2011-01-01

Development Of An Expert System To Aid In The Selection Of Sustainability Design Engineering Methods

Pedro Renato Acosta
University of Texas at El Paso, pracosta@miners.utep.edu

DEVELOPMENT OF AN EXPERT SYSTEM TO AID IN THE SELECTION OF SUSTAINABILITY DESIGN ENGINEERING METHODS

PEDRO RENATO ACOSTA HERRERA

Department of Mechanical Engineering

APPROVED:

Noe Vargas Hernandez, Ph.D., Chair

Connie Gomez, Ph.D.

Heidi A. Taboada Jimenez, Ph.D.

Patricia D. Witherspoon, Ph.D.
Dean of the Graduate School

Dedication

The work in this research is dedicated to my parents and sisters who have provided me with the resources to continue my education. I would also like to dedicate this work to my wife who gave her unconditional support these two years of graduate course work. I would also like to give special thanks to Dr. Noe Vargas Hernandez for giving me the opportunity of performing research in the area of design and for this thesis completion. His knowledge and guidance are fundamental elements contributing to the completion of this research work.

DEVELOPMENT OF AN EXPERT SYSTEM TO AID IN THE SELECTION OF SUSTAINABILITY DESIGN ENGINEERING METHODS

by

PEDRO RENATO ACOSTA HERRERA, B.S.ME

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER SCIENCE

Department of Mechanical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

May 2011

Acknowledgements

The author gratefully acknowledges the support of the United States Department of Agriculture grant. The project is funded by USDA Award #2009-38422-19963. The opinions expressed in this thesis do not necessarily reflect those of USDA.

Abstract

The objective of this thesis is to present the development of an expert system to aid designers in the selection of design methods, in particular for sustainability methods. When practicing engineers need help in their design process, they look for design methods and tools; this is a challenge especially for inexperienced engineers in the sustainability area. Engineers, due to time constrains, will only utilize one or few methods during their professional life. The origin of this situation can be traced to engineering education, where it is typical that an instructor prefers one or few methods in particular, and even when he or she attempts to teach other methods, students may get confused since it is different to learn a method than learning how to select from a set.

This thesis work presents a concept for an expert system that has been developed from the characterization of key elements found in the design for environment (DfE) methodologies such as principles, guidelines, and tools. Each element brings a vast set of variables that are not, most of the times, well defined. An approach is taken by synthesizing a conceptual and logical model to represent the fundamental characteristics of a sustainable method selection tool. The result is a sustainable expert system (SES) that provides the functionality of recommending DfE methodologies according to an input defined through a set of questions given on a sequence. Moreover, the SES accepts the input from the designer as a series of simple questions such as: what is the design stage, the solution characteristics, among others, and it maps information through a database (while following a pre-defined logic) to find matching DfE methodologies. It is foreseen that this SES will be used primarily by an engineering student focusing in the design subject and secondly by practicing design engineers. The SES will also reveal cases for which methods do not seem to exist; these can be identified as areas of research opportunity.

Table of Contents

Acknowledgements....v

Abstract....vi

Table of Contents.... vii

List of Tables x

List of Figures....xi

Chapter 1: Introduction....1

1.1 The Emergence of Sustainable Design 2

1.2 General Overview of Sustainable Design....4

1.2.1 Hannover Principles....4

1.2.2 Sustainable Design Applications 6

1.3 Green Technologies 7

1.3.1 Definition....8

1.3.2 Solar Principles....9

1.3.3 Water Recycling 11

1.3.4 Wind Energy....12

1.3.5 Green Building....13

1.4 Institutions Performing Sustainability 14

1.5 Closing Statements 17

1.5.1 Need....17

1.5.2 Problem Statement....17

1.5.3 Hypothesis 18

1.6 Chapter Overview....18

Chapter 2: Background....20

2.1 Design for Environment 20

2.2 Origins 21

2.3 Design Philosophies....21

2.4 Techniques and Methods 22

2.4.1 Case Studies....24

2.4.2 Impacting Enterprises 25

2.5 Design for Environment Research....25

2.5.1 History 26
2.5.2 Institutions and Universities 27
2.5.3 Books 32
2.5.4 Government 34
2.6 The Design Process Influence 36
2.6.1 Design Education 37
2.7 Artificial Intelligence 38
2.7.1 Knowledge Representation 38
2.7.2 Case-Based Reasoning 39
2.7.3 Database Management Systems 41
Chapter 3: State of the Art 44
3.1 Design Method Selection 44
3.1.1 Current trends 45
3.2 Sustainable Method Selection 46
3.3 Current Expert Systems 49
Chapter 4: Proposed Solution 52
4.1 Approach 52
4.2 Methodologies and Relationships 53
4.3 Expected Outcomes 54
Chapter 5: Expert System Development 56
5.1 The Design Process 56
5.2 Conceptual Layer 57
5.2.1 Relationships 57
5.2.2 Entities 60
5.2.3 Conceptual Model Development 61
5.3 Logical Layer 62
5.3.1 Entity Relationship Diagram 62
5.3.2 Standard Query Language (SQL) 63
5.4 Physical Layer 64
5.5 Description Of The Final Product 66
Chapter 6: Validation 69
6.1 Factors 69

6.2 Response 69
6.3 Design of Experiment 69
6.4 Design task 70
6.5 Execution –Detailed Instructions 71
6.6 Results 72
6.6.1 Quantitative Measurement – Time 72
6.6.2 Quantitative Measurement – Accuracy 74
6.6.3 Qualitative Measurement – Debriefing Section 77
Chapter 7: Concluding Remarks 78
7.1 Discussion 78
7.2 Conclusion 78
7.3 Contribution 80
7.4 Future Work 80
References 82
Appendix A 86
Appendix B 92
Annex 95
Vita 103

List of Tables

Table 2.1: Differentiation of environmental design philosophies. 21

Table 5.1: Sample R1 and R2 58

Table 5.2: Sample R3 58

Table 5.3: Sample R4 59

Table 5.4: Sample R5 59

Table 5.5: Sample R6 59

Table 5.6: Sample R8, R9 and R10 60

Table 5.7: Approaches table in phpMyAdmin 65

Table 6.1: Time results 73

Table 6.2: Accuracy results 74

Table 6.3: T-test results 76

List of Figures

Figure 1.1: Solar panel technology 10
Figure 1.2: Natural water cycle [14] 11
Figure 1.3: Wind technology example 12
Figure 1.4: BedZED facility 13
Figure 2.1: Techniques and tools. 23
Figure 2.2: Hydrology and climate 27
Figure 2.3: Thermal process device 29
Figure 2.4: Sustainable development and global competitiveness 29
Figure 2.5: The Scram tool 31
Figure 3.1: Selection stages 46
Figure 3.2: Material's database 47
Figure 3.3: Sample graph 47
Figure 3.4: The limit stage 48
Figure 3.5: The tree stage 48
Figure 3.6: Dominic's Architecture 50
Figure 4.1: The expert system framework 52
Figure 4.2: Product life cycle and sustainable design tools 53
Figure 4.3: Relationships among variables 54
Figure 4.4: SES approach 55
Figure 5.1: Sustainable Design Method Approach 56
Figure 5.2: Conceptual model 61
Figure 5.3: Entity relationship model 63
Figure 5.4: phpMyAdmin application 64
Figure 5.5: Visual Studio code 66
Figure 5.6: The Sustainable Expert System application 67
Figure 5.7: Guideline example 67
Figure 5.8: Tool example 68
Figure 6.1: Elapsed time chart 73
Figure 6.2: Question 1 accuracy chart 75
Figure 6.3: Question 2 accuracy chart 75
Figure 6.4: Question 3 accuracy chart 76

Chapter 1: Introduction

Throughout the history of mankind, earth has provided numerous resources including renewable and not renewable types to human beings. Nothing in life is infinite and there are some limitations as for resource quantity and availability. Human beings, by nature, tend to overuse resources whenever aspects such as money and power are involved. Today, earth is undergoing climate changes and consequently disasters thanks to the excessive use of environmentally non-safe products, forest fires and industrialization. It is known that the temperature has been increasing in the last years due to factors like pollution causing the effect commonly known as Global Warming. Such climate changes have caused the emergence of alternatives to reduce the environmental impact of products and processes. One of the alternatives is the design for environment (DfE) methodologies. Within DfE, there are principles and guidelines that can modify or transform our products and processes to diminish resource usage, hence, contaminating less. "Design for Environment (DfE), or green design, guidelines serve as a means for preserving, disseminating, and translating techniques for achieving better environmental performance" [1]. Additionally, there are available tools that can either help designers on inventing new products using a sustainable approach or to assess a product's performance in terms of environmental impact

Guidelines, derived from principles, are utilized to improve a product's performance by modifying design decisions to mitigate environmental impact during their development. A principle represents a group of guidelines addressing general objectives i.e. design for disassembly, reduce energy usage, and the guideline is more specific in regards to a recommendation. In a perfect world, guidelines would be used by designers to improve the characteristics on a product to the extent of reducing resource usage and hence diminishing pollution. However, there are considerable aspects that affect the correct use of these guidelines. Although various researchers propose different guidelines, their development is incomplete and their relationship to the product life cycle stage is unclear [1]. A similar situation occurs with the DfE tools which tend to be more of a practical approach to either develop new sustainable product or to assess environmental performance. According to Reyes and Rohmer [2], limitations have been identified from the practical use of tools. Vast availability of tools for designers, uncertainty on their practical use, unclear relationship with a company's industrial context and the

unclear linkage with strategic practices from a company are some limitations [2]. It can be stated that the correct use of any DfE methodology, either a guideline or tool, is still unclear from the design standpoint and that further research is required to improve their effect on product development. It is for this reason that an approach to try solving this methodology problem is proposed by the author. The objective of this research work is to describe and present the development process of an auxiliary tool that can potentially mitigate some problems derived from the selection and use of DfE methodologies. Chapter 1 will provide an overview of sustainability and its relevance on the engineering world.

1.1 THE EMERGENCE OF SUSTAINABLE DESIGN

As the demographic population increases, resource usage increases as well. Industrialization and technology advancements are also relevant causes of potential contaminants. According to Bahmra and Lofthouse, the concept of design for Sustainability first emerged in the 1960s when Packard (1963); Papanek (1971); Bonsiepe (1973) and Schumacher (1973) began to criticize modern and unsustainable development and suggest alternatives [3]. There were two more waves that emerged in the 1980s and 1990s which coincided with the green consumer revolution. In 2000, these movements have gathered power and have become popular among people due to the fact that companies and enterprises have started using sustainable design measures.

The United Nations, being an institution that cares about the environment, held a World Summit on Sustainable Development in Johannesburg to assess global change [3]. Among the various subjects and facts discussed, it was found that:

- A third if the world's population lives in countries suffering from moderate to high water stress
- 80 per cent of all disease in developing countries us caused by consumption of contaminated water
- 12 per cent of bird species, 25 per cent of mammal species and 34 per cent of fish species are under threat of extinction
- Air pollution is estimated to cause 5 per cent of the world's deaths each year
- 113 million of the world's children do not have access to primary education while 20 per cent of adults are illiterate, two thirds of these are women

- Global consumption of mineral, wood, plastics, and other minerals increased by 240 per cent between 1960 and 1995

Other events around the world have taken place in order to discuss and find a potential solution to this same issue. It is important to mention that the frequency in which these events occur has been increasing as industrialization keeps its pace. Several other conferences and events have occurred since the movement started; the events include [4]:

- Stockholm conference on the Human Environment and the establishment of the UNEP in 1972
- Limits to Growth report
- U.S. Global 2000 Report to the President and its response The Resourceful Earth
- World Conservation Strategy
- IIASA report Sustainable Development of the Biosphere
- U.N. report Our Common Future

Thanks to the events and conferences being held throughout the world, the environmental consciousness has acquired interest from major enterprises. Global manufacturers, in virtually every industry category, are adopting sustainability goals, and environmental activist groups have begun to collaborate with them [5]. In addition, several companies have started answering the call for the environment by using sustainable methods to produce and manufacture their products. Some of the companies include FORD, GE, Shell, Honda, and HP. These companies have begun reporting their "green achievements" by publishing yearly sustainability reports in which every single action and implementation is presented to the people in general. Sustainability has also made its way through politics.

The U.S. has initiated environmental movements through the administration of Federal Government programs such as The Department of Energy (DOE), the Environmental Protection Agency (EPA), and the Defense Advanced Research Projects Agency (DARPA). The initiatives provide funding for industry-university cooperative research that can aid in the utilization and application of green technologies for manufacturing purposes and supporting research with the purpose of finding alternative energy sources [5].

1.2 General Overview of Sustainable Design

In the engineering world, there are a handful of disciplines that are either specific to a topic or multidisciplinary in nature. Nowadays, sustainability can be applied to common disciplines in the design domain such as Mechanical Engineering, Electrical Engineering, Industrial Engineering, etc. Sustainability, by itself, has not become an engineering discipline yet: however, this technique can be utilized and applied in any process or product by any discipline following the principles and guidelines. Design on the other side, is a tool used in the development and creation of any product or system. Design follows detail processes to successfully generate a product. In combination, both tools can be seen as an applied science that, based on guiding principles, is able to create products of processes to reduce environmental impact.

By definition, sustainable design is an enabling force to shape more sustainable patterns of production and consumption. By incorporating design for sustainability into product design and development, organizations gain a fresh perspective on established practices resulting in new ideas and solutions [3]. According to Kutz [6], Green Engineering addresses environmental problems by changing the underlying composition of a product, process, or system or by changing the context in which the system operates. These aspects make the use of methodologies favorable to decrease contamination while stimulating innovation on products.

Design of Sustainable Product Life Cycles is one of the widely used approaches of sustainable design. Different from designing a specific device to perform a task, this approach alters the product life cycle based on decision making and process selection. It analyses the full life cycle including design, manufacturing, assembly, usage, service, and disassembly and recycling. Life Cycle Assessment evaluates environmental performance by analyzing the effects of products and processes during their entire life cycle [7]. This includes the selection of a raw material up to the use and end of life. This approach is mainly practiced by manufacturers of any type of product.

1.2.1 Hannover Principles

Hannover principles are one of the first approaches on defining generic principles to implement sustainability on a product. Authors describe these principles in different fashions; however, they end up

referring to similar concepts. The McDonough website [8] illustrates the Hannover principles which were presented in the "Humanity, Nature, and Technology" expo in the year 2000. Such principles are to be considered by any designer, engineer, planner, etc., to set priority towards the environment. The Hannover principles, also known as the Bill of Rights of the earth, read as follows:

1. ***Insist on rights of humanity and nature to co-exist*** – in a healthy, supportive, diverse and sustainable condition
2. ***Recognize independence*** – The elements of human design interact with and depend upon the natural world, with broad and diverse implications at every scale. Expand design considerations to recognizing even distant effects
3. ***Respect relationships between spirit and matter*** – Consider all aspects of human settlement including community, dwelling, industry and trade in terms of existing and evolving connections between spiritual and material consciousness
4. ***Accept responsibility for the consequences of design*** – decisions upon human well-being, the liability of natural systems and their right to co-exist
5. ***Create safe objects of long term value*** – Do not burden future generations with requirements for maintenance of vigilant administration of potential danger due to the careless creation of products, processes or standards
6. ***Eliminate the concept of waste*** – Evaluate and optimize the full life-cycle of products and processes, to approach the state of natural systems, in which there is no waste
7. ***Rely on natural energy flows*** – Humans designs should, like the living world, derive their creative forces from perpetual solar income. Incorporate this energy efficiently and safely for responsible use
8. ***Understand the limitations of design*** – No human creation lasts forever and design does not solve all problems. Those who create and plan should practice humility in the face of nature. Treat nature as a model and mentor, not as an inconvenience to be evaded or controlled
9. ***Seek constant improvement by the sharing of knowledge*** – Encourage direct and open communication between colleagues, patrons, manufacturers and users to link long term

sustainable considerations with ethical responsibility, and re-establish the integral relationship between natural processes and human activity

Rather than being requirements or prescriptions, the principles act as a way of thinking. They take the form of a framework, based on the enduring elements of Earth, Air, Fire, Water and Spirit [8]. These principles encourage the various professions to include and practice sustainability measures in their daily operating and designing.

1.2.2 Sustainable Design Applications

Sustainable design has been represented in various flavors and colors. Since design is a discipline that can be applied to any subject, thing, product or process, it can be applied to any technology in combination with sustainability. Nowadays, sustainable design is known in different categories and it is used on different subjects. Subjects are commonly known as DfE, Solar Energy, Wind Energy, Landscape Design, Water recycling, etc. The main objective of these disciplines is to take advantage of the natural resources provided by nature. For instance, DfE focuses mainly on modifying processes and performing environment-conscious design decisions to reduce contaminants.

Probably being one of the relevant subjects in the sustainable design field, DfE is the systematic consideration of design performance with respect to environmental, health, safety, and sustainability objectives over the full product and process life cycle [5]. In other words is the science that practices sustainable design in the product launch process of the product going up to the end of life of the product. In part, DfE provides guidelines that are applied in the development phase of any product. As stated in Joseph Fiksel book [5], some of the major examples include design for dematerialization, design for detoxification, design for revalorization and design for capital protection & renewal. Design for dematerialization refers to reducing the amount of material used to manufacture an assembly and it also includes the reduction of processes to accomplish the assembly. Design for detoxification relates to minimizing the use of materials that possess hazardous properties that can cause waste affecting human beings. Design for revalorization stands for recovering, recycling and reusing materials to reduce virgin resource usage. Finally, design for capital protection and renewal focuses on ensuring the safety, integrity, vitality, productivity and continuity of resources.

Different from using principles and guidelines, green technologies also provide a clean approach as for alternative energy sources. The advantage of using the energy provided by Earth is that, on top of everything, it is a free resource and is abundant. Solar energy, wind energy and water recycling are technologies were all the sustainability aspects appear.

Besides from the earth elements, landscape design can also be used towards sustainability. In the Ecological Design and Planning book [9] Landscape Architecture is portrayed as the design and planning of physical environments. It can include the design and arrangement of significant or minor structures, from highways and water management structures to buildings and urban districts [9]. In other words, this discipline is related to the transformation and architectural change of all the city landscapes to take advantage of resources.

As a result of resource depletion and excessive contamination, several companies have started developing designs that utilize the sustainable design principles. Since 1994, Seiko has been using the Kinetic wristwatch which is powered by human movement. It uses a swinging weight that records movements and transforms it into energy that can run for 5 months [10]. Fiat, the car company has developed a car called the Fiat Panda that is powered by hydrogen. The engine undergoes a reaction including oxygen and hydrogen producing water and heat avoiding the generation of emissions. This car has an operating range of 200 km and at full change it can reach up to 130 km/h having a diminished charge time of less than 5 minutes [10].

1.3 GREEN TECHNOLOGIES

Besides the options available for the practice of sustainable design, there are technologies that can be used towards the health of the environment. Different from the other existent methodologies and techniques being among others design for environment, life cycle assessment, green design, etc. the green technologies elements are provided by nature for the good of itself. This area of sustainability is related to the use and transformation of nature’s elements towards reducing the use of energy and resources hence diminishing contaminants and carbon footprint. Nature can also be considered as a guide to DfE. By following some biological trends, ideas on creating devices or completely new designs

are inspired by the natural systems. Being this another method of developing environmental safe systems.

Among the elements that can be used towards sustainability, there are four that cover the entire range of variations; these are solar energy, water, wind energy, and green building. Rather than focusing on modifying a process or applying guidelines to a product or process to reduce contaminants of material usage, green technologies relate to the creation and development of devices that perform a certain task using the elements provided by the ecosystems to fulfill a requirement. Although some of the elements in different forms are considered harmful to human beings i.e. tornados, hurricanes, excessive sun light causing skin deformations, tsunamis, floods, and erosions, green technologic devices are designed to take advantage of these elements since they are provided by nature and their usage leads to clean emissions.

