy Repair are accomplished by quality assurance and the modularity of the carpet tile system that allows easy and selective replacements. Design for Reuse and Exchange of Products is accomplished by the recycling system in place. For strategy Transitional Systems, Design Upgradable Products, and Design for Reuse of Components, these are met by Interface's modular system, TacTiles, and the recycling system. Finally, the strategies Optimized End of Life, Design for Disassembly, Design Recycling Business Model, and Integrate Methods for Used Product Collection are all achieved by Interface's recycling systems.

The Natural Step had a direct influence on Interface from the time that Ray Anderson engaged Karl-Henrik Robèrt as an advisor for the company (Anderson, 1998). This learning process became apparent by way of the lexicon people at Interface used. Concepts like dematerialization and disconnecting from the lithosphere used by some of the interviewees are not often used other than in The Natural Step literature.

Furthermore, System condition 1 "In the sustainable society, nature is not subject to systematically increasing concentrations of substances extracted from the Earth's crust", and system condition 2 "In the sustainable society, nature is not subject to systematically increasing concentrations of substances produced by society" (Robèrt, 2002, p. 65), are directly applicable to the petroleum-based materials that Interface was using in its carpets. Over time the company has definitely moved forward to comply with these system conditions, and it has done so by implementing the recommendations of The Natural Step.

The specific recommendations of The Natural Step that relate to Interface's developments are: handle all materials taken from the Earth's crust in such a way that concentrations of metals, minerals, and fossil fuel fumes do not build up in the biosphere; do not mine or extract materials for short-term dispersal in society; switch to renewable fuels and materials; establish sophisticated recycling systems; use substances produced by society efficiently; and recycle substances when used (Robèrt, 2002).

Biomimicry is also a deep rooted approach to environmentally responsible design used at Interface. It has been part of several projects including TacTiles and Cool Blue. The concept of biomimicry was included as an improvement option within strategy 1 Innovation of the Ecodesign Strategy Wheel (White, et al., 2013), and is not included in The Natural Step.

Use of life cycle assessment in Interface.

LCA began as an addition to other metrics that Interface was already using. Ecometrics, which preceded LCA is still used and is an important data source for LCA. What LCA gave the company was a wider scope to look at the environmental impacts in order to include life cycle stages that occurred outside of its manufacturing facilities. Today LCA is used on every product of the company. It is also are implementing a supply chain model to expand its use up and downstream. Furthermore, people working on research and development made a promise that they will not put a new product in the marketplace if it does not improve the LCA results.

Conclusions about the research problem

Several factors helped Interface to move forward in their progress toward sustainability.

- Commitment to environmental responsibility from the top executive level of the company was a key element that made possible the change of Interface toward becoming an environmentally responsible company. This finding is consistent with previous research about sustainable product design by product manufacturing companies (Yang, 2005).

- A vision and a mission for the company to become sustainable was another strong influencing factor that helped to align employees toward the sustainability goals of the company. This finding is consistent with what was found by Collins and Porras regarding the importance of a vision for a company's success (1996).

- Incorporating outside knowledge from literature and networking was also an important element as was acknowledged by all the interviewees and also explained by Mr. Ray Anderson in *Mid-course Correction* (1998).

- Environmentally responsible product and process design is what made possible the creation of products and machinery to manufacture them in more environmentally sound way. In the case of Interface process design was particularly useful because the company makes the products in their facilities.

This is not applicable for companies that design products that are manufactured by external suppliers.

- Measurement systems to monitor progress toward the sustainability goals and used for every Interface product was also an important factor of success in the implementation of environmentally responsible design. The integration of environmental assessments in environmentally responsible design processes was recognized as being powerful to achieve a better environmental performance of products (Lewis & Gertsakis, 2001).

Implications for theory

Implications for education.

From his experience while studying engineering, John Bradford brought a clear example of how education can help students to be better prepared for the challenges that will increasingly be part of everyday work in the future:

> One of the assumptions that always came into play in a machine design was, assume that raw materials are abundant and consistent. So much, many of machinery designers coming out of school even today take that assumption for granted. They design these machines that can only run virgin materials. If they don't have virgin material inputs, they can't make an acceptable output. . . . We have to wash that . . . educational foundation away and assume that raw materials aren't going to be abundant and consistent going forward (J. Bradford, personal communication, November 14, 2013).

This educational foundation is also true for design and architecture. Learning to integrate environmental considerations in their professional endeavors would be important to every professional, but even more so in those design professions that have such strong effect in using materials and chemicals in large scale such as engineering, architecture, urban planning, construction, industrial design, agriculture, forestry and bio technology, for example. It is also important for education in every profession where students later occupy high level positions in governments, industry and international politics.

Design education traditionally informs students about form, aesthetic aspects of the product, its usability, ergonomics, materials, and manufacturing processes, among other topics that are relevant for the creation of products. While environmental considerations for design are increasingly being taught as well, it is important that this topic is given a high level of relevance in design education.