1.3.1 Definition

The basis of green technologies lies on the renewable energy concept meaning that the purpose of this approach is to utilize energy that can be replenished without exhausting resources and that are somehow unlimited. There are numerous names for this technology, for instance Environmental Technology, Green Technology and Clean technology which are known by the contractions envirotech, greentech and cleantech respectively [11]. By definition, green technology is simply the use and application of the environmental sciences to preserve the natural environment and its resources and to prevent negative impacts created from human beings being sustainable development the core of these technologies [11]. These elements can either be used separately or in combination to fully achieve a function. One clear example is green building in which all the elements can be combined producing the so called intelligent homes. Another example is a solar energy system supplying a water recycling system.

Green technologies are also based on the “learning from nature” principle. Several designs used today are inspired by insects or plants found in the diverse ecosystems. These designs have led to elegant solutions that have evolved over millions of years providing innovations. One example is Velcro

which was inspired by the structure of an insect's feet or new designs relating to turbine blades which are similar to the flippers of a whale [5].

There are other major examples were the actual behavior of the earth or ecosystem is mimicked to perform a sustainable measure using renewable energy. Take for example an ecological system having food webs, in this system the webs have evolved into a fashion that every single bit of biomass is consumed by an organism occupying a niche. Such system has been copied by the industrial systems called "industrial ecology" which acts in a similar manner transforming waste material or consumption activities into "food" for processes in the industry [5]. To conclude, green technologies use and take advantage of the energy provided by nature to fulfill a need or perform a task.

1.3.2 Solar Principles

Being the largest energy source available on the planet, solar energy provides an unlimited resource that can be used towards environmental sustainability. Through the means of installing solar panels on streets, homes and buildings, solar energy is accumulated and transformed into electric energy that can supply any electro domestics as well as emergency lights or any king of illuminating device. In order for a solar energy device to be successful, certain elements have to be taken in account before even designing [12]:

1. Geographic location
2. Time of the day
3. Season
4. Local landscape
5. Local weather

These elements [12] are needed thanks to the fact that the sunlight directly hits the earth's surface. It actually depends on the angle the sun rays enter the atmosphere, when vertical, the amount of heat is at its maximum, when slanted, the intensity of the rays is diminished. It is crucial to take these elements in account before creating a conceptual design utilizing solar energy. Solar energy, being the largest available on earth, is not being properly utilized by earth. The majority of the energy is deflected by the earth while the only natural process taking advantage of this energy is photosynthesis which only

captures 0.1% of the energy emitted by the sun. If there is a desire of using this energy, there must be technical intervention utilizing human-made devices such as photo-voltaics, wave generators and others that have not been invented [4]. Solar energy has the advantage over other fossil and nuclear energies due to the fact that the use of solar energy through electricity generation does not produce any contaminants. It is considered one of the cleanest energy sources available, figure 1.1 gives an example of a solar energy application:

Figure 1.1: Solar panel technology

There are applications were solar energy can be used, the majority these fall into the green building category. Take for instance the study performed by a research group in Nuremberg, Germany. The study is related to the application of photovoltaics in the German households [10]. The study shows that an $8m^2$ solar panel along with passive water heating can supply the entire set of appliances with direct current. Appliances with alternating current would need $30m^2$ solar panels. Such solution could be used for countries in which the alternating current system has not been fully introduced. However, there are available applications were the use of solar energy is solely for energy creation and can be specific for any device. Another example of energy innovation found in the Design for Environment book by Fiksel [5], is the Tata BP Solar which is an energy source supplied by solar energy means to the rural

villagers of Uttar Pradesh, India. This project is basically a set of applications such as village lighting, water pumping and telecommunications. Although this technology of grid power is not available to all the citizens in that area, the Indian banks have started offering finance opportunities to villagers implement solar-home-lighting systems.

1.3.3 Water Recycling

As the name describes, water recycling has become an important aspect nowadays. It is known that 70% of earth's surface is covered by water meaning that there is a considerable amount of this element to avoid scarcity [13]. Within that 70%, 97% is saline and makes part of the oceans. The remaining 3% is fresh water or "drinking water" and it is distributed among lakes, rivers, swamps, glaciers and ground water. That 3% is the only percentage reserved for human use and it should supply the entire population around the globe. Time goes by and population increases, hence technologies must be developed to reduce the waste of water and increase recovery. Earth using its natural processes, can filter the water and re-fill rivers and lakes. The process involves the collection of water from rivers, lakes and oceans, evaporating from the liquid state to condense and form clouds, and the precipitation in the form of rain being this the [6] "new product".

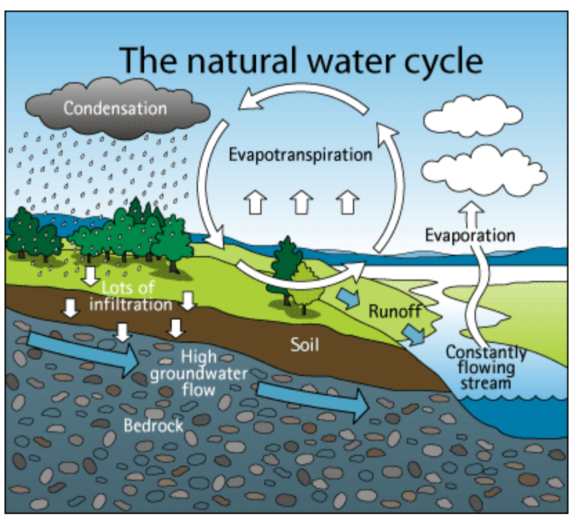

Figure 1.2: Natural water cycle [14]

Nonetheless, this natural process is not capable of recycling the required amount of water per capita. According to [15], "Globally, one in five of us does not have access to clean drinking water. Two

in five do not have adequate sanitation facilities – water to wash with and to clean with, or even a safe place to answer nature's call". Thanks to these facts, several devices have been created to address the water consumption global issue. There have been strong initiatives to recycle dark and grey water. Although it takes several steps to recycle the water, there are water treatment plants that filter and re-inject the water to the aquifer, waiting for nature to continue with its natural process. Other initiatives are recycling the shower grey water, harvesting rain water, fog catching, water purification, permeable pavement, etc [15]. As stated before, some of these initiatives can be combined with the other green technologies to enhance the level of sustainable design implemented.

1.3.4 Wind Energy

Wind energy has started gaining popularity thanks to the growth and sophistication of wind generation systems. "Wind power is the cleanest alternative energy source; harvesting wind via windmills or turbines emits no air pollution. Large wind farms generate the most wind power, but small clusters of megawatt-range utility scale turbines are popping up" [15]. Wind energy devices are mainly used to transform energy potential into electricity. Devices mainly utilized to produce such energy are commonly flying windmills and turbines in different variations as for design. Flying windmills are placed on open areas with high masts allowing the rapid turning of the wings generating more electricity [15].

Figure 1.3: Wind technology example

Turbines are mainly utilized for this type of energy development and sometimes they can be placed offshore attached to the ocean floor or in extensive landscapes were the wind velocity is high. As an example of the world largest wind turbine, the Enercon E-126 with a diameter of 126 meters for the rotor can produce more than 7 megawatts which is enough power to supply 5,000 households [5].

The question arises, how come the wind energy being the cleanest and an unlimited source of energy not being used in every single part of the country? The answer is cost. Wind energy [15] has historically been more expensive than other fossil fuels such as coil, oil and natural gas. However, thanks to the people developing wind farms and the research done in this domain, the price has dropped considerably during the last years.

1.3.5 Green Building

Probably the most used popular green technology used nowadays, green building is an area that has gained momentum and popularity thanks to the available applications and styles it has provided in addition of being benefic to nature. Having the characteristic of incorporating the already discussed green technologies into a whole system, green building has made an impact on the way houses should be built. Some organizations have emerged thanks to the green building movement such as the U.S. Green Building Council and the LEED which stands for the Leadership in Energy and Environmental Design [15]. The USGBC along with the LEED certification system provides professional training and accreditations related to the green building anywhere in the U.S. In addition, the council provides information regarding new-green building innovations overseeing the LEED rating system.

Figure 1.4: BedZED facility

An example of green housing (figure 1.4) can be found in south London were the Beddington Zero Energy Development (BedZED) is located [15]. It is basically a high-design facility that provides a low impact complex with eighty two available units. This facility covers most of the sustainability concepts and incorporates them into the inside and outside walls. To begin with, BedZED uses recycled and renewable materials within a 35 mile radius to turn them into a green space by freeing area and reusing materials. Also, this building is characterized for being a "zero-carbon" unit. Among the abundant implementations, there are solar panels installed on the outside generating electric energy used as the main power. There are triple-glazed windows with the purpose of isolating energy in the inside and reducing the energy waste to the outside. Water is recycled and water harvesting is practiced as well.

Green technologies are alternatives to sustainable design that have been proven effective to suffocate contamination and carbon footprint generation. By designing a specific device and considering the energy principles, green technologies can provide alternate energy generation methods without creating any waste out of the transformation processes. These technologies can be divided into 4 main areas of green energy, solar energy, water recycling, wind energy and green building. These areas provide guidelines and recommendations regarding principles to develop a more effective design. To conclude, green technologies are a complement of the design for environment guidelines and methodologies, it rather focuses to a device performing a task than to modifying a process.

1.4 INSTITUTIONS PERFORMING SUSTAINABILITY

Sustainable design has become popular among important institutions throughout the United States. Since the emergence of sustainability, several schools started performing sustainable measures all around the campus to initiate the developing of a conscious way of thinking among students. Schools have also started developing classes that illustrate the application of sustainable design by incorporating several green technologies. In addition, the development of sustainable design projects has also been possible with the help of design for environment. Teaching sustainability as a class is another initiative universities are taking in order to elevate the popularity among students.

UCLA is one of the universities that have started using sustainability. In 2005, they established the UCLA Campus Sustainability Committee with the purpose of creating a green environment among students [16]. They are also recognized as one of the top 10 greenest campuses. The following are some facts that show what UCLA does in order to mitigate contamination and resource depletion:

- Software Central coordinates a campus-wide initiative to recycle old CD, CD-ROM and DVD disks
- Health system has eliminated the use of mercury-based instruments
- 3.8% of UCLA’s fleet are alternative fuel vehicles
- New heating ventilation and air conditioning (HVAC) modernization will reduce carbon footprint by 17,000 tons/year
- Has installed over 112,000 energy efficient bulbs and 3,600 low energy exit signs

This university has been giving events to promote sustainability not only on campuses but also throughout the city. Some of the events include Serve and Save the Environment, Federalism and Climate Change and Smart Grid Thought Leadership forum.

ASU is also another institution that has taken sustainability to higher levels. They have created the Global Institute of Sustainability which takes a trans disciplinary approach in its curriculum addressing a broad spectrum of global challenges, including: energy, materials, and technology; water quality and scarcity; international development; ecosystems; social transformations; food and food systems; and policy and governance [17]. The actual building has been design with the most sustainable materials as possible. It incorporates green technologies towards the use of natural resources. Different from various schools, ASU offers Bachelor’s Degree, Master’s Degree and PhD in sustainability. They have students organizations mainly focused on holding social events to create a more sustainable model in Arizona. Some of the campus initiatives include:

- Solar powered parking structure
- ASU energy conservation project which basically involves the retrofitting of lighting systems replacing motors, cooling towers, upgrading HVAC systems, insulating steam pipes, etc.

- ASU requires the Leadership in Energy and Environmental Design (LEED) silver certification for all new construction of University-owned buildings
- Campus-Grown Foods program
- The trees on campus produce limequats, lemonquats, kumquats, lemons, tangelos, limes, oranges and dates
- ASU recycling services offers bins all around campus for aluminum, plastic, and paper

UTEP has also started the journey of becoming a sustainable community by starting initiatives on the campus. The student population has taken an active role in supporting environmental stewardship and sustainability initiatives [18]. The Student Government Association promotes environmental goals. The following are some initiatives started by this university:

- Academics and Programs: From Industrial Engineering, the Sustainability class is being taught
- Climate Protection: UTEP has set the goal of reducing the greenhouse gas emissions and in addition limit our carbon footprint
- Energy Efficiency: El Paso Electric along with our University have agreed to launch the SCORE program, the $2.5 million savings are a result of this agreement
- Recycling: There is a current recycling program called the three R's of recycling being Reduce, Reuse and Recycle
- Sustainable Buildings: UTEP, as other institutions, has adopted the Leadership in Energy and Environmental Design (LEED) certification and is a member of the United States Green Building Council

The discovery or invention of sustainable design has revolutionized all green movements and any environmental safe activity. Sustainable design is not a recognized science, it is rather a way of thinking were creativity and imagination come together to produce viable alternatives reflected on the application in real world projects or the invention of sustainable devices. This technique is mainly driven by the principles and guidelines which serve as a manual to practice design in the sustainable field. Institutions have started implementing sustainable measures on campus, as a result, students become

aware of the reduction on environmental impact this causes. As stated before, sustainable design can be used to either create a device that performs a specific task or to modify a process and selection phases as it is done in the life cycle assessment.

1.5 CLOSING STATEMENTS

1.5.1 Need

Several authors propose a set of principles, guidelines, and tools to implement sustainability either on the life cycle of the product or in a specific development phase. It has already been discussed that principles and guidelines provide recommendations to implement or improve sustainable product on a product. Yet, the use of such guidelines can lead the intended user (most of the times designers) to a vague understanding since these only provide general product strategies to be applied in the decision phase of the design process. Another aspect that complicates the selection of a guideline for an application is the similarity among their description and targeted outcome. Tools on the other side, help designers perform assessments on the product and stimulate creativity for concept generation. Again, vast availability of tools and not having the necessary knowledge or experience on applying them to engineering practice makes practical application difficult. Hence, there is a need of a tool that could incorporate all the previous aspects and provide a recommended guideline and tool as an outcome, suitable methodologies related to the user's actual scenario.

1.5.2 Problem Statement

The use of DfE methodologies has been gaining momentum as new legislation on product development is required by manufacturing companies. There are several factors that keep companies from fully adopting sustainable practices such as the utilization of design for environment methodologies and tools in the product life cycle process. According to O'Hare et. al. [19] possible causes may include a lack of demand on environmental regulations set as product requirements.

A possible cause is the lack of time to consider the environmental constraints of the product; there are already problems in the development and manufacturing of a product to consider using DfE methodologies. In addition, tool developers do not take in consideration the designers' requirements when developing methodologies. Another strong reason is the vast availability of tools complicating the

appropriate selection process causing designers in some instances to not use a tool at all. Finally, poor integration of the tools to the mainstream product process, tools not having a specific application and the lack of systematic implementation are potential causes of why the use of DfE methodologies may be difficult for a company to adopt [19].

According to Telenko, "The difficulty with DfE principles and guidelines is that they are scattered throughout the literature, in various forms and levels of abstraction, and often with focused emphases on specific life-cycle stages, products, or industries" [20]. Consequently, there is a need to organize and synthetize methodologies to provide them in a useful way to engineers and designers.

1.5.3 Hypothesis

Being the SES a software tool that helps the user choosing a design method, including DfE guidelines and tools, the functionality can be tested by designing a word problem to be solved in the fashion providing design methodologies. By using this software tool, the user can obtain accurate results in a timely manner without depending on their professional or educational background or knowledge on the subject. In order to verify the effectiveness of the system to find appropriate design methodologies, the time an accuracy of the chosen methodologies will be measured from this experimentation. Time to provide answers and accuracy on the provided answers will be measured. The objective is to verify if the SES does make a difference in terms of proposing methodologies.

1.6 Chapter Overview

Clearly, research done in the sustainability area has evolved technology and more alternatives as to use renewable energy have been developed. Moreover, researchers have developed methodologies such as principles, guidelines and tools to tackle environmental pollution through design changes on a product or process.

Chapter 1 has covered the main definitions of sustainability and some history regarding the emergence of this discipline. It also provides an overview of the available technologies and their practical applications while covering what institutions are doing to implement sustainability on their daily practices.

Chapter 2 will provide an overview of the history behind Design for Environment and its potential applications which is the basis for this research work. This background section will cover all the material needed to understand the expert system framework. Subjects such as DfE methodologies, the design process, and artificial intelligence are subjects in which the expert system was build. This Chapter 2 section is intended to give an overview of the elements in which the proposed expert system was built upon.

Chapter 3 will cover state of the art illustrating current technologies related to method selection. In other words, what is out there to mitigate the previously explained problem? What is the closest that has been developed to tackle the method selection problem?

Chapter 4 is intended to provide a description of what was the process to develop the sustainable expert system for design method selection. This chapter will describe the three phases needed to construct the expert system which are conceptual, logical and physical. The section is to describe a detailed description of each phase and its development followed by an overview of the final product.

Finally, Chapter 5 provides a validation and results of the expert system. In this final chapter, the validation process and results will be presented in order to assess the expert system's performance.

Chapter 2: Background

As industrialization advances, human beings continue developing technology to high levels of complexity and state of the art. However, these advancements bring together contamination and resource usage. In addition to those, there is waste produced by the majority of enterprises carrying over technological advancements. Of course, all the actions involved affect the environment in different ways. There are several indicators throughout the world that relate to global warming. More than ever, climate change has occurred in places were extreme temperatures were not usually presented. Nowadays, natural disasters are increasing in regions that did not use to have severe weather conditions. One of the trends identified by scientists, being global warming, is followed by a rising on sea level, scarcity of fresh water, reduction on real state of arable land, forests disappearing, and a threat to biodiversity [5]. However, there are measures and ways to reduce the environmental impact caused by these indicators. That measure is DfE which provides methodologies of a different nature to modify our products and processes reducing excessive carbon footprint generation and excessive energy usage. By definition, design for environment is the systematic consideration of design performance with respect to environmental, health, safety, and sustainability objectives over the full product and process life cycle [5]. As all explored sciences, this methodology is part of sustainability and it is composed by various elements. Such elements will be discussed in the following paragraphs.

2.1 DESIGN FOR ENVIRONMENT

Probably being one of the most important subjects in the sustainable design field, DfE is a set of methodologies that relate to the reduction and reutilization of resources and processes to reduce excessive contaminants and waste. Each area includes methods which can be used for a specific application being a process used on any manufacturing plants. There is an existent interrelationship among all the principles and guidelines due to common characteristics or approaches contained within each area, for instance design for source reduction regarding packaging reduction is similar to design for product recovery recommending the use of reusable packaging [5]. In addition, some of the areas

breakdown into several sub-areas that discuss a guideline more in depth providing a detailed description of any potential application.

2.2 ORIGINS

Different books provide different data related to the emergence of this methodology. For instance, Bhamra and Lofthouse claim that the concept of design for sustainability started on the 1960s when scientists started criticizing unsustainable actions [3]. Moreover, there is concurrence in this development represented by a wave in the late 1980s and 1990s when the green consumer revolution started. Bhamra and Lofthouse also state that from that time, the wave kept growing until 2000 when design for sustainability gained momentum [3]. Design for Environmental Sustainability by Vezzoli and Manzini, states that the introduction of sustainable development was introduced in 1987 when the document named Our Common Future, also called the Brundtland Report, was presented on the World Commission for Environment and Development (WCED) [10]. The presented document contained information related to being responsible to have a certain future and the questioning of current ideas for development. Other books like Design for Environment by Joseph Fiksel, inform that the emergence of this technique started from the 1990s driven by a group of private firms that intended to create environmental awareness in the product development process [5].

2.3 DESIGN PHILOSOPHIES

Researchers assign or name DfE with different names. Although the same principles and guidelines are followed, it is defined on some other wording of concept. The following is a table that describes the different definitions used and the explanation illustrating the variation [3]:

Table 2.1: Differentiation of environmental design philosophies.

Green Design	Green design focuses on single issues, for example the inclusion of recycled or recyclable plastic, or consideration of energy consumption
Eco Design	Environmental considerations are considered at each stage of the design process
Design for sustainability	Design that considers the environmental (for example resource use, en of life impact) and social impact of a product (for example usability, responsible use).
Sustainability	Sustainability is considered to be more of a direction than a destination that we will actually reach.

2.4 TECHNIQUES AND METHODS

Vezzoli and Manzini [10] define Design for Environmental Sustainability as the interaction with product life cycle processes and life cycle assessment. Processes are usually divided into preproduction, production, distribution, use and disposal. Fiksel [5] divides methodologies into four major concepts:

- Design for dematerialization
- Design for detoxification
- Design for revalorization
- Design for capital protection and renewal

Each major concept suggests guidelines for the application on any product or process by following a principle. These practices have interrelationships that, somehow, communize characteristics. Vezzoli and Manzini suggest methodologies arranged by principles and guidelines [10]:

- ➢ Minimizing Resource Consumption
- ➢ Selecting Low Impact Resources and Processes
- ➢ Product Lifetime Optimization
- ➢ Extending the Lifespan of Materials
- ➢ Facilitating Disassembly

Each principle has its own set of guidelines which describe more in depth the different potential applications. Principles describe the general subject and guidelines describe different applications regarding that general subject. These methodologies can be defined as abstract recommendations to inspire green design on products. On the other hand, there are techniques and tools that aid in the sustainable development when designing a product. These tools can either be employed in the beginning of the design process or whenever a principal solution has been obtained. These techniques and tools have proven to be relevant to users and have been grouped into five sections [3]:

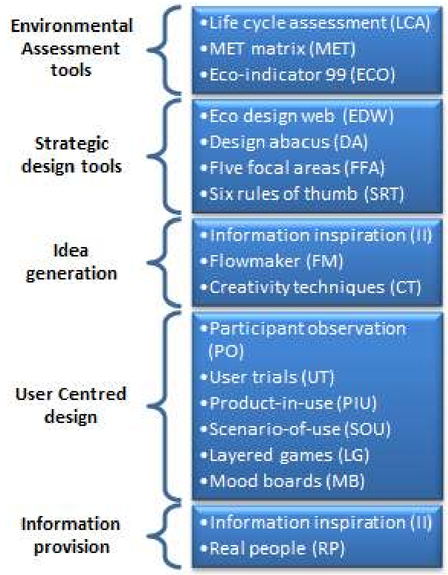

Figure 2.1: Techniques and tools.

Environmental assessment tools can help evaluating the performance of a product in terms of assessing sustainability aspects while identifying opportunities for further improvement. Strategic design tools help in the evaluation of the product once it has been manufactured to find potential improvements. Idea generation methods aid the engineer in the generation of new ideas towards sustainable development and it can be used in any stage of the product development process. User centered design provides techniques to gather information regarding the use phase of the product enhancing the product's architecture. Finally, information provision is related to the user's requirements and preferences in terms of utilizing products [3]. The research performed by the author will be mainly based on principles and sub-principles proposed by Vezzoli [10] and techniques and tools proposed by Bhamra [3] which all represent DfE methodologies. The use of these methodologies is viewed as benign to improve product's quality while reducing environmental impact.

Reyes and Rohmer [2] state that the aim of the eco-design practices is to enhance environmental performances of a company providing an edge among other industrial entities in terms of competitiveness. Companies adopting sustainable approaches are able of producing goods with a good balance between economical an ecological aspects giving companies a competitive edge among green practices. The origination of eco-design and eco-innovation tools (including principles, guidelines and

tools) was accomplished due to new legislation on potential environmental impact on the designing and developing of products incorporating sustainable aspects [19]. As a result, new product requirements have been implemented in the product life cycle process, the eco-design tools and eco-innovation tools have been developed to assist designers address such requirements**.**

2.4.1 Case Studies

As a result of the continuous energy usage and resource depletion, several designers have started their contribution to the environmental cause by designing products that are in essence less harmful to the environment. According to Design for Environmental Sustainability book [10], devices can be designed to accommodate different strategies used to mitigate environmental impact. Minimizing resource consumption, selecting low impact resources and processes and product life optimization are some categories in which the devices can be designed from.

One clear example from the minimizing resource consumption category is the solar cooker which is an easy to build and cheap cooking system. It is made of a parabolic reflective panel and a plastic bag. In countries were the sunlight is strong, it can save up to half the combustible used for cooking. Hence, reduced consumption of firewood can avoid deforestation [10]. Another example related to this category is the i-Magic Fortius being an exercise bicycle that while being used, it stores energy to a network ready to be utilized by any electronic device such as a computer or television.

Designers in the category of selecting low impact resources and processes have created devices that utilize non-toxic energy to perform their function. The Seiko wristwatch uses the kinetic technology which is powered by human movement. Basically any human movement is transformed into a magnetic charge and then stored into a rechargeable battery capable of running 5 months [10]. Another example worth mentioning is the hydrogen powered FIAT panda car. Unlike other harmful combustibles such as gasoline or diesel, the use of hydrogen does not produce any contaminants or emissions harmful to the environment.

Product life optimization is driven by products that are designed to provide more than one function. Some of the products regarding this category include all-in-one printers having fax, scan, copy and printer and laptops which incorporate hard drives, monitor and keyboard into a single device [10].

Other applications involve the ease of maintenance like the Engine BR 700 from BMW and Rolls Royce. This device provides a modular structure with easy access to maintainable components to facilitate maintenance.

2.4.2 Impacting Enterprises

And of course, DfE has an important impact on enterprises. According to Ehrenfeld, business is the largest and most powerful global institution in terms of financial power, exceeding the historically dominant role of governments [21]. DfE has demonstrated to be effective by diminishing the production costs speeding time to reach market while driving innovation on new products. Thanks to the effectiveness demonstrated in case studies, several companies have embraced this technology in order to become vanguardists and have encountered some value out of the output [5]. Some of the companies currently using DfE and creating annual reports containing the actions being taken to mitigate environmental impact include Shell, General Electric, Honda, Hewlett Packard and Ford. Such companies have used it to either change a process in the development stage of a product or have created a device that performs a specific action.

2.5 DESIGN FOR ENVIRONMENT RESEARCH

As industrialization and technology advance, the need for natural resources becomes a priority. Growth sometimes brings drawbacks and negative effects; in this case all effects are directly affecting nature and its ecosystems. This of course creates climate changes and hence disasters affecting human beings and the manner nature acts. As a result, institutions as well as individuals have started the journey on exploring the use of technologies to mitigate the high risk actions caused by the misuse of natural resources. Such institutions and individuals have made their focus on research to specific topics involving Geology, Hydrology, Environmental Fluid Mechanics, Heat transfer among others [22]. In the sustainable design world, there is an infinite amount of areas and topics that can be investigated. Generally speaking, sustainable design can be divided into areas that cover the strategic use of the natural elements and the modification and change of the processes to reduce waste and energy usage.

Common sustainable design topics include the use of green technologies to take advantage of resources which are given by nature in an unlimited fashion. Research and design innovation is

performed on elements such as fire, water, wind energy and solar energy. The Technology, Humans, and Society book by Richard C. Dorf [23] provides an informational context about the available applications for the potential uses of the green technologies towards the sustainable world. Other research approaches involve the use of the life cycle assessment of a product to audit the material selection, manufacturing processes and recycling methods used to reduce environmental impact. One of the clear examples is the approach taken by Joseph Fiksel which details methodologies to create eco-efficient products and processes [5].

This section is intended to provide a topic research survey of the institutions and individuals that have developed or that are currently performing investigation of the sustainable design kind. In other words, the purpose of this section is to provide information regarding the topics of research being done in sustainable design by faculty and scientists. Research on new sustainable design areas is mainly being performed by universities having faculty members leading the effort of innovating and finding new ways of enhance energy and resource usage. Although the vast majority of topics are covered by these institutions, there are still issues that have not been addressed by the investigation previously done in some fields. The following information will provide an insight of the sustainable design research subjects detailing the abundant available areas of investigation.

2.5.1 History

As our civilization has made advancements, there is a background of inventions that have changed our history in terms of innovation. The initiative of the changes civilization has suffered started back in the 15th century with the emergence of the commercial structure. In the 17th century, Francis Bacon pointed out three main technological innovations that made significant changes to humanity such as the magnetic compass, the printing press, and gunpowder. These and other innovations were seen as man dominating nature stressing the fact that this was a harmonization of science and technology. Descartes, Bacon and other individuals believed that technology was somehow master of nature [23].

Other inventions like the electric bulb by Thomas Alva Edison have affected the technological advancements as well, increasing the pace in which humanity grew in terms of technology. According to the textbook Technology, Humans, and Society, "The scale and speed of technological change may well

have outstripped the ability of our institutions to control and shape the human environment" [23]. This means that the previous innovations may have affected our ability to control our energy and resource usage to avoid full depletion. A response to the environmental concerns came in later in 1985 by the UN General Assembly creating the World Commission on Environment and Development (WCED) creating the first report on sustainability in 1987 named "Our Common Future" [10]. This report emphasized that the economic growth meeting people's needs would not compromise the ability of future generations to support themselves.

2.5.2 Institutions and Universities

As stated before, schools and institutions have started making process in the recuing of the world in the sense of research. Some of the schools have a different approach as for topics of investigation and areas of sustainability. The University of Colorado at Boulder is currently performing research in various areas being some of them Hydrology, Water and Environmental Fluid Mechanics, Building Systems Engineering, Construction Engineering Management, Geotechnical Engineering and Geomechanics and Environmental Engineering [22]. Of course, all of these graduate programs include both the scientific and sustainable part. The first area performs research regarding topics such as transport processes, hydrology, climate change and hydrosystems.

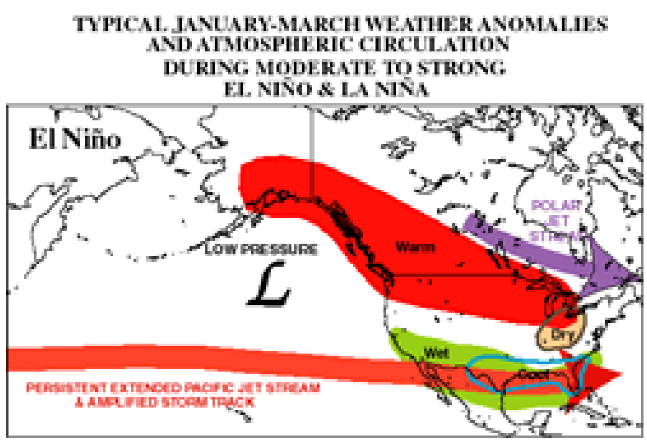

Figure 2.2: Hydrology and climate

This research program mainly focuses on studying the water level change due to climate change, chemical transportation and water resource management to meet requirements. The building systems program performs research in the broad area of energy management. The research topics include modeling and simulation, laboratory and field testing and illumination. Design of a prototype soft energy community (SEC) in the Fukuyama city, Japan, development of HVAC and solar systems diagnostic, optimization of heating and cooling systems, testing of a matrix solar central receiver, design and field testing of a photovoltaic device for beam insulation measurement and the design and assembly of LED laps achieving color temperatures in accordance to a feedback for specific indoor lighting conditions are some of the topics being investigated by the building systems program. Lastly, the Environmental Engineering program offers research in the areas of air quality monitoring, environmental mass spectometry, biodegradation and bioremedation and acid mine drainage characterization and treatment among others. All of these research interests are offered through a master's or doctoral's degree [22].

In addition, the Institute of Technical Thermodynamics located in Stuttgart, Germany is currently doing investigation on efficient energy conversion with low environmental impact and on the improve use of renewable resources [24]. This institution divides areas of study on departments such as the System Analysis and Technology Assessment, Solar Research, Thermal Process Technology and Electrochemical Energy Technology. The first department analyzes decisions taken in the energy sector which have a long term impact in terms of the environment. Such department identifies pro-active decision making in accordance to the new technologies and potential negative effects. The Solar Research department is considered one of the world's leading groups in the thermal systems group. With the purpose of creating sustainable energy supplies, this group focuses on the development of concentrating systems for heat, power and fuel generation. Such effort is fueled in part by laboratories and facilities in Europe being the Plataforma Solar in Almeria, Spain one of them. The Thermal Process Technology (figure 2.3) implements concepts with the purpose of storing thermal and chemical energy for the injection into power plant cycles.

Figure 2.3: Thermal process device

` They are also involved in the investigation of high temperature heat exchangers of high performance for energy transfer processes used in power, systems and process engineering [24].

Stanford University is doing some extensive sustainable design research as well. The institution maintains various laboratories and research centers related to sustainability [25]. The Center for Sustainable Development & Global Competitiveness performs research and develops educational programs that engage with business development strategies and leadership practices. The research areas shown by figure 2.4 are Science & Technology, Culture & Social Ethics, Management Skill and Leadership in sustainable development to ensure enterprise growth in a sustainable environment.

Figure 2.4: Sustainable development and global competitiveness

The Collaborative for Research on Global Projects on the other way targets globalization in terms of mobility of goods, provided services, industrialization, technology advancements and capital. Basically, this research area investigates the approaches, tools and systems required to minimize dimensions of distances and integrate them taking in account the different languages. One example is the Institutional Knowledge Acquisition & Transfer project which involves the understanding of global development, involvement of engineering firms and construction to address infrastructure projects. The Environmental Fluid Mechanics Lab is another research center maintained by the Stanford University [25]. This lab studies the fluid turbulence and mixing in the water flow, energy systems involving natural and forced convection, mass transfer and energy between the ocean and the atmosphere and other topics of interest. Some of the current research programs include Coupled Carbon and Phosporus Cycling in Benthic Beef Communities and Land/Ocean Biogeochemical Observatory for Nitrogen Cycling.

The Institut de Ciència i Tecnologia Ambientals also offers several research areas regarding sustainable design. The objective of this institution as stated in their webpage is to "promote and carry out research, and to train researchers who can contribute to our understanding of the environment and meet the challenges posed by the interaction between society and the environment" [26]. Some of the research areas offered by this institution include Industrial Ecology, ACV, E&MFA and ecodesign, Ecological Economics, Environmental Sociology, Public policies and Environment, Environmental monitoring, Pollution, Aerobiology, etc. The Ecological Economics research group, for instance, targets the economy embedded into a biophysical ecosystem. It focuses on analyzing issues such the social, economic, biophysical, cultural an ethical that can affect management causing changes in the interaction of the human economies with the world. On the other hand, the Sustainability and environmental prevention research group studies tools applied in products or processes that minimize environmental impact. Some of the tools include life cycle analysis, ecodesign, ecoefficiency, industrial ecology and material and energy flow analysis applied to industrial urban and agricultural systems. One of the current projects is developing an environmental analysis methodology that can assess the type and amount of waste generated in trade fair events [26].

The University of Ohio is also a strong advocate of sustainability by doing research in the Center for Resilience. It offers tools to minimize environmental impact and design improvement such as the Supply chain resilience assessment & management, ECO-Flow benefit optimization for byproduct synergy networks, ECO-LCA which is the Life Cycle analysis for embedded natural capital, C-FAR carbon footprint assessment & emission reduction planning; T21-OHIO integrated socio-economic-environmental policy analysis and the DFE-Advisor guidelines for design of sustainable products and processes [27].

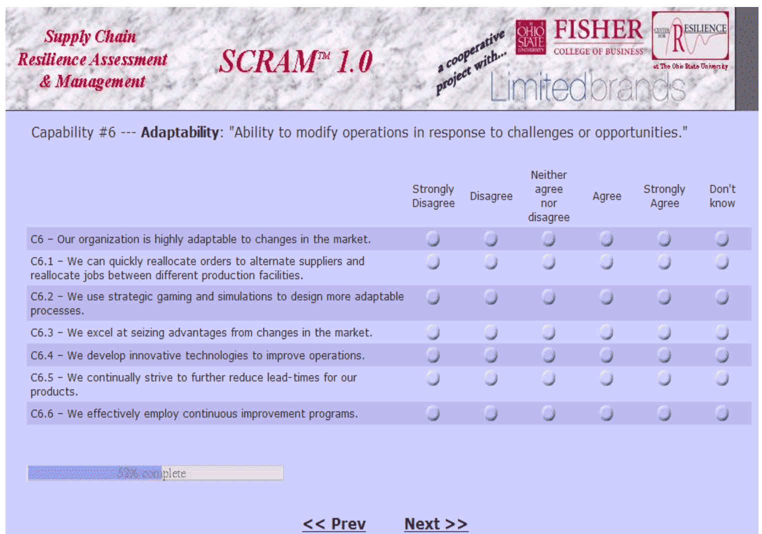

Figure 2.5: The Scram tool

The University of Ohio is also involved in sustainability projects such as the Enterprise Resilience - A new approach to risk management, Resilience in Supply Chain Management, Industrial Ecology and By-product Synergy, Sustainable Life Cycle Design of Products and Processes and the Sustainable Campus - Green Design, Construction and Operation. This last one includes the use of an Institute of Energy and the Environment within the OSU. The IIE is an institution created by 5 OSU colleges with the purpose of investigating the energy and environmental issues fueled by the economic future of OSU, proposals in sustainability and developing alternatives to fossil fuels and the environmental problems caused [27]. Among the countless research programs IIE offers, the Internal

Combustion Engines ; Fuel Cells Systems; Hybrid-Electric Vehicles, Geography - remote sensing of natural resources and Aerodynamics; wind energy are some areas with particular interests.

2.5.3 Books

Books are also a reflection of current investigation and thorough research illustrating the informational aspects and details of a study. For instance, The Green Gold book by Moore and Miller provides a full description and background regarding zero-emitting vehicles [28]. General Motors being the designer of a "clean" vehicle, proposed a platform fueled by thirty-two lunch pail-sized batteries using aerodynamic tires mounted on low weight wheels and having the chassis made of heat-filtering glass. Paul McCready possessing an impressive background on designing sustainable devices such as the human-powered airplane and the sunRaycer, which is a solar powered car that could potentially become a museum artifact, participated in the design of the GM vehicle. Although all the American car companies did an effort on reducing environmental impact by using alternative fields, they turned their backs on moving forward with the environmental programs due to the economical drawbacks caused by stopping petroleum consumption. Honda, however, continued with the development of not just electric cars but hybrids and alternative fuels [28]. Past efforts on moving to alternative fields have transformed the car industry in the sense the companies have at least four or five platforms governed on electric power combined with another type of fuel. Car companies continue performing research on the alternative fuel area.

There is also a strong interest on performing research in the renewable and bio-compatible materials area. The Design for Environmental Sustainability textbook [10] depicts various case studies illustrating examples on how this technology is being implemented and applied. To begin with, in Lixeha in Hanoi, Vietnam, a bicycle with metal parts substituted by bamboo was developed in response to materials usage. This bicycle is composed by a bamboo frame with a surface finish of clear glue. Another clear example is the Ain Shams University in Egypt which design a piece of furniture made of palm leaf midribs very close to wood. Jan Velthuizen, a designer from Netherlands fabricated a soft container using a pumpkin grown in a mould. Spain is also contributing to the cause by developing a material made out of pulverized almond shells and synthetic powder. Such material can be injection

mould it to create any product substituting the use of thermoplastics. The growing interest of implementing devices of this kind is being adopted around the world [10].

Opportunities to reduce energy usage and improve efficiency on machines are sought in the industrial piping systems found in the textbook Whole System Design [29]. There is a huge amount of energy required to move a liquid from one place to another since pipe friction requires that in order to override head loss. Such application of moving fluids is presented on most industrial companies. The research presented regards the enhancing of pipes to reduce friction, hence reducing industrial energy consumption as well and consequently mitigating greenhouse emissions. Actually, if a single unit of pumping is saved, more than ten times of energy is fueled as well. As a fact, a hundred units of fuel input are needed to achieve 9.5 units of energy output within the piping system. Moreover, the book also emphasizes in the use of small and large pumping systems, stating that small systems are widely used by companies over large systems. However, companies utilizing large pumping systems are prone to have major losses due to a poor designed system having a power rating in kilowatts and megawatts needed to successfully operate [29].