Making appropriate design decisions requires having the appropriate information on which to base these decisions. On the same token, to make appropriate design decisions in making environmentally sound products requires to incorporate environmental information based on evidence during the design and development processes. Therefore, design education should encourage and help students to become familiar with scientific knowledge, so they can be conversant with relevant literature and learn how to incorporate this knowledge in design processes.

Implications for policy and practice

Private sector managers.

As has been discussed, top management commitment to conduct business with environmental responsibility is a necessary condition, although not sufficient, to succeed.

To the extent that top management positions become convinced to work in achieving this goal, progress can be made. Extensive research and work should be undertaken to find the best ways to do achieve such goals within the characteristics of the company and industry sector.

Public sector policy analysts and managers.

Connie Hensler shared an opinion that is fundamental to the success of environmental initiatives when talking about how energy use is measured at Interface: “Also, we did these in per square yard production because we . . . wanted to grow. We wanted to make more square yards. If we were just measuring direct energy use, it would be going up, right?” (C. Hensler, personal communication, November 15, 2013). Hensler suggests that even if Interface becomes highly efficient in using energy for its production, as the business grows production will increase and therefore the total amount of energy used will increase, regardless of efficiencies achieved. Every business needs to grow. This is required by how the economic system works. If a company does not grow in a marketplace where every competing company grows, then it may eventually be out of business. Also, the increase in the number of companies over time will only continue to increase the demand on resources. Despite the extensive achievements that can be made on a per company basis, the economic system in which companies operate needs to change in order to allow for the lowering of aggregate resource demands. The concept of Ecological Economics provides answers to this challenge (Daly & Farley, 2011), as does the concept of Performance Economy (Stahel, 2010).

Further research

Further research must be undertaken to understand why some persons, like Ray Anderson, become so highly motivated to go against common practice in pursuit of a cause for the common good like environmental responsibility or sustainability. This type of research would be useful to understand how future generations can perhaps be educated so that such kinds of leaders are more abundant.

There is a need of case studies about the successful implementation of environmentally responsible design in companies where the initiative began not from the top executive level, but from other levels, in order to understand how this happened.

As for design with regards to environmental responsibility and sustainability, further research could contribute to the desicion making processes involved in deciding which strategies and improvement options should be prioritized depending on the nature of the product or service within its specific industry sector.

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APPENDIX

A INSTITUTION REVIEW BOARD FORMS

INFORMATION LETTER - INTERVIEWS

Integrating environmentally responsible design approaches and life cycle assessment in product design and development for sustainability

November 14th, 2013

Mary Anne Anderson Lanier
Trustee
The Ray C. Anderson Foundation

Dear Ms. Anderson Lanier:

I am a PhD candidate working under the supervision of Professor Philip White in The Design School at Arizona State University. I am conducting a research study to understand how environmental assessment methods are integrated with environmentally responsible approaches to product design, by business firms with experience and commitment to become more environmentally sustainable.

Interface is well known for its progress in this direction, as well as Mr. Ray Anderson's epiphany and determination to make his company more sustainable. It seems not possible to understand fully Interface's journey to sustainability, without understanding the kind of awareness that Mr. Anderson developed as well as factors in his life that may have made this possible. Your insights about these matters constitute invaluable assets for this research; therefore I am inviting your participation.

Your participation involves being interviewed about your father. The interview would last around an hour and will be based on open questions. Your participation in this study is voluntary, you can choose not to participate, skip questions if you wish, or withdraw from the study at any time with no penalty. There are no foreseeable risks or discomforts to you from participating in the study. Your responses will be kept confidential. To assure this a pseudonym will be used instead of your real name throughout the study, unless you indicate otherwise. The results will be used in my dissertation, presentations or publications, but your real name or any identifiers will not be used, unless you give permission. If you would like to be quoted and identified, please sign below.

If you agree, I would like to audio-record the interview so it can be transcribed into text for analysis. This is important for the accuracy of the analysis and study results. The recording will be deleted after transcription and no identifiers will be available to connect it with your person. The interview will not be recorded without your permission, and you can also change your mind after an interview starts.

If you have any questions concerning the research study, please contact Oscar Huerta at (480) 567-8578, ohuertag@asu.edu; or Prof. Philip White, (602) 349-6866, p.white@asu.edu. If you have any questions about your rights as a participant in this research, or if you feel you have been placed at risk, you can contact the Chair of Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788.

With best regards,

Oscar Huerta. T: 480 567 8578, email: ohuertag@asu.edu

By signing below you are agreeing to be quoted by name in any publications:

Name: Mary Anne Lanier

Signature: Mary Anne Lanier

Date: 11/15/2013

INFORMATION LETTER - INTERVIEWS

Integrating environmentally responsible design approaches and life cycle assessment in product design and development for sustainability

November 13th, 2013

Connie Hensler
Director of Corporate LCA Programs
Interface Inc.

Dear Ms. Hensler:

I am a PhD candidate working under the supervision of Professor Philip White in The Design School at Arizona State University. I am conducting a research study to understand how Life Cycle Assessment (LCA) is integrated with environmentally responsible approaches to product design and development by business firms.