One of the mostly discussed elements in the sustainable environment is carbon. Moreover, this element is known for its suspected roll in global warming in terms of contaminants released into the ozone. Carbon is released in the form of smoke into the atmosphere every time a fossil fuel is burned from the industrial processes causing an amount increase of the so called carbon footprint. However, carbon is not that harmful to the planet or to human beings. It is the primary constituent of some plants and it is used in some medical applications i.e. medicines. Actually all leaving tissues are compounded by carbon. One sustainable application for carbon is nanotechnology which is a carbon based [30]. This technology has already made way on creating good results in medical, codlings and sensors. As a sustainable application, nonmaterial is used to clean waste sites of hazardous content. Furthermore, carbon is an element that cannot be catalog as good or bad; in green engineering, the use of carbon becomes advantageous when it is combined with other elements to form chemicals compounds. Research is performed investigating chemical combinations carbon can assimilate. One other form in which carbon emissions can be control is carbon sequestration and it is mainly influenced by human

activity. Two clear examples of sequestration are protecting forest, woodlands, wetlands and keeping the soil in place [30]. There are certain guidelines that must be followed in order to comply with soil requirements.

Recently, humanity has developed various means of transportation such as water, air, railroad, and public transportation as going from riding a bicycle to ride the subway or boarding an airplane. According to Dorf [23], transportation has become so important into people's daily lives and activities. As an example, China has increased its motor vehicles population from 613, 000 in 1970 to 13 million in 2000. All this has been done looking forward on spending less money, in other words to minimize our economy and environmental components. This means on how it can also minimize our energy consumption, emissions, and as air and water quality. As the transportation efficiency is being optimized it still the fuel source as one of the most common modes of transportation. While transportation is being optimized, the need of time, capacity, energy efficiency, pollutions emissions, load factor, safety, reliability and availability had become one of the most important issues as a user of these resources. This means that to build a better transportation for the future, all these aspects have to be taken in consideration. Also, the government in various countries encourages the use of bicycles in urban cities as an extra option. Another clear example that has been revealed by the French Railways shows that a plane uses four times more energy than a TGV per passenger-kilometer, and a car 2.5 times more than a TGV [23]. Moreover, it has been proved that it is more efficient for people as community, the use of transportation in order to minimize economy and to reduce the usage of vehicles specially traditional mass transportation services in developing countries that help those who do not own an automobile; reduce congestion effects, pollutions, accidents and other negative effects.

2.5.4 Government

DfE has also made a considerable impact in government. Governments from countries like the United States and Australia are some examples of vast sustainable initiatives and research in the design area towards energy usage and waste reduction. Such initiatives are either carried out by the government itself or a particular institution, possibly a university funded by specific grants.

The U.S. General Service Administration has started to implement and mainly develop green building programs. The information regarding the sustainable initiative is provided by the "Sustainability Matters" program which has been around 30 years already. The GSA [31] has participated in developing healthy indoor air quality building protocols and programs involving the reduction of toxicity on cleaning products. The research done by the GSA involves a collaborative creativity method in which integration occurs at a global level starting with the client requirements which are addressed to the architect who analyzes the requirements in terms of building a place. Such requirements are then communicated to the contractor who performs an assessment in a cost wise approach. Now, all the information is transferred to the mechanical engineer who provides a preliminary analysis of the heat transfer process proposing a feasible solution in terms of energy saving and cooling-heating efficiency. Afterwards, information is then communicated once more to the contractor who calculates costs of the optimized solution. Finally, the electric utility representative is offered substantial rebates regarding the previously proposed changes.

The Australian government has also started important initiatives towards sustainable design. The Department of the Environment, Water, Heritage and the Arts is responsible for sustainable innovations. It is also responsible for the development of several research programs such as the National Environmental Research Program performed in the Commonwealth Environment Research Facilities focusing on biodiversity [32]. The program basically addresses environmental management and policy and decision making in both short term and in the future. It explores ecosystems function by analyzing their health, managing the resilience and investigating how to better take advantage from the markets to use them towards biodiversity protection.

It seems like the majority of the institutions, individuals and books explore a common type of research topic. Most research is done in the areas of Life Cycle Assessment, Green Design related to the use of technologies involving natural resources i.e. solar energy, wind energy, water treatment, etc., Energy Resource Management, and Global Project Assessment. However, there are some other areas or topics that have not been fully explored such as carbon and its applications like Nanotechnology of carbon sequestration for instance. There is current information describing the chemical behavior of

carbon and its effects on earth when is released by either a natural process or a human activity or when it is combined to another element. This element, if it is correctly investigated, can yield vast amounts of information as for applications in the sustainability section. The carbon element provides an extensive research area opportunity to develop sustainable measures.

2.6 The Design Process Influence

A well-developed product can be regarded as the result of the following the design process. The use of the design process is encouraged in order to have a desirable finished product. In the sustainability field, there are whole system design methodologies that incorporate sustainable practices into product development. Still, such methodologies lack of specific application guidelines and are generic in nature; this makes difficult their selection and use. A reason for this is that sustainable design is still evolving and it will take some time to be able to fully evaluate its application to the design process. On the other hand, engineers working in a company are required to utilize methodologies to carry out the product development process.

In numerous cases, the engineers tend to fixate on one/few methods even if there are additional methods available. This is often related to avoiding time-consuming methodologies or the ability to learn other design tools. All these aspects produce a lack of understanding on selecting an appropriate method during the design process. It is true that sustainability methods follow principles and guidelines, but the principles and guidelines to apply sustainability towards a product provide a "vague" description of methodologies raising the complexity of utilizing and successfully applying them. This in part complicates the application of the sustainable design principles on a product. Similar situation occurs with the selection of idea generation methods. In summary, there is a clear need for a tool to help a designer select an appropriate method without the need of extensive professional expertise. The objective of this research work is to introduce a sustainable expert system (SES) that engineering students can use to select methods while understanding the reasoning mechanism as part of their education process.

2.6.1 Design Education

Although there are several design methods and tools for idea generation, the majority are not known by educators or engineers hence there is a lack of knowledge for options. For example, a design engineer may use brainstorming for all occasions; there can be numerous reasons for this, some of them understandable. First, learning a new method may require some time, further, identifying which method is more appropriate to learn for the particular design problem can be difficult. The knowledge or expertise to identify which method(s) are most appropriate for each design problem, takes time to develop, and when considering multiple areas or disciplines in the design process, one can imagine the difficulty of becoming expert in more than one area (e.g. design quality, design creativity, sustainable design, etc.). Second, schools tend to provide curricula covering scientific-based courses rather than touching the design-based courses.

If design-related courses are offered, students can learn in a breadth fashion covering more options rather than sticking to just one option [33]. Third, engineering educators teach only selected design methods, this seems necessary due to the time and resources constraint. A typical dilemma for an engineering educator is which design methods to teach. If students are exposed to the bare minimum, there is a good chance that they will learn them. If students are presented with a variety of methods, there is a risk of becoming lost not knowing which one to use and how to successfully apply it. Probably the best approach is to achieve a balance when teaching engineering students by introducing an ordered variety of methods and a selection logic to navigate and select them; this can be part of a life-long learning approach were engineers learn how to learn new methods. It would be necessary for engineering educators to select a few methods to teach at some depth, but a two-pronged approach would allow the student to learn key methods and know how to select and learn other methods (i.e. get the fish and also the fishing rod). It is important to mention that most engineering classes taught in institutions tend to follow a traditional approach contradicting broad and integrated styles such as the design process [33]. The practice and application of engineering classes is needed to demonstrate the practical use of the knowledge transmitted during courses; otherwise students may not acquire the grasp of engineering practice.

2.7 ARTIFICIAL INTELLIGENCE

In order to develop a framework capable of using Artificial Intelligence (KR) to find the best design process for given parameters or situations, an expert system can be used. The expert system provides tools for mapping information provided by the user using an input with a database containing information that had been previously compiled. It will also be responsible for characterizing knowledge by identifying problems and methods, mapping them through a common database developed from the sustainable design methods. With this Sustainable expert system, the designer will be able to choose a design process based on a problem, status and conditions. The expert system, based on knowledge representation, can mainly be composed of elements such as Knowledge-Based Reasoning (KBR), Case-Based Reasoning (CBR), an entity relationship model and a Database Management System (DBMS). Knowledge-Based reasoning will be of use when characterizing methods and problems and representing knowledge in a manner easy to communicate to the user. Case-Based reasoning provides tools to solve problems based on previous cases. The new problem is potentially solved with solutions related to past problems, if the solution is not the most suitable one, it can be adapted. Lastly, the DBMS acts as the communicating element among all entities. The management system organizes information to coordinate the mapping and make data transfer efficient. All these elements are fundamental for a successful expert system and constitute the working structure of the framework.

2.7.1 Knowledge Representation

Knowledge representation is basically a tool that in general terms standardizes and integrates elements from a catalog to provide an abstract view of the real world [34]. A simple definition from the University of Oregon [35] states that KR studies how the knowledge related to the world can be presented and the types of reasoning that are linked to that knowledge. KR is also based on a logical reasoning using inferences to create relationships among structures of entities. In the expert system, KR plays an important role in communizing aspects in the design processes through transformations, decomposition, reconstruction, mapping and extraction [34]. According to Brachman [36], "While KR has almost always been thought of as the Heart of AI, for most of the field's history, it was nonetheless a backstage activity". KR has been evolving throughout the years to become a fundamental aspect for AI.

Researchers began to understand the nature and limitations of knowledge-based systems and realized that a common structure shares different task domains [36]. Same approach that would suit the necessities of the expert system mapping processes.

Another practical example for the use of KR is the design of complex electro-mechanical systems were several tasks with information continuously transforming function-behavior-form. On these complex systems, it is necessary to develop relationship models in order to successfully deliver information through all the different structures. The use of the KR approach allows the development of a representation schema that utilizes a specific vocabulary to create structures that narrow the integration flaws (i.e. gaps). The representation schema solves the variation problem of tasks and functions developing a common catalog with the purpose of standardizing and integrating [34]. Somehow, this approach can be used to solve the sustainable design processes problem. Currently, there are numerous processes to reduce environmental impact that can either be applied to the manufacturing process of a product or a modification in the product's composition (i.e. material, recycling content). Such processes, although well defined, cannot be simply used by an inexperienced designer even with considerable experience. The application of the guidelines and considerations to a product is sometimes vague to the designer since what is being specified is general for several other products. In addition, the environmental problems caused by the misuse of materials and processes become an issue when creating relationships with the guidelines and considerations. Environmental problems must be covered in a broad manner in order to accomplish a comprehensive assessment. By using Knowledge Representation, the problems and processes can be interrelated using a mapping system containing a common catalog with standardized process structures. This will allow the user to choose a design process that will provide the best output in terms of product design.

2.7.2 Case-Based Reasoning

Case-Based reasoning is another fundamental element for the adequate functioning of the expert system. The Georgia Institute of Technology, states that "Case-based reasoning means using old experiences to understand and solve new problems. In case-based reasoning, a reasoned remembers a previous situation similar to the current one and uses that to solve the new problem" [37]. In other

words, the intent of case-based reasoning is to try adapting old solutions to emerging problems by using reasoning in old cases to create a potential solution to a new problem. The problem solving tool can be formalized in four steps that describe the working structure to approach a problem [38]:

1. Retrieve. Past cases from memory including problem, solution and annotation
2. Reuse. Perform mapping of a solution targeting a problem. Adapting solution may be required
3. Revise. Validate solution by testing it in real world
4. Retain. Record results from the validation and stores the results as a new case in memory

In a paper written by Aamodt and Plaza [38], the Case-Based reasoning process starts with defining a framework in which all subsequent descriptions and discussions will refer to. Such framework is to be influenced by newly developed methodologies related to knowledge level descriptions. The paper named Case-Based Reasoning: Foundational Issues, and System Approaches states that CBR does not solely rely on general knowledge from a problem domain, or in associating relationships in a generalized nature among problem descriptions and conclusions to solve problems [38]. It rather uses past knowledge from previous cases to develop a solution for a new problem using concrete validated information. The paper also mentions that CBR is a sustained lifelong learning tool since it is constantly recording and retaining solutions utilized to solve problems every time CBR is used. "Learning in CBR occurs as a natural byproduct of problem solving" [38]. When the output of a solution to a problem is successful, that solution is retained as reference to solve future problems. If the solution output is not as desired, the reason causing the failure is retained to avoid similar situation on future cases.

Methodological Variations Case-based reasoning will be used in the expert system as a database for guidelines and considerations that have already been stored in previous design changes or new product designs. Although design for sustainability is a discipline that has not been around for a long time, several schools and governmental institutions have started performing sustainable measures (i.e. conferences, guidelines) to reduce depletion of natural resources. There are available records of designers implementing successful sustainability changes. For this particular case, the sustainable expert

system will contain a database with past cases in which the guidelines and processes have already been applied to a manufacturing process of product. The database will employ the four steps of the working structure acting as a living recording system. This database is to be linked to the knowledge representation schema permitting the mapping of emerging problems with past cases enhancing the problem solving methodology.

2.7.3 Database Management Systems

Any expert system needs an organized way to manage information exchange with precision and speed. The way to accomplish such task is called Database Management System (DBMS). The DBMS is computer software that processes large mainframes of data collection called databases. DBMS have been constantly used since the emergence of minicomputers and microcomputers. According to Gorman [39], such computer programs are widely used on any domain in need of a database for instance, medical, industrial, government, financial, personnel, educational, and engineering. In addition, Gorman also refers to databases as a concept of organization using clarity and precision [39]. An expert system needs a manner to interconnect past research, present investigation and future work to an actual requirement. A database contains vast amounts of information from knowledge; however, mapping is needed in order to link such data to a system. In order for DBMS to be successful, they are executed and operated, "…success is impossible without the codification of and adherence to data semantics, which are rules for meaning, validity and usage. DBMS utilize an ISO reference model that provides a framework of common basis for the coordination of standards development. By itself, the reference model specifies services available from the DBMS which are the following [39]:

- **Dictionary Definition:** the specification of the types of data that an organization requires in its dictionary system. This provides the schema for the dictionary database, referred to as the dictionary schema.
- **Dictionary Use:** the storage and retrieval of dictionary data relating to all aspects of other information systems with special dictionary capabilities, such as keeping several versions of data. The dictionary database includes the data definitions for application databases.

- **Application Schema Definition:** the specification of the schema in the form appropriate to the DBMS. Depending on support for the DBMS provided by an IRDS, the dictionary system may provide the schema based on its data description.
- **Application Database Use:** the storage and retrieval of data from an arbitrary database structure.
- **Database Creation:** the establishment of a database.
- **Database Maintenance:** the changes to a database required as a result of changes to its schema.

These services compromise the framework in which the DBMS operates. The framework is also responsible for coordinating the development of existing and future standards. In addition to the services, the reference model also describes 4 fundamental common levels or representation that must exist on a DBMS [39]:

- Fundamental
- Dictionary Definition
- Dictionary
- Application

For the DBMS to be comprehensive, all these four data levels must be present along with their level pairs. The fundamental level defines the elements of Information Resource Dictionary System (IRDS) in terms of its schema and associated data, editing, and validation rules required to determine the IRDS. Dictionary definition level is utilized to characterize the data store within the data dictionary and its structures. The instances at this level are defined as data record, data record element, and relationship. Secondly, after the establishment of the IRDS, individual databases containing own schemas, data editing and validation rules come into existence. The elements just mentioned are to represent and serve all data in the database. It can be stated that at this level, individual data models exist. The dictionary level is utilized to validate the received requests with the data record elements names making sure they are well referenced. The application level arises whenever the database begins to exist. A database may have applications functioning and serving different purposes through the programming of dissimilar languages. Each of these applications, having own schematics of data, provide sets of data along with edition and validation rules controlling services demanded by the application [39]. To resume, DBMS

provide a framework that supports and manages data at different levels utilizing services for the coordination and development of data structures.

Chapter 3: State of the Art

Nowadays, as product quality constrains become more rigid, the use of methodological strategies as for product development is a reality. The design process as well as other methods is being used by designers to improve product quality meeting customer requirements. In order to develop a project having an impacting relevance, certain guidelines and approaches must be followed in order to generate quality ideas. At a glance, there are no defined processes regarding ideation methods except for the ones investigated in the marketing field which already have a framework on how to pursue opportunities and find needs. In the sustainability discipline, there are resources available that aid in the development of ideas to generate successful projects. Among others, current ideation design methods can be combined with available resources with the purpose of creating a device to perform a sustainable task. Some of the established ideation methods include Brainstorming, the Delphi method, asking experts on the field, etc.

Sustainable ideation methods include investigating books related to design for sustainability providing information regarding current projects on minimizing resource consumption, selecting low impact resources and processes, product lifetime optimization, extending the lifespan of materials, facilitating disassembly and system design for eco-efficiency [10]. Other sources to search ideas include looking at news, for instance the CNN or the Environmental Protection Agency, searching for conferences investigating developed projects, finding current projects developed on Universities and other institutions and find out what other organizations have been done to mitigate pollution. This section will illustrate of the various available methods on the engineering domain dealing with design method selection and design for sustainability. An expert system is proposed to tackle sustainable design method selection, although there are available expert systems for other applications, an expert system being that specific could not be found.

3.1 Design Method Selection

Design methods used on the early stages of a design are a fundamental part of the development of a product in order to successfully meet customer requirements. Authors have generated design tools that can help designers improving their products quality while gaining knowledge in that field. However,

their selection is a part of the design process that has not been fully defined. There is established manner as to choose a design method; there is a world of different ways on how to choose a design method.

3.1.1 Current trends

The selection of design methods has made its way through engineering design by means of research work in countless areas. One example is the Visualization Platforms for Conceptual Design. In this research work Opiyo identifies visualization platforms for conceptual design by assessing different platforms through questionnaires, a survey and an expert evaluation [40]. Visualization platforms are mainly elements of visual imagery that aids designers to better understand 2D models or 3D models displayed on a flat panel. Opiyo [40] also states that 3D visualization has been created to further explore the features and ergonomics of designs while simulating its use. In order to conduct a visualization platform selection, the author performs a literature review and finds tasks that need to be accomplished. Then, the platforms were characterized by type and compared to the tasks using Boolean rules. Then, results along with tests subjects were used to conduct a questionnaire asking subjects to find the most suitable visualization platforms according to the task. Finally, experts were utilized in order to perform a similar task.

Another approach to select appropriate design methods is the observation, annotation and analysis proposed by Rasoulifar [41]. Observation can represent a holistic view of the designer and its relationship to elements such as artifacts, socio-cultural context and designer communication. The main technique used here is the video in which human-machine interactions along with argumentation analysis is captured. Then, researches are subjected to analyze and provide comments using pen and paper. Annotation is possible through a series of available software packages that incorporate audio and video. Lastly, information is analyzed and compared to certain criterion and results are provided to the user. These are two different examples in which an approach is taken as to select a method following a procedure. The two papers show that, as for selection methodology, none follow established guidelines. On the contrary, they both propose different approaches to tackle method selection.

3.2 SUSTAINABLE METHOD SELECTION

In the sustainability field, several researchers have developed methods to generate ideas; however, it is difficult to find information regarding the selection of sustainable design methods. Nonetheless, extensive research has been done in the field of material selection and this subject is well known in the sustainability field.

The CES Edupack software provides tools for selecting a material following certain parameters. Selection of materials involves seeking the best match between design requirements and the properties of the materials that might be used to make the product. The strategy of the selection is first listing the requirements that the material must meet, expressed as constraints and objectives [42]. The design requirements for a component of a product specify what it should do but not what properties its materials should have. So the first step is one of translation: converting the design requirements into constraints and objectives that can be applied to the materials database [42].

The next task is that of screening, eliminating the materials that cannot meet the constraints. This is followed by the ranking step, ordering the survivors by their ability to meet a criterion of excellence, such as that of minimizing cost, embodied energy, or carbon footprint. The final task is to explore the most promising candidates in depth, examining how they are used at present, case histories of failures, and how best to design with them, the step called documentation [42]. Although the main element involved in the selection process is a material, the approach taken by Ashby is similar to one for a method selection. The selection project, provided by this software, requires input by the user through three selection stages; the example window is shown in figure 3.1:

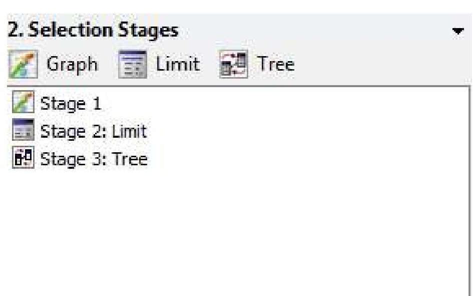

Figure 3.1: Selection stages

It also provides a comprehensive database of materials and processes that can be used towards the selection process. Each material and process has a description followed by attributes and properties including eco-properties.

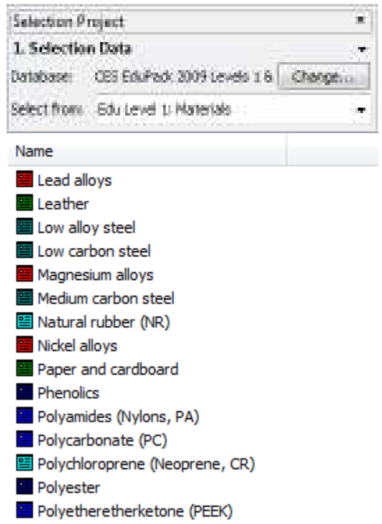

Figure 3.2: Material’s database

The first selection stage is the graph method in which a comparison or parameters is made by specifying category and attribute. In this graph, lines with a slope can be drawn according to desired values on the axes and matching materials can be found. Figure 3.3 shows and example of a graph:

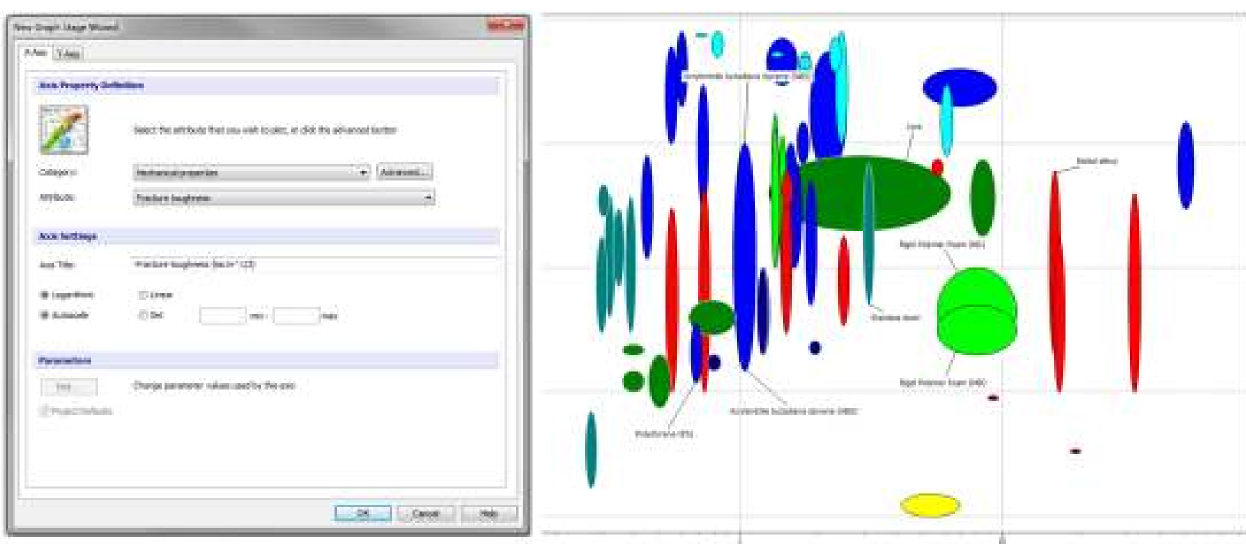

Figure 3.3: Sample graph

Second selection phase is the limit stage. Categories of materials can be narrowed down by defining Min Max properties. Some of the fields include general, mechanical, and thermal properties. After a value has been placed on the tables, the software tool filters out materials on the database that comply with the parameters. Figure 3.4 shows an example of the limit window:

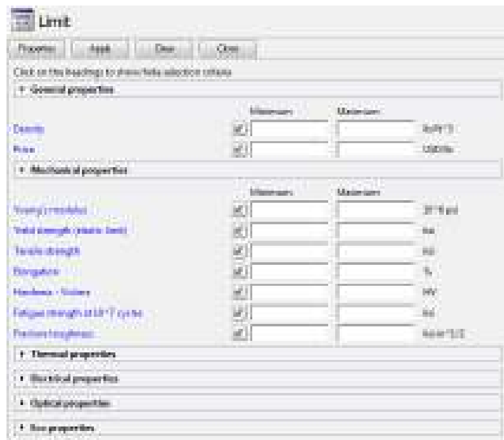

Figure 3.4: The limit stage

The third selection phase is the tree stage which is mainly used to narrow the search into the desired category. If a category is selected, all selections will be done within that category, it basically simplifies the search for a material of process. The software automatically filters only the materials that fall within that group.

Figure 3.5: The tree stage

All three stages can be combined to further narrow the filtering process. This tool could be compared to a design method selection application if the materials were changed to design methods. Through the filtering process, the user can input data and obtain an outcome based on the information provided. This is the basis of the proposed expert system.

3.3 CURRENT EXPERT SYSTEMS

Artificial intelligence is a branch from software engineering that is directly related to the development of robotic devices and other intelligent software applications. As of now, artificial intelligence has been known to "give life" to unanimated electronic devices. The applications of artificial intelligence range from language translation systems, intelligent highways all the way to air traffic control systems [43]. By definition, artificial intelligence is a discipline that entails the design and study of programming that behaves intelligently. Such programs are created with the intention of behaving the same manner an intelligent human or animal would behave [43]. This branch of software engineering provides the decision-taking ability to machines after a reasoning of some kind has been done. Some of the advantages of implementing artificial intelligence are aiding humans in taking decisions, exploring information and controlling objects of complex nature by executing flawless numerical calculations and processing considerable amounts of information [44].

One application of interest from artificial intelligence is the expert system. Boden [45] defines the expert system as knowledge acquired from human experts utilized to develop problem solvers. The expert system does have problem-solver tools available within the framework; however, it needs human knowledge attained from personal experiences. Negnevitsky states that in order for an intelligent system to be built, expert human knowledge needs to be compiled, organized and employed on some specific area of expertise [44]. This implies that the expert system significantly depends in human knowledge to successfully operate.

The intended use for the expert system is to make decisions based on an input and provide a recommended design process including enhancing tools as an output. An expert system by definition is a computer program derived from Artificial Intelligence that takes reasoning and knowledge from humans and converts it to an intelligent engine following logical reasoning and capable of solving problems [46].

Since the invention of expert systems, thousands of applications have become a reality thanks to the features and functionality provided by this engine. The majority of the expert systems developed so far have been built for software applications even though expert systems are now becoming fundamental in other applications such as design method selection which is the research subject of this thesis work.

One example of an expert system used to select methods is proposed by Shindy et al. on the paper Development of an expert system for EOR (enhanced oil recovery) method selection [47]. The EOR methods are expected to be utilized on some of the Egyptian oil fields somewhere in the future. The expert system is developed from human expertise and outcomes of previous applications regarding oil recovery methods. This paper also states that the basis of the expert system is the knowledge-based reasoning and that it was developed in three stages being data acquisition, system formulation and system verification. The first stage is a literature review of successful oil recovery projects and a production of rules related to the formulation of the expert system. Secondly, rules are transformed into logical information using a computer. Finally, the system is subjected to verification and validation stage in which the functionality is tested by proposing strategies and the relevant information to mitigate any potential problem with the enhanced oil recovery [47].

Dominic is a clear example of an expert system developed in the design domain. This program, whose main function is the design process, decomposes problems into sub problems until the complexity has been reduced to a minimum [48]. Then, iterative redesign is used to solve the decomposed problems. Figure 3.6 illustrates the framework in which Dominic was built:

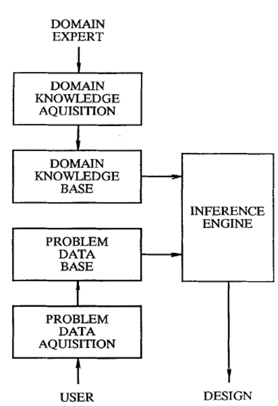

Figure 3.6: Dominic's Architecture

In essence, iterative processes are the main working structure of the software. The decomposition of the problems into sub problems, which is before a design solution is proposed, is also an iterative process. Dominic's architecture is built both on user's knowledge and expert domain knowledge. First a database is created compiling knowledge from experts using an acquisition module. Specific information regarding problem needing solving comes from the user as an input. These two are input to the inference engine which provides a design as an end result. After a design has been proposed by the program, there is a feedback process in which design is analyzed and improved in terms of performance. This iterative process ends whenever the design performance is acceptable through analysis and improvement being the last step of the design selection process [48]. Dominic is a similar approach to the proposed sustainable expert system since it is built on a knowledge-based reasoning and it requires data from the user in order to operate. It also utilizes elements such as databases which are common to the proposed expert system. Researchers have developed expert systems for several applications but it is difficult to find one similar and specific to the proposed sustainable expert system.

Bellatreche et al. propose an expert system named SimulPh.D or Database Designer (DBD) that is related to physical design and database management systems [49]. The designing of DBD requires four phases in order to successfully build the software tool. Phases are conceptual, logical, physical and tuning. During the conceptual phase, a conceptual model is defined and is converted into a logical model using rules. Furthermore, the physical phase takes the logical model and presents it to the user in order to be operated. All phases are interrelated since they depend on the inputs and outputs of each one. The purpose of the expert system is to facilitate the selection of optimization techniques including the selection of modes and selection of algorithms. In other words, this tool is intended to help designers on improving their design selection while increasing their choices as for methods.

Although there are numerous applications and well established expert systems it is difficult to find an application specific for selecting sustainable design methods. What is more is the fact that researchers do develop idea generation methods for instance; however, selection method tools are still a research area that needs improvement.

Chapter 4: Proposed Solution

With all the known functionality and features provided by Artificial Intelligence, a SES is proposed to tackle our current design selection method problems. The proposed expert system is intended to record data regarding methodologies and provide the user with a recommended design method according to the user's input. For this specific application, a knowledge-based expert system suits the need for qualitative data rather than quantitative data. Furthermore, the reason is related to expert system designers trying to portray the expertise of an experienced individual by understanding the nature of the subject rather than the quantitative formalization [45]. In other words, due to the nature of the sustainability topic, the knowledge-based type expert system can provide means to facilitate the design selection process while reducing time and improving accuracy. The following sections will explain the approach and expected outcomes of the software tool.

4.1 APPROACH

The following figure illustrates the approach for the SES framework; it is divided in 3 phases covering the conceptual, logical and physical aspects:

Figure 4.1: The expert system framework

The three described phases can also be referred as layers. Compared to the Database Designer on the state of the art section, all three layers are required to build and validate the software tool. Layer one, being the conceptual phase, deals with the conceptualization and characterization of methodologies, including principles, guidelines and tools. In this phase, tables with relationships are created and a conceptual map is generated as a result. Layer two takes a software engineer approach to convert all conceptual information into logical information. During the development of this phase, the conceptual model is transformed into an entity relationship model defining cardinality and relationship type. On the last layer, databases are created and standard query language (SQL) is utilized to extract information using simple commands. In this last phase the SES is created and tested using mechanical engineering students.

4.2 METHODOLOGIES AND RELATIONSHIPS

In order to fully understand the context of how an expert system works, the principles and tools utilized to incorporate sustainable measures must be explained. The intended use of the guidelines and tools find place in the decision phase of the design process. This is where the methodology or/and tool is utilized to make a pronounced impact on later phases of the product life cycle. Of course, there are sustainable methodologies available that apply after designing the product on the life cycle process such as manufacturing, distribution, or disposal tools, conversely, research work only focus on design decisions. As shown in figure 4.2, DfE methodologies exist for every step in the product life cycle process, the focus of this research is on methodologies that can be applied during the design process (although decisions made during the design process directly affect later stages of the product life cycle).

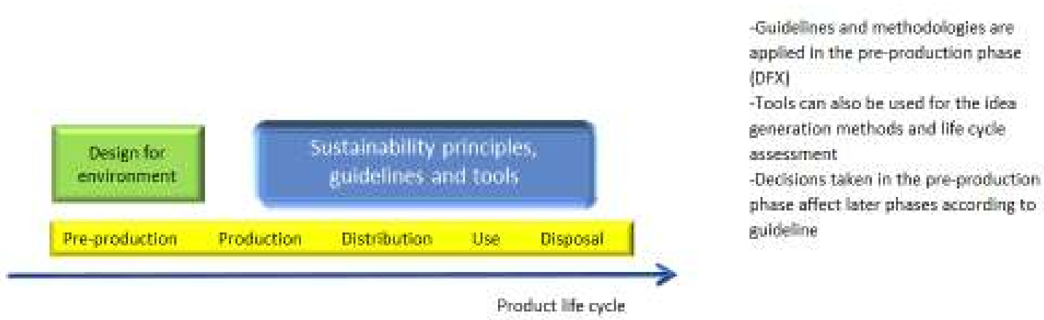

Figure 4.2: Product life cycle and sustainable design tools

The development of the SES is composed by the characterization of problems, guidelines and tools with the purpose of finding the appropriate methodology for the user. By following a conceptual map, all guidelines and tools are catalogued into matrices with the purpose of finding relationships and providing the suitable methodology. Main relationships have been discovered from the characterization of principles and tools. Figure 4.3 shows that there are direct relationships between objectives-principles, principles-tools and design process-tools. This is the basis for finding appropriate tools during the decision process.

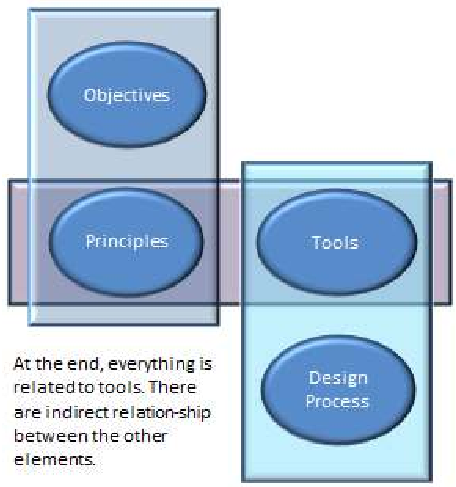

Figure 4.3: Relationships among variables

Principles and tools are the elements with the most relationships. In this diagram, principles are used to illustrate the relationship; guidelines derived from principles are also related to the other elements. These will be identified as pivots later on when the conceptual model is generated.

4.3 EXPECTED OUTCOMES

By using the SES, the user should be able to obtain a recommended design method either a guideline or tool. An input is required from the user which is obtained by answering questions provided on a sequence. The following picture describes the reasoning of the sustainable expert system including the sequence in which design methodologies are obtained:

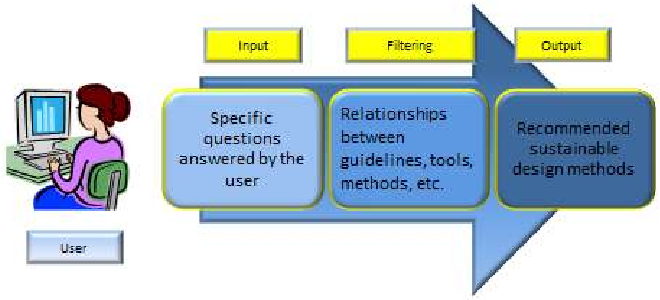

Figure 4.4: SES approach

Figure 4.4 depicts the working structure of the expert system. The first step is the user input which is identifying objectives and design process by asking strategic questions. Questions used for this sustainable expert system can be the following:

- What is your design objective?
- What product life cycle would you impact?
- What is your approach?
- Where are you in the design process?
- What type of methodology would you choose?

Such questions are intended to identify potential answers according to the user's input. There is an order or sequence to ask such questions and all questions must be answered in order to obtain an output. The outcome of the sustainable expert system will depend on how detailed data is provided by the user. It is important to mention that due to the nature of the tables and relationships an answer may not be provided by the software tool in a number of cases. Secondly, having the user's input, the filtering process takes place on the characterized information. In this step, relationships are created among all principles, guidelines, and tools. Lastly, the outcome of the SES is acquired by obtaining a recommended a design methodology. The SES development section will give an overview of the three layers describing the functionality of the expert system.

Chapter 5: Expert System Development

Sustainable design methods and tools are relatively recent and its use in the design process has not become popular. Ideally, an expert engineer is expected to select an appropriate method depending on the design situation. Principles, guidelines, idea generation tools and the expert system framework are elements needed to build an expert system for the sustainable design method selection shown in figure 5.1:

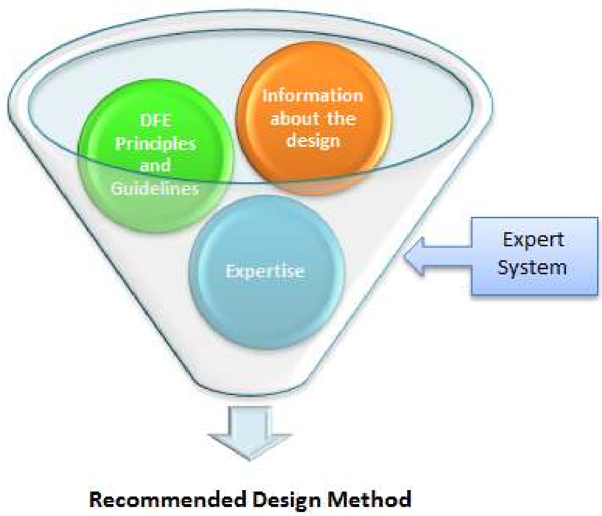

Figure 5.1: Sustainable Design Method Approach

The basic concept is to characterize design for environment principles, guidelines and tools to incorporate them to the expert system framework. The system will combine expertise, information regarding the affected design and DfE methodologies to provide a recommended design method. This section will describe and explain the SES development and the description of the final product.

5.1 THE DESIGN PROCESS

The design process has become a fundamental aspect required to attain a desirable output in terms of quality and functionality when developing a product. According to Ulrich [50], "A product development process is the sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product." Same principle applies to the design process which is used to build a product by generating ideas and concepts according to customer specifications. The design process

described in the book Engineering Design [51] is covered in 4 main phases being the planning and task clarification, conceptual design, embodiment design and detail design. During the conceptual design phase, ideas must be generated in order to conceive a product in which the idea generation methods come into play.

Within the design process, design methods have been developed in order to aid in the generation of ideas for concept development. Concept generation methods have considerably gained attention to become key players in the design process regarding the idea generation approach [52]. Such methods have evolved throughout history from being utilized to generate vague ideas under brainstorming to more developed formal methods like morphological matrices, 6-3-5/C-sketch and TRIZ [52].

5.2 CONCEPTUAL LAYER

The development of a knowledge based expert system requires conceptualization of data in a manner that can be entered into a database management system. In the sustainability discipline, there are thousands of principles and guidelines available from several authors that present them in different groups. There are also several assessment and ideation tools available for designers to improve product quality. To accomplish the characterization of methodologies, criteria related to the potential applications and characteristics of each methodology had to be established [20]. Once established, tables having relationships among methodologies were constructed.

5.2.1 Relationships

The conceptual model was built from the iterations among all elements involved in the selection process. There is at least one connection among all entities involved in the selection process. This is due to the fact that each entity is related by means of a table. Each arrow represents a table that characterizes each entity according to certain properties. There are a total of ten relationships for this model; each relationship represents a relational table. The explanation of the ten relationships is as follows. Only a segment of each table will be shown for simplicity purposes:

R1: Type of Methodology vs. Techniques and Tools and R2: Design process vs. Techniques and Tools

These relationships are related to the design for X principles which consider decision making when initiating the design process and it is usually a downstream impact [53]. Left column represents design process stages recommended by Pahl and Beitz [51] and the right column represents techniques and tools provided by Bhamra [3]. Techniques and tools have been grouped to their type of methodology and catalogued according to the applicable design process stage. Meaning of the acronyms can be found in table 2 which shows categorization of techniques and tools.

Table 5.1: Sample R1 and R2

Design process	Techniques and Tools		
	Environmental Assessment	Strategic Design	Idea generation
Task	LCA, MET	DA, FFA	FM
Requirements list	LCA	EDW, FFA	FM
Principle solution	MET	EDW, SRT	II, FM, CT
Preliminary layout	ECO	SRT	II, FM, CT
Definitive layout	ECO		FM
Product documentation		DA	FM

R3: Principles vs. Techniques and Tools

This relationship is related to the characterization of principles – techniques and methods, similar to table 3. Left column shows the five main principles from Vezzoli [10] and, again, techniques and tools by Bhamra [3].

Table 5.2: Sample R3

Principles	Techniques and Tools		
	Environmental Assessment	Strategic Design	Idea generation
Minimizing resource consumption	LCA, MET, ECO	EDW, DA, FFA, SRT	II, CT
Selecting low impact resources and processes	LCA, MET	EDW, FFA, SRT	CT
Product lifetime optimization		EDW, FFA, SRT	FM. CT
Extending the lifespan of materials	LCA	EDW, DA, FFA, SRT	II, FM, CT
Facilitating disassembly	MET, ECO	EDW, DA, FFA	FM, CT

R4: Principles vs. Objectives

Principles can be catalogued relating them to criteria. Authors propose groups of objectives in order to facilitate the organization of principles. Left column shows principles by Vezzoli [10] and right column describes objectives to applicable principles.

Table 5.3: Sample R4

Principles	Objectives: Extend Usage	Transportation costs	Recyclability
Minimizing resource consumption		x	
Selecting low impact resources and processes			x
Product lifetime optimization	x		
Extending the lifespan of materials		x	x
Facilitating disassembly	x		x

R5: Sub-principles vs. Objectives

Table 6 shows sub-principles from Vezzoli [10] against applicable proposed objectives.

Table 5.4: Sample R5

Sub-Principles	Objectives: Extend Usage	Reduce material usage	Reduce maintenance costs
Design for appropiate lifespan	x		
Design for reliability	x		
Design for upgrading and adaptability		x	
Facilitating maintenance			x
Facilitating repair			x
Facilitating reuse	x		
Facilitating remanufacture		x	
Intensify reuse	x	x	

R6: Life Cycle Impact vs. Sub-principles and R7: Principles vs. Sub-principles

Athalye et al. reports that most commonly employed methods such as guidelines focus on impacting life-cycle stages [54], table 7 shows an example of categorization including principles, sub-principles and the impacting life cycle stage being pre-production, production, distribution, use and disposal.

Table 5.5: Sample R6

Principle	Sub-Principles	Life Cycle Phase: *Pre-production*	*Production*	*Distribution*
Selecting low impact resources and processes	Select non-toxic and harmless materials		X	
	Select non-toxic and harmless resources	X	X	X
	Select renewable and bio-compatible materials			
	Select renewable and bio-compatible resources	X		

R8: Approach vs. Sub-principles, R9: Guidelines vs. Sub-principles and R10: Approach vs. Guidelines

Show a correlation between sub-principles, guidelines and proposed criteria. Sub-principles and guidelines are provided by Vezzoli [10]. Left column represents sub-principles while the right column shows guidelines correlated to proposed criteria according to their description.

Table 5.6: Sample R8, R9 and R10

Sub principle	Approach	
	Reduce material	Product specification (Geometry)
Minimizing Material Content	Avoid over-sized dimensions	Dematerialize the product or some of its components
	Reduce thickness	Apply ribbed structures to increase structural stiffness

Whenever an input is received from the user; the expert system maps through the tables finding guidelines and tools. The qualifying methodologies are then located and provided to the user. In some tables, there is a need to compare methodologies with the purpose of identifying which methodology applies for both criteria. This is the case for relationships one, two and three for finding tools and techniques and relationship eight, nine and ten for finding guidelines.

5.2.2 Entities

The entity relationship model shown in figure 5.2 is composed of nine entities. Moreover, some of the entities are defined as inputs and outputs while there is also the presence of pivots (i.e. principles that help connect different entities in the model). The entities were established as a result of analyzing available literature. Additionally, some of the entities were defined by the authors; it is possible for entities to be defined in other ways. Each input entity represents a question made to the user. Questions asked to the user are the following:

- What is your design objective?
- What life cycle stage would you impact?
- Where are you in the design process?
- What is your desired approach?
- What type of methodology would you choose?

An example of what can be presented is shown by figure 5.2. Choosing an objective such as extend usage or lower environmental impact or selecting an approach the sustainable expert system could provide a recommended methodology or tool once the selection and mapping process has been completed. It is intended for the system to propose at least one guideline and one tool or technique once

the input has been given. Finally, pivot entities were defined as such since all relationships between inputs/outputs are related by these entities. In other words, each input, no matter where it starts will constantly pass through the principle and sub-principle entities.

5.2.3 Conceptual Model Development

The first step on the developing of the conceptual model and the conceptualization was to create a correlation between the five main principles proposed by Vezzoli [10] and objectives related to the principles. Next, similar conceptualization was applied to the techniques and tools proposed by Bhamra [3]. At first, these characterizations seemed unconnected. It was though a trial and error approach and learning at each step that the different elements seem to relate. These were identified as pivots in the entity relationship diagram. As it is depicted in figure 5.2, the breakthrough came when principles and sub-principles were identified as common linking elements between the different entities in a sequential and trial and error approach. Other entities such as objectives, approach, guidelines, etc., were connected. Every relationship implied an analysis of two lists, for example, objectives and principles to define the relationships between the elements of those two lists.

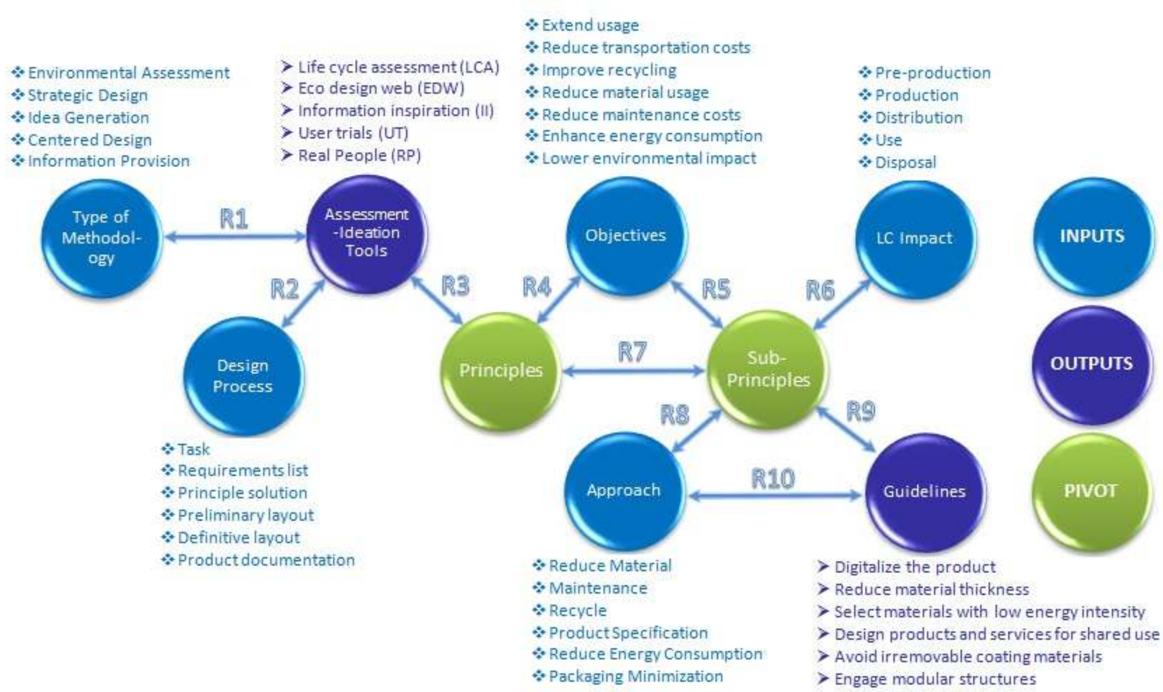

Figure 5.2: Conceptual model

Following the model in figure 5.2, it can be seen that some entities act as inputs and some as outputs. The inputs refer directly to specific questions, such as what is the objective? Or what stage in the decision process are you? The outputs are the outcome of the expert system; tools or techniques or both and guidelines recommended to the user. Questions were proposed as a form of input due to the fact that these can often lead to a greener product when such are made in the product development process [54].

In principle, it is possible for the user to define one or more of the inputs; the output will depend on how the inputs are defined and the relationships between the entities, it is expected that the sustainable expert system outcome be proportional to the number of input constraints, this means that it is possible to have several recommendations or none at all. A balance should be recommended to the user for effective recommendations. It is important to mention that for this model, users can define one or more inputs as desired.

5.3 LOGICAL LAYER

5.3.1 Entity Relationship Diagram

In this phase of the expert system development, the conceptual map is transformed into an entity relationship model. According to Dietrich, "The goal of a conceptual data model is to capture the constrains of the enterprise at a higher level of abstraction than the level of implementation" [55]. The Entity Relationship (ER) model, utilizing a graphical notation, is used to represent the enterprise constrains. The ER can have numerous elements depending on the situation; the one generated for the sustainable expert system is mainly composed by the following elements [55]:

- Entities
- Attributes
- Relationships
- Cardinality ratios
- Participation constrains

Entities on the ER model have characteristics called attributes represented by the ovals connected to the entities. Relationships between entities are represented by the ovals and they usually

have a verb that describes the type of relationship. Cardinality ratios define constrains regarding the times an entity can be involved in a relationship, these can be one to one (1:1), many to many (M:N),and one to many (1:N) or vice versa. Participation constrains state whether an entity does or does not need to participate in a relationship and it is represented by a single and double line. Double line represents an entity that must participate in the relationship while a single line represents a partial participation. The following figure illustrates the ER model for the sustainable expert system:

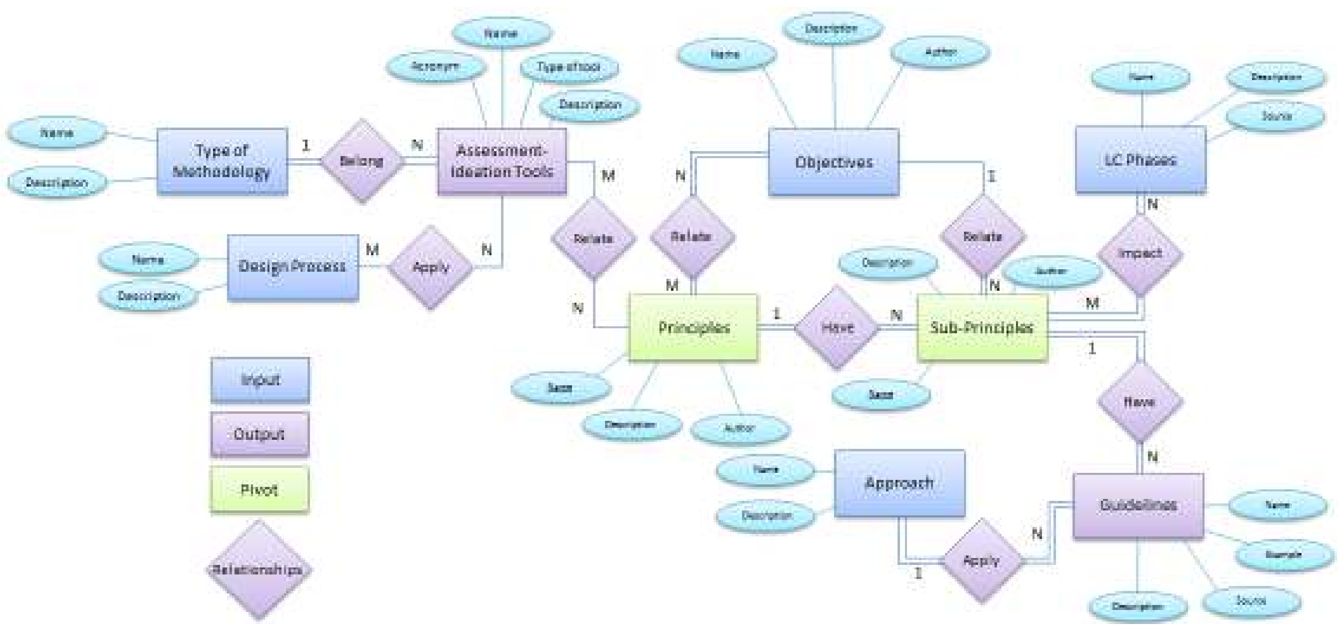

Figure 5.3: Entity relationship model

Figure 5.3 depicts the logical reasoning of the sustainable expert system. As previously stated, this diagram is acquired from transforming the conceptual model into a logical basis. The legend on the lower left hand side illustrates which entity is an input, output or pivot while indicating the relationships using the diamond. The purpose of this diagram is to facilitate data extraction from the query engine by creating relationships in the relational databases. This process will be explained in the following sections.

5.3.2 Standard Query Language (SQL)

In order to retrieve data contained within the databases, common standard query language (SQL) was used. SQL is a declarative language that provides tools to retrieve data by means of the mapping an

expression to an equivalent algebra expression [55]. Following the guidelines on the W3Schools website [56], syntax was developed to extract information from the databases any time the software receives an input from the user. The following is an example of one of the commands used in the expert system:

"select Tool_id from dp_vs_tools where Desing_process_name =(" + Label36.Text + ") and Methodology =(" + Label33.Text + ")"

SQL commands were created for every single situation in which the user has options of selecting different entities. All these commands were placed into debugging software to allow the software tool to extract data from the databases.

5.4 PHYSICAL LAYER

In the physical layer, the conceptual and logical layers are converted into tangible elements. In other words, software applications are utilized to develop the sustainable expert system.

The phpMyAdmin software tool was utilized to create databases using the conceptual data. It is a free software tool that provides means to administrate data through the development of databases including features to export and import data using the SQL syntaxes [57]. All information from the tables was inserted into this application yielding a database called expert system which can be illustrated by figure 5.4:

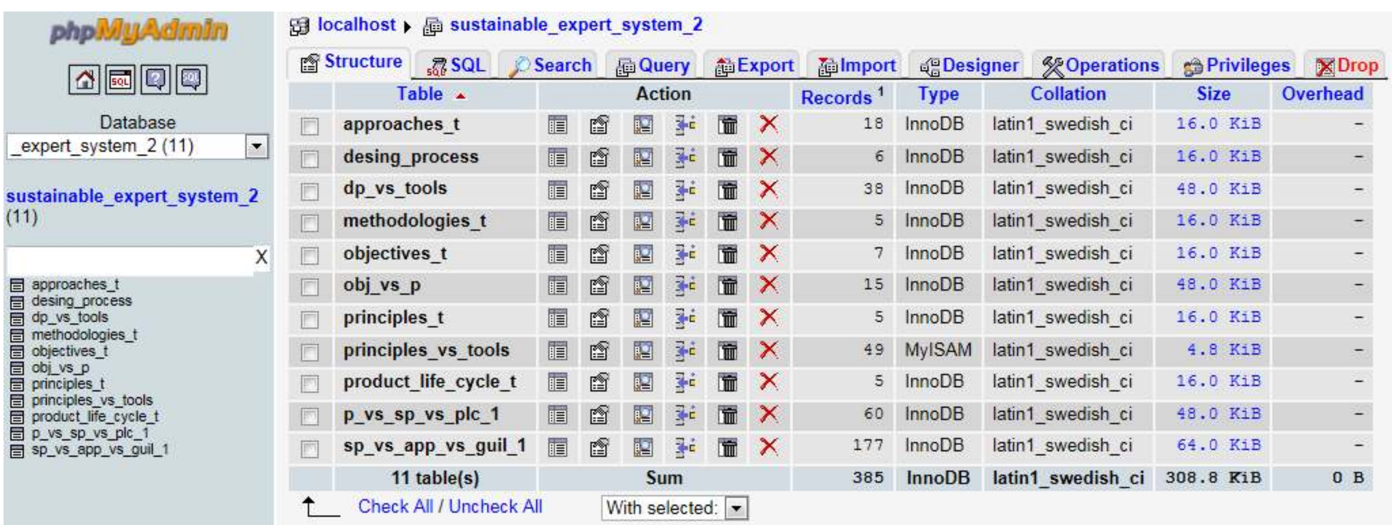

Figure 5.4: phpMyAdmin application

The right hand side of the figure shows every single table created for the sustainable expert system. To create this database, data derived from the tables was used to create tables in the form of table 5.7. This is the same information as in the conceptual layer tables; however, structure had to be modified in order to allow SQL communication.

Table 5.7: Approaches table in phpMyAdmin

Approaches_id	Approaches_name	Description
C	Cleaning	Design product with features facilitating cleaning...
DRC	Diminish resource consumption	Design product to consume less resources in the us...
EPU	Extend product usage	Modify or implement features on products to extend...
ERS	Energy resource selection	Device product to utilize alternate energy sources...
EU	Enhance use	Improve product use by following the user's enviro...
M	Maintenance	Design product with features facilitating maintena...
MS	Material selection	Select materials with low environmental impact
PM	Packaging minimization	Reduce material usage on packaging
PSDI	Product specification (Design intent)	Define design strategies to implement sustainable ...
PSF	Product specification (Features)	Define product's features on specifications
PSG	Product specification (Geometry)	Modify the product's geometry to comply with a spe...
PSS	Product specification (Standard)	Define sustainable product requirements on specifi...
R	Recycle	Implement strategies to enhance recycling properti...
RDC	Reduce design complexity	Include less components on the assembly
REC	Reduce energy consumption	Improve energy consumption features on product to ...
RM	Reduce material	Minimize amount of material content used in a desi...
SHFS	Substitute hardware for software	Add features to the product replacing material usa...
UF	Upgrading features	Design products to be upgradable, extending lifesp...

A total of eleven tables were generated and all these tables were connected to the debugging software through an ODBC connector utilized to connect the databases to the debugging program. Finally, in order to create a graphical user interface that would cross reference data to a user's input, the Visual Studio software was used. Visual studio is a software application that allows designing and deploying windows-based applications through the use of codes [58].

This software tool is what most computer programs are made of. There are other available programs that aid in the design of graphical user interfaces but this program was chosen because of the capabilities and ease of use. Using the Visual Studio Application, the interface was created. Although the SES program was developed with the necessary interface elements, fancy features could not be incorporated because of time constrains. Figure 5.5 illustrates a screenshot of the application including commands and codes derived from the development of the sustainable expert system:

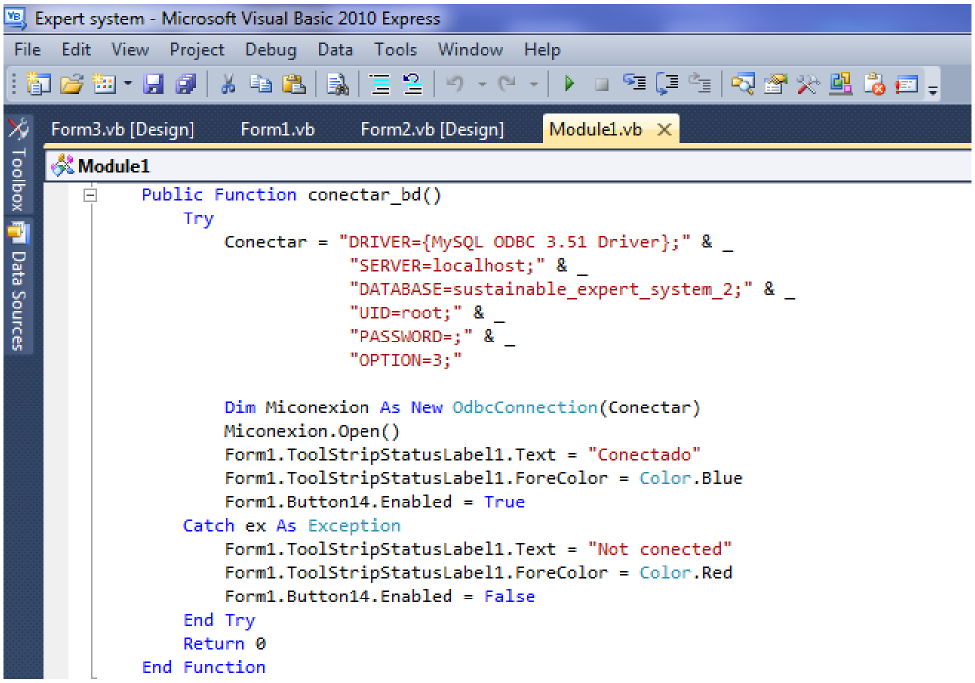

Figure 5.5: Visual Studio code

This tool along with the phpMyAdmin and the ODBC connector made possible the development of an expert system providing a graphical user interface with features that will be explained in the following section.

5.5 Description Of The Final Product

Throughout the development of the three layers, conceptual, logical and physical, a final software tool was obtained. The final product is a program with a friendly graphical user interface that allows the user to rapidly familiarize with the mechanics behind the functionality of the software while learning the educational basis in which the software reasoning was built upon. A screen shot of the application can be illustrated by figure 5.6. One of the accessible features provided by this application includes the option of selecting among three choices in the beginning of the question sequence. You can either choose guidelines and tools, guidelines or tools depending on the situation. If the first option is selected, the expert system asks 5 five questions in order to provide answers (guidelines and tools). If second option is selected, the expert system asks 3 questions providing a guideline as an outcome while the third option only asks for the input of 2 questions providing a tool as an output.

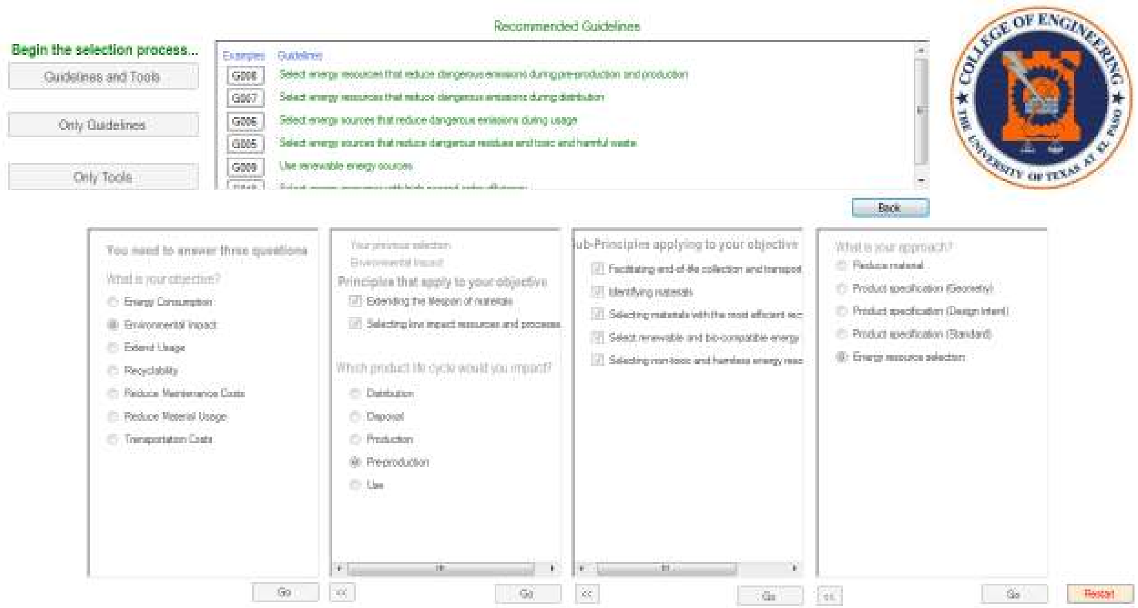

Figure 5.6: The Sustainable Expert System application

Additionally, the software tool allows users to further filter a selection by providing qualifying principles and sub-principles after answering the first two questions (guidelines-tools, guidelines option). Here, the user can check off principles and sup-principles he/she may not think apply to their situation. This can reduce the amount of outputs making the final answer more specific. Another feature worth mentioning is the availability of examples every time an output is obtained. Examples are both provided when obtaining a guideline or tool as an output. Figure 5.7 shows an example obtained from the G008 guideline shown in a separate window after the guideline button is clicked:

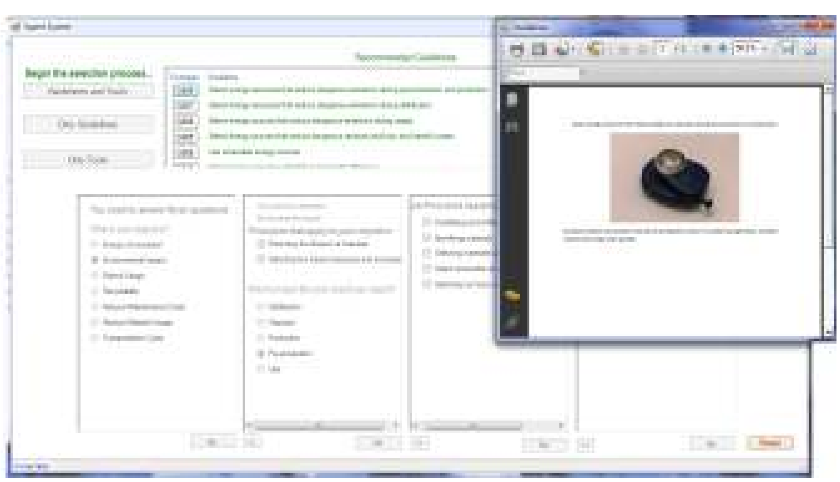

Figure 5.7: Guideline example

The example shows a case study and a description of the product in which the guideline is applied. This feature can help designers in the stimulation of generating ideas to apply guidelines onto their own product. The example feature is also available in the tool output:

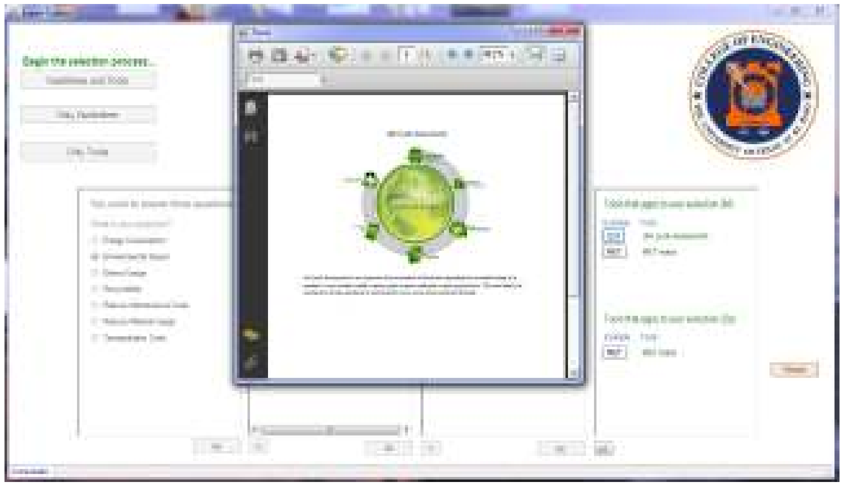

Figure 5.8: Tool example

In this example, the LCA is obtained as a result and a description along with a picture can be viewed by clicking on the LCA button. Such feature helps designers understand the type of tool and its potential applications. Again, this tool is intended to provide means to rapidly select methods without having a considerable amount of knowledge in the subject regarding sustainable design. In order to test the functionality of the software, a validation was executed. The following section will provide an overview of the validation used to test the sustainable expert system.

Chapter 6: Validation

Validation on a product is usually performed to verify if the hypothesis or intended use is met. In this case, the SES is subjected to test subjects to test for accuracy and time spend on providing recommended guidelines and tools that could potentially solve a design requirement. Tests subjects are provided with three questions that must be answered using book resources on one side and the SES on the other side. The validation process and details are explained by the following sections.

6.1 FACTORS

The functionality of the SES to be tested by exposing engineering students to DfE problems that needs to be solved. Problems have been identified as sustainable implementations made by important companies to tackle environmental impact on their products. Although the SES does not need a plentiful sustainable design background from the user in order to be utilized, the undergraduate students do have a background on design. All of the test subjects will be utilizing the SES as one resource and will use the provided textbooks or controlled information as the other resource to find a suitable answer. Ten undergraduate students are the intended test subject involved in the experimentation.

6.2 RESPONSE

To authenticate the functionality of the expert system, a simple comparison of the design methods selected by the students against the answer will be measured. Additionally, the time it takes the user to submit design methodologies will also be quantified. This will be performed with the end purpose of qualitatively and quantitatively assess the performance of the SES. Results will be recorded from test subjects for simple comparison purposes.

6.3 DESIGN OF EXPERIMENT

The experiment will start off by providing undergraduate engineering students with a series of problems that require the proposal of DfE methodologies in order to be solved. Students participating in this experiment will be randomly selected but with the background in mechanical engineering. A simple comparison of the student answer against the key answer will be performed. This in turn relates to a qualitative measure of the expert system which can lead to vague results since a simple comparison is

being made. For that reason, alternate key answers will be developed and compared to any alternate answers provided by the students. Alternate answers will be given a weight to better calculate a final score. All results will be compared against the key and alternate key answers and a final score will be calculated to verify the accurateness of the expert system. Comparisons will also take place against people using the SES and people reading from the provided resources. To verify the hypothesis, time and accuracy to choose design methods will be measured. Time measured from the utilization of books against the SES will be compared from the group of students. Accuracy on the other side, will be assessed by performing a t-test between the two groups.

6.4 DESIGN TASK

A design task will be carried out in order to test for functionality and accurateness. The task will consist on giving students specific questions related to sustainable implementations companies have adopted as a trend to mitigate environmental impact. These implementations require methodologies in order to be accomplished; such methodologies will be proposed by examinees using different approaches. All students are intended to use resources, the SES and sustainable design textbooks. Time and accuracy on matching the key answer will be measured. The following information describes the task provided to students [59][60][61]:

Many companies have initiated the processes of becoming more environmental friendly by implementing sustainable practices. Such companies develop sustainability reports in order to publish their achievements in transforming their products in the sustainable aspect. This exercise will test the Expert System functionality and accurateness by using it as a software tool to find applicable methodologies.

1) HP, as well as other companies, has started the prohibition of certain substances in their products in order to reduce contaminants released into the environment. The manner this is being carried out is with the generation of a standard that forbids the use of certain materials. This standard is composed of tables specifying the allowed amount of material content in their products of certain materials that can be harmful to the environment.

Using the expert system, propose guidelines to accomplish HP's previous approach to become sustainable. As an engineer, which guidelines would you use to achieve the previous sustainability goals?

2) The FORD Company, being one of the biggest and successful car manufacturers in North America, has set goals to reduce 30% of the carbon dioxide (CO_2) emissions in their vehicles by 2020. To accomplish such goals, alternative energy resources must be selected as the main source of energy of a car.

   Make use of the expert system to find applicable guidelines and tools. These two methodologies must be able to propose a strategy to implement design for sustainability on a product and to assess the performance of the proposed changes. What guidelines would you recommend to reduce CO_2 emissions? What tools would you choose to measure performance?

3) Apple is a growing company continuously developing products utilizing state of the art technology. However, the initiation of this technology era is also responsible of causing environmental impact although the features on some products are intended to be of a green aspect. According to Apple's sustainability reports, they have continuously reduced their CO2 production in all the phases of the product life cycle.

   Use the expert system to find applicable tools that can assess a design decision. What tool can Apple use to measure the effectiveness of their sustainable changes? Which tool can measure how effective your design changes are?

Based on this information, students should be able to provide an answer using either their intuition or background. An answer key was generated containing potential guidelines and tools applicable for the design task. Test subject answers will be compared to the key answer in order to obtain a final score.

6.5 Execution –Detailed Instructions

The following instructions will be followed by the examiner:

1. Examiner will begin by introducing him/herself and providing a background about him/her major and thesis work
2. Explain what the problem is and how the exercise will take place (design task). The examiner must give a brief explanation about the expert system and its intended functionality followed by a brief detailing regarding the exercise and the expected outcome.

3. Questions and answers
4. The group of engineering students is first provided with the exercise sheet and auxiliary textbooks in which the information will be searched. Later, the group is provided with the sustainable expert system software. With the given information, students must provide their best answers as what they would propose to solve the questions on the exercise sheet. Experimentation begins when students are provided with the necessary materials and time starts being recorded. There is no time constrains to solve the problem although time will be measured for comparison purposes.
5. Examiner collects the answers and thanks students for their time

6.6 RESULTS

After the design task was provided to students, results were recorded after each test subject finished answering the three questions. Two aspects were measured from the design task exercise, time to answer the three questions and the accuracy on matching the key answers. The following two sections will describe the outcomes from the design task exercise.

6.6.1 Quantitative Measurement – Time

A time assessment was performed from measuring time spent from each student on providing a methodology i.e. guideline and tool. The validation consisted in asking three questions to ten students, who were used as test subjects, particularly mechanical engineering students. During the assessment, students spent a considerable amount of time in familiarizing with the subject being DfE. Time was also spent on answering questions from students even though a question-answer activity was done before the exercise. This time was also included in the assessment. Afterwards, students were able to propose solutions to the design task exercise. After the students finished their reading and researching, their time spent was recorded. Students completing the first reading assignment were asked to use the SES software to answer the same questions and the time elapsed was also recorded.

A table was generated making a comparison of time spent using books against the use of the SES. Time recorded for the books column clearly shows higher values than the ones recorded for the SES column meaning that students clearly spend more when using books as resources to search for

methodologies. A maximum and minimum value recorded of 25 minutes and 43 minutes was recorded for the use of books. On the contrary, when students utilized the sustainable expert system as the auxiliary tool, divergent results were obtained as maximum and minimum values were smaller using the SES tool. Student one only took five minutes to propose guidelines and tools while student four spent 24 minutes. This clearly depicts that the use of the SES is encouraged to diminish time usage.

Table 6.1: Time results

	Books (min.)	Expert System (min.)
Student 1	30	5
Student 2	40	17
Student 3	26	10
Student 4	43	24
Student 5	35	7
Student 6	29	8
Student 7	38	8
Student 8	25	12
Student 9	33	10
Student 10	40	15
Average	33.9	11.6
Standard Deviation	6.297	5.680

Average time and standard deviation were also calculated as means for comparison. The average time recorded for each student, as it can be shown in the table 6.1, was significantly different from reading a book than for using the SES. Standard deviation was also a factor to analyze since it was found that it is smaller than the one from the books section. A chart (figure 6.1) was also generated to illustrate a side by side comparison from each student:

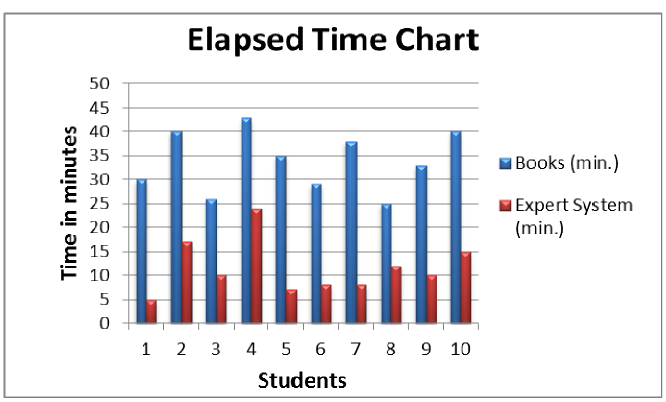

Figure 6.1: Elapsed time chart

Although these results could vary with students that are not engineering majors, this expert system is friendly user software that can be utilized by any engineering student not requiring vast knowledge in sustainable design. Nonetheless, results can fluctuate according to current knowledge.

6.6.2 Quantitative Measurement – Accuracy

An accuracy assessment was also performed after the design task was completed. Certain values were given to each potential answer and points were provided to each student matching the answers. However, for every wrong answer, points were deducted. Three and two points were subtracted for each wrong guideline and tool respectively. Again, the two resources employed were books and the SES. At the end of the design task, points for were recorded in the following table 6.2:

Table 6.2: Accuracy results

	Using Books			Using Expert System		
	Question 1	Question 2	Question 3	Question 1	Question 2	Question 3
Student 1	8	2	10	26	26	18
Student 2	26	19	16	35	32	18
Student 3	27	16	8	22	16	24
Student 4	15	17	0	28	32	18
Student 5	25	20	14	36	35	16
Student 6	19	22	18	27	0	18
Student 7	23	0	24	24	26	0
Student 8	19	21	0	23	21	16
Student 9	11	4	10	28	0	10
Student 10	23	0	8	19	22	14
Average	19.6	12.1	10.8	26.8	21	15.2
StanDev	6.76	8.83	7.94	4.92	13.20	6.78

Points were summed for each question including the calculation of the standard deviation and the average. By simple inspection, values registered for the sustainable expert system were higher than the ones recorded for the books. There are registered values were students did not score and this is due to various erroneous guidelines and tools provided. As for the average for each question, the SES provided more accurate results on the three questions. The standard deviation though was higher for the SES in question two compared to the one from the books column. Charts were constructed to depict a side by side comparison of the student's scores. Figure 6.2 shows scores for the first question, the x-axis represents what each student obtained as final score and the y-axis represents the points obtained for answering each question correctly:

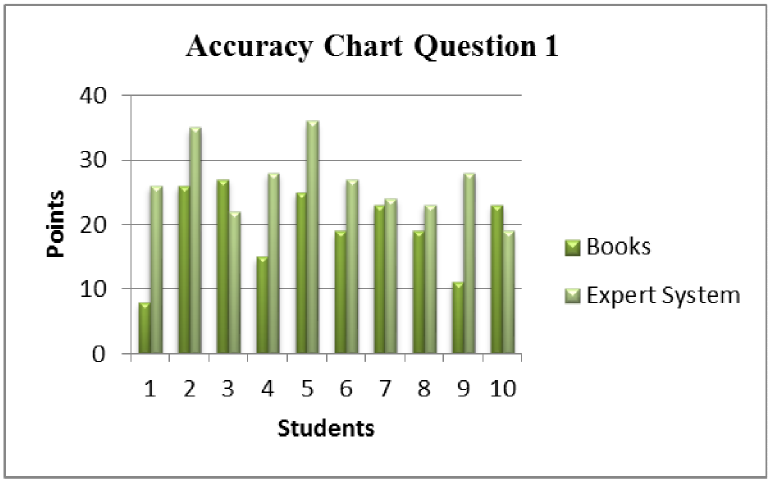

Figure 6.2: Question 1 accuracy chart

A chart for the second question was also built to show the behavior of the scoring trend, in this chart there are students that either failed to match a guideline or proposed numerous erroneous guidelines. Chart of question two can be shown by figure 6.3:

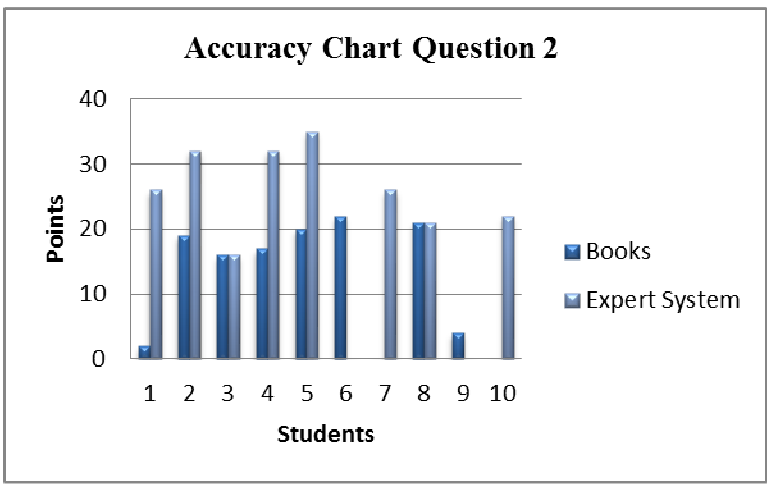

Figure 6.3: Question 2 accuracy chart

Lastly, figure 6.4 illustrates scores obtained from question three. It can be seen that there is a similar scoring trend and also there are students that did not score when proposing methodologies. The possibility on having such trends could be related to the amount of possible points available to students from questions two and three.

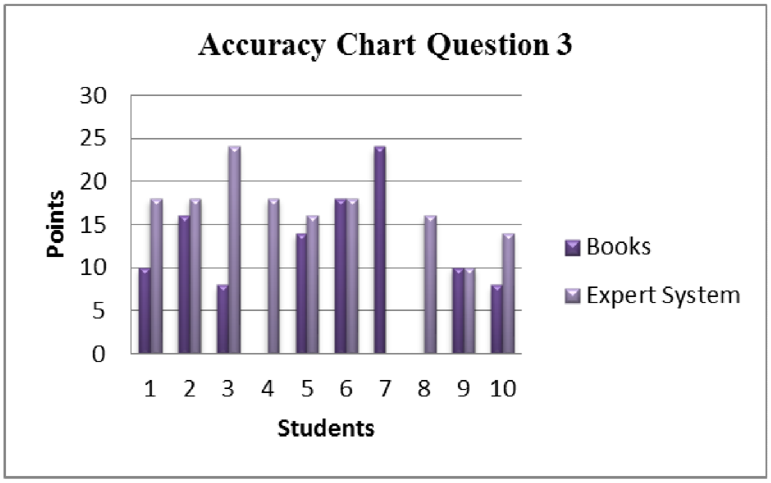

Figure 6.4: Question 3 accuracy chart

A t-test analysis was done in order to compare the averages of two similar independent data sets of the same kind. Calculations were performed using a t-test calculator accessed from the Dimension Research website [62]. A 95% confidence interval was used to compute the three needed t-values, table 6.3 presents values obtained using the already mentioned tool:

Table 6.3: T-test results

Confidence interval $\alpha = .05$
Degrees of freedom = 18

Comparison	t-value	Sig. Different?
Question 1	2.7224	Yes
Question 2	1.7716	No
Question 3	1.3321	No

According to the values obtained, only question one confirms the hypothesis. By using the SES, accurate methodologies can be obtained in a reduced time frame. The question one comparison yields a t-value that confirms that the mean averages are significantly different. As for question two and three, this is not the case since both t-values are under the required value to make a mean average significantly different.

6.6.3 Qualitative Measurement – Debriefing Section

A post-design task activity was performed with the purpose of verifying the effectiveness of the graphical user interface and whole functionality of the SES. Tests subjects were interviewed to investigate what aspects of the SES could be improved in order to enhance its functionality and educational relevance. The following aspects were recorded as potential improvements:

- Add hyperlinks with descriptions to every question option shown in the SES tool
- Students would like to choose more than one objective
- Relationships among entities should be shown somewhere on the SES graphical user interface
- Methodologies should be obtained without answering all questions
- Add description to applicable sub-principles available after each question is answered when obtaining a guideline

Most students expressed interest on the examples provided at the end of the question answering process; the actual examples can help them understanding the nature of the guideline. Examples also stimulate their idea generation skill in order to apply a guideline to another product with the end purpose of improving its sustainable characteristics. The more important factor expressed from the use of examples was that students can fully understand the nature of the guideline and acquire the general objective of the DfE methodologies as a whole. In addition, same comments were made from the tool's examples which helped students on familiarizing with state of the art DfE tools.

.

Chapter 7: Concluding Remarks

7.1 Discussion

Method selection can be a challenging activity. Vast availability of methodologies defined by multiple authors makes characterization even more difficult. There is not ample information available regarding the organization of methods and presenting them to the user for appropriate use. Method selection involves the integration of various elements in order to be accomplished. The presented work is just an example of how methods can be organized to be implemented on an expert system.

As for time assessment, the table shows tangible results that can easily compared to each other. These time results have been collected for practical purposes in order to find out how effective the SES could be in future assessments. Greater impact is derived from the use of the SES tool since most students already felt familiar with the software tool which did not occur with the use of book resources. A significant mean difference on average time spent can be noted from results concluding that in essence the use of the SES considerably reduces time.

The accuracy assessment confirmed the hypothesis only on question one. Although results from the tables show that most scores obtained from the SES are higher than the books, the t-test informs that only the outcomes from the first question are significantly different. Although these numbers represent an improvement, other data may be acquired from students coming from different disciplines and hence having divergent backgrounds. Number of test subjects involved in the experiment may be another factor that could affect measurements.

Most students, before the design task exercise, did not have a grasp of sustainable design. During the debriefing section, students made questions regarding the subject its potential applications. As a result, students understood how sustainable design is applied to a product through guidelines and tools. Additionally, they could realize that there are potential opportunities on improving a product's sustainable properties through the use of DfE methodologies.

7.2 Conclusion

This research work starts by providing an overview of the DfE history including its potential applications by researchers and institutions. It also gives an overview of the literature available in the

sustainable design domain and how the DfE terms are handled by different authors. Then, it dives into an explanation of the different methodologies available in the sustainable design domain focusing on principles, guidelines and tools. There is vast methodology availability for engineers or designers; however, they tend to be of an abstract nature complicating their use and application.

Background delivers supporting information related to the SES development such as the design process, the overview of the DfE methodologies and artificial intelligence. In addition, potential applications of the DfE methodologies are provided as case studies and research being done by universities. Moreover, the state of the art section talks about different trends in the design method selection subject and in the artificial intelligence domain. This section provides examples of current design selection methods regarding the design process and sustainability including examples of expert systems utilized for different applications but following a similar framework as the one developed for the SES. The proposed solution section dives into In the expert system development section an overview of the proposed conceptual model is given described by a diagram portraying the functionality based on entities and relationships. Principles and sub-principles are fundamental for the model as they act as pivots for all relationships. The conceptual model is then transformed into an entity relationship diagram which is composed mainly by logical reasoning. Finally, the SES is obtained from the use of relational databases and SQL. The user can interact by providing multiple inputs and obtaining outputs. Inputs are obtained from entities, which are relatively easy to respond, and outputs are provided by the SES as sustainable design methodologies. The mapping of the information is carried out by relationships represented by tables. These tables, proposed by the author, illustrate relationships among entities which are neither unique nor perfect. The SES is then validated as a potential solution to a design task generated from the sustainability implementations performed by important companies. The SES is compared to book resources in terms of time and accuracy to propose a design method. Undergraduate mechanical engineer students are employed as the test subject.

Although the expert system facilitates the selection of design methods, the user is required to make some decisions. The conceptualization and the working structure of the logical model may provide a grasp on an educational basis to the user allowing him/her to understand the basic concept. However,

the user must be aware that skills are also needed in order to successfully apply methodologies [36] which can be acquired either by professional experience or by studying the correct subjects. The SES is not completely finished; it is a program that can be updated with new information in form of methodologies from other authors.

7.3 CONTRIBUTION

A specific expert system of this kind can be responsible for pioneering design method selection in the DfE environment. The following contributions have been identified from the development of the software tool:

- A novel system that can aid students or engineering professionals choose a design method has been developed
- Since a program tailored specific to DfE methodologies has not been developed yet, this software tool can provide an alternative to selecting methods
- This software tool is one of the pioneering software packages in the area of sustainable design
- This approach can stimulate the development of other expert systems for other subjects such as creativity
- The design community will now have a tool with a principle that can be used for other purposes (creativity)

Although there might be other contributions, these have been identified as the most important and relevant to the SES. Main contribution identified so far is the use in the senior design class and the educational content it can provide to students by teaching the reasoning behind DfE method selection.

7.4 FUTURE WORK

Research work is planned in the current trend to improve the functionality and relevance of the sustainable expert system. Including principles and guidelines from other authors can broaden the availability of methods and it is certainly an area that needs to be further investigated. Also, adding more tools available in the design for environment domain can increase options available to users. Additionally, increasing functionality is intended to enhance the use of the system by providing more features to the user enhancing educational learning in all levels. A graphical user interface, presenting

the conceptual map to users, can help students and professionals understand the logic behind the software tool. More features include adding case-based reasoning functionality and including practical examples on outputs to stimulate creativity on user. The end objective of the system is to educate students and early professionals about method selection and the dynamics behind it. Experienced designers or engineers may also take advantage of the capabilities of the system.

References

[1] Telenko, C., Seepersad, C. C. and Webber, M. E. 2009. A Method for Developing Design for Environment Guidelines for Future Product Design. DETC2009-87389. San Diego: Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2009.

[2] Reyes, T. and Rohmer, S. 2009. The Trojan Horse Method as a Vector of Ecodesign Integration: A Case Study at a French SME. 7-173. Stanford: International Conference on Engineering Design, ICED'09.

[3] Bhamra, T. and Lofthouse, V. 2007. Design for Sustainability: A Practical Approach. Hampshire: Gower Publishing Limited.

[4] van der Bergh, J. C. J. M. and van der Straaten, J. Eds. 1994.Toward Sustainable Development: Concepts, Methods, and Policy. Washington D.C.: Island Press.

[5] Fiksel, J. 2009. Design for Environment: A Guide to Sustainable Product Development. New York: The McGraw-Hill Companies Inc.

[6] Kutz, M. Ed. 2007. Environmentally Conscious Mechanical Design. Hoboken: John Wiley.

[7] Niemann, J., Tichkiewitch, S. and Westkamper, E. Eds. 2009. Design of Sustainable Product Life Cycles. Berlin: Springer.

[8] McDonough, W. 1992. The Hannover Principles. Design for Sustainability. < http://www.mcdonough.com/principles.pdf>

[9] Thompson, G. F. and Steiner, F. R. Eds. 1997. Ecological Design and Planning. New York: John Wiley & Sons, Inc.

[10] Vezzoli, C. and Manzini, E. 2008. Design for Environmental Sustainability. London: Springer.

[11] Wikipedia. The Free Encyclopedia. 2011. Environmental Technology. <http://en.wikipedia.org/wiki/Environmental_technology>

[12] Articlesbase. 2008. Solar Energy – Basic Principles. <http://www.articlesbase.com/technology-articles/solar-energy-basic-principles-649460.html>

[13] Brooks, D. B. 2004. Encyclopedia.com. Water. <http://www.encyclopedia.com/topic/water.aspx>

[14] Auckland City Council. 2011. Stormwater: The Water Cycle <http://www.aucklandcity.govt.nz/council/services/stormwater/about.asp>

[15] Steffen, A. Ed. 2006. World Changing: A User's Guide for the 21st Century. New York: Abrams.

[16] University of California, Los Angeles, UCLA. UCLA Sustainability. 2011. What UCLA is Doing, What You Can Do. <http://www.sustain.ucla.edu/>

[17] Arizona State University, ASU. 2011. Global Institute of Sustainability. <http://sustainability.asu.edu/index.php>

[18] The University of Texas at El Paso, UTEP. 2008. UTEP Goes Green.

<http://gogreen.utep.edu/>

[19] O'Hare, J., Dekoninck, E., Turnbull, A. and McMahon, C. 2009. Adapting Eco-Innovation Tools to the Needs of the Company: A Case Study. 7-265. Stanford: International Conference on Engineering Design, ICED'09.

[20]Telenko, C., Seepersad, C. C. and Webber, M. E. 2008. A Compilation of Design for Environment Principles and Guidelines. DETC2008-49651. Brooklyn: Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2008.

[21] Ehrenfeld, J. R. 2008. Sustainability by Design: A Subversive Strategy for Transforming Our Consumer Culture. New Haven and London: Yale University Press.

[22] University of Colorado Boulder, CU. 2011. Civil, Environmental, and Architectural Engineering.
<http://ceae.colorado.edu/?i=research-by-area>

[23] Dorf, R. C. 2001. Technology, Humans, and Society: Toward a Sustainable World. San Diego: Academic Press.

[24] DLR. 2011. German Aerospace Center. Institute of Technical Thermodynamics
<http://www.dlr.de/tt/en/desktopdefault.aspx>

[25] Stanford University. 2011. Civil and Environmental Engineering.
<http://cee.stanford.edu/research/centers.html>

[26] The Institut de Ciència i Tecnologia Ambientals, ICTA. 2008. Universitat Autonoma de Barcelona. Research Areas.
<http://icta.uab.es/investigacion/index.jsp>

[27] The Ohio State University, OSU. Center for Resilience.
<http://www.resilience.osu.edu/CFR-site/aboutus.htm>

[28] Moore, C. and Miller, A. 1994. Green Gold: Japan, Germany, the United States, and the Race for Environmental Technology. Boston: Beacon Press Boston.

[29] Stasinopoulos, P., Smith, M. H., Hargroves, K. C. and Desha, C. 2009. Whole System Design: An Integrated Approach to Sustainable Engineerng. London: Earthscan Publications Ltd.

[30] Vallero, D. and Brasier, C. 2008. Sustainable Design: The Science of Sustainability and Green . Engineering, Hoboken: John Wiley & Sons, Inc.

[31] U.S. General Services Administration, GSA. 2008. Sustainability Matters.
<http://www.gsa.gov/graphics/pbs/Sustainability_Matters_508.pdf>

[32] Department of the Environment, Water, Heritage, and the Arts. 2011. National Environmental Program.
<http://www.environment.gov.au/about/programs/nerp/about.html>

[33] Morris R., Childs P. and Hamilton T. 2007. Sustainability by design: a reflection on the suitability of pedagogic practice in design and engineering courses in the teaching of sustainable design. European Journal of Engineering Education. 32(2).

[34] Vargas-Hernandez, N., Shah, J. J. and Lacroix, Z. 2002. Knowledge Representation for Conceptual Engineering Design. Madrid: 3rd ACIS International Conference, SNPD'02.

[35] Kaufmann, M. 1993. Knowledge Representation. San Mateo.

<http://www.cirl.uoregon.edu/research/kr.html>

[36] Brachman, R. J., Levesque, H. J. and Reiter, R. Eds. 1992. Knowledge Representation. Cambridge: The MIT Press.

[37] Kolodner, J. L. 1992. An Introduction to Case-Based Reasoning. <http://web.media.mit.edu/~jorkin/generals/papers/Kolodner_case_based_reasoning.pdf>

[38] Aamodt, A. and Plaza, E. 1994. Case-Based Reasoning: Foundational Issues, Methodological Variations, and System Approaches. <http://www.iiia.csic.es/People/enric/AICom.html>

[39] Gorman, M. M. 1991. Database Management Systems: Understanding and Applying Database Technology. Wellesley: QED Information Sciences, Inc.

[40] Opiyo, E. Z. 2009. Visualization Platforms for Conceptual Design. 5-13. Stanford: International Conference on Engineering Design, ICED'09.

[41] Rasoulifar, R., Meillon. B., Thomann, G. and Villeneuve, F. 2009. Observation, Annotation and Analysis of Design Activities: How to Find an Appropriate Tool? 5-193. Stanford: International Conference on Engineering Design, ICED'09.

[42] Ashby, M. F. 2009. Materials and the Environment: Eco-Informed Material Choice. Oxford: Butterworth-Heinemann.

[43] Dean T., Allen J. and Aloimonos Y. 1995. Artificial Intelligence: Theory and Practice. Redwood City: The Benjamin/Cummings Publishing Company, Inc.

[44] Negnevitsky, M. 2004. Artificial Intelligence: A Guide to Intelligent Systems. King's Lynn: Addison – Wesley.

[45] Boden M. A. Ed. 1996. Artificial Intelligence. San Diego: Academic Press Inc.

[46] Edgelmore, R. S. and Feigenbaum, E. 1993. Expert Systems and Artificial Intelligence. Maryland: Loyola College. <http://www.wtec.org/loyola/kb/c1_s1.htm>

[47] Shindy, A. M., Darwich, T. D., Sayyouh M. H. and Osman, A. –A. 1997. Development of an Expert System for EOR Method Selection. <http://cat.inist.fr/?aModele=afficheN&cpsidt=6242444>

[48] Dixon, J. R., Howe, A., Cohen, P. R. and Simmons, M. K. 1987. Engineering With Computers. Dominic I: Progress Toward Domain Independence in Design by Iterative Redesign. New York: Springer-Verlag.

[49] Bellatreche, L., Boukhalfa, K. and Alimazighi, Z. 2009. SimulPh.D: A Physical Design Simulator Tool. Database and Expert Systems Applications 20th International Conference, DEXA 2009. Berlin: Springer-Verlag.

[50]Ulrich K. T. and Eppinger S. D. 1995. Product Design and Development. 1995. Baskerville: McGraw-Hill, Inc.

[51] Pahl G., Beitz W., Feldhusen J. and Grote K. H. 2007. Engineering Design: A Systematic Approach. London: Springer.

[52] Weaver J. M. et al. 2009. Increasing Innovation in Multi-Function Systems: Evaluation and

Experimentation of Two Ideation Methodsus. San Dego: International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/ICE ’09.

[53] Sutcliffe, L. F. R., Maier, A. M., Moultrie, J., and Clarkson, P. J. 2009. Development of a Framework for Assessing Sustainability in New Product Development. 7-289. Stanford: International Conference on Engineering Design, ICED’09.

[54] Athalye, S. A., Govindarajan, S. K., Lopez, C. A., Esterman, M. Jr., and Rothenberg, S. 2009. Challenges in Incorporating Sustainability Into Product Development: An Exploratory Study. DETC2009-87637. San Diego: Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2009.

[55] Dietrich, S. W. 2001. Understanding Relational Database Query Languages. Upper Saddle River: Prentice Hall.

[56]W3Schools. 2011. SQL Tutorial. <http://w3schools.com/sql/default.asp>

[57] phpMyAdmin. 2011. About. <http://www.phpmyadmin.net/home_page/>

[58] Microsoft Visual Studio. 2011. What is Visual Studio? <http://www.microsoft.com/visualstudio/en-us/home>

[59] Hewlet Packard, HP. 2009. HP Standard 011 General Specification for the Environment. <http://www.hp.com/packaging/Documentation/gse-2009.pdf>

[60] Ford. 2009. Blueprint for Sustainability: The Future at Work. <http://corporate.ford.com/doc/sr09-blueprint-summary.pdf>

[61] Apple. 2010. iPad: Environmental Report. <http://images.apple.com/environment/reports/docs/iPad_Environmental_Report.pdf>

[62] Dimension Research, Inc. 2011. Independent Groups T-Test for Means Calculator. <http://www.dimensionresearch.com/resources/calculators/ttest.html>

Appendix A

Answer Key
Guidelines vs. Approaches Tables

Answer Key

Question 1 answers

Avoid toxic or harmful materials for product components (10 points)
Avoid materials that emit toxic or harmful substances during pre-production (8 points)
Avoid materials that emit toxic or harmful substances during usage (8 points)
Avoid materials that emit toxic or harmful substances during disposal (9 points)
Avoid materials that emit dangerous substances during incineration (7 points)
Minimize the hazard of toxic and harmful materials (6 points)
Avoid additives that emit dangerous substances during incineration (4 points)
Indicate the existence of toxic or harmful materials (4 points)
Total points 56

Question