I am inviting your participation, which involves being interviewed about a project you have worked on in which LCA has been integrated with design and development processes to make products more environmentally sustainable. The interview would last around an hour and will be based on open questions. The data gathered by this means will be analyzed using qualitative techniques.

Your participation in this study is voluntary. You can choose not to participate, skip questions if you wish, or withdraw from the study at any time with no penalty. Although there are no direct benefits to you, a possible benefit of your participation is that the study makes a contribution to the body of knowledge on product design for environmental sustainability. There are no foreseeable risks or discomforts to you from participating in the study. Your responses will be kept confidential. To assure this a pseudonym will be used instead of your real name in the study results and intermediate stages, unless you indicate otherwise. The results of the study will be used in my dissertation, presentations or publications, but your real name or any identifiers will not be used, unless you give permission. If you would like to be quoted and identified, please sign below.

If you agree, I would like to audio-record the interview so it can be transcribed into text for analysis. This is important for the accuracy of the analysis and study results. The recording will be deleted after transcription and no identifiers will be available to connect it with your person. The interview will not be recorded without your permission, and you can also change your mind after an interview starts.

If you have any questions concerning the research study, please contact Oscar Huerta at (480) 567-8578, ohuertag@asu.edu; or Prof. Philip White, (602) 349-6866, p.white@asu.edu. If you have any questions about your rights as a participant in this research, or if you feel you have been placed at risk, you can contact the Chair of Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788.

With best regards,

Oscar Huerta. T: 480 567 8578, email: ohuertag@asu.edu

By signing below you are agreeing to be quoted by name in any publications:

Name: Connie Hensler

Signature:

Date: 11-15-13

INFORMATION LETTER - INTERVIEWS

Integrating environmentally responsible design approaches and life cycle assessment in product design and development for sustainability

November 13th, 2013

Erin Meezan
Vice President of Sustainability
Interface Inc.

Dear Ms. Meezan:

I am a PhD candidate working under the supervision of Professor Philip White in The Design School at Arizona State University. I am conducting a research study to understand how Life Cycle Assessment (LCA) is integrated with environmentally responsible approaches to product design and development by business firms.

I am inviting your participation, which involves being interviewed about a project you have worked on in which LCA has been integrated with design and development processes to make products more environmentally sustainable. The interview would last around an hour and will be based on open questions. The data gathered by this means will be analyzed using qualitative techniques.

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With best regards,

Oscar Huerta. T: 480 567 8578, email: ohuertag@asu.edu
By signing below you are agreeing to be quoted by name in any publications:

Name: Erin Meezan

Signature:

Date: 11/14/2013

INFORMATION LETTER - INTERVIEWS

Integrating environmentally responsible design approaches and life cycle assessment in product design and development for sustainability

November 13th, 2013

John Bradford
Chief Innovations Officer
Interface Inc.

Dear Mr. Bradford:

I am a PhD candidate working under the supervision of Professor Philip White in The Design School at Arizona State University. I am conducting a research study to understand how Life Cycle Assessment (LCA) is integrated with environmentally responsible approaches to product design and development by business firms.

I am inviting your participation, which involves being interviewed about a project you have worked on in which LCA has been integrated with design and development processes to make products more environmentally sustainable. The interview would last around an hour and will be based on open questions. The data gathered by this means will be analyzed using qualitative techniques.

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With best regards,

Oscar Huerta. T: 480 567 8578, email: ohuertag@asu.edu

By signing below you are agreeing to be quoted by name in any publications:

Name: JOHN P. BRADFORD

Signature:

Date: 11/14/13

INFORMATION LETTER - INTERVIEWS

Integrating environmentally responsible design approaches and life cycle assessment in product design and development for sustainability

November 13th, 2013

Stuart Jones
Vice President of Research & Development
Interface Inc.

Dear Mr. Jones:

I am a PhD candidate working under the supervision of Professor Philip White in The Design School at Arizona State University. I am conducting a research study to understand how Life Cycle Assessment (LCA) is integrated with environmentally responsible approaches to product design and development by business firms.

I am inviting your participation, which involves being interviewed about a project you have worked on in which LCA has been integrated with design and development processes to make products more environmentally sustainable. The interview would last around an hour and will be based on open questions. The data gathered by this means will be analyzed using qualitative techniques.

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With best regards,

Oscar Huerta. T: 480 567 8578, email: ohuertag@asu.edu
By signing below you are agreeing to be quoted by name in any publications:

Name: Stuart A. Jones

Signature:

Date: 11-14-13

ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Philip White AED
for From:	Mark Roosa, Chair SM Soc Beh IRB
Date:	03/11/2013
Committee Action:	**Exemption Granted**
IRB Action Date:	03/11/2013
IRB Protocol #:	1303008938
Study Title:	Integrating environmentally responsible design approaches and life cycle assessment in product design and development for sustainability

The above-referenced protocol is considered exempt after review by the Institutional Review Board pursuant to Federal regulations, 45 CFR Part 46.101(b)(2).

This part of the federal regulations requires that the information be recorded by investigators in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. It is necessary that the information obtained not be such that if disclosed outside the research, it could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

You should retain a copy of this letter for your records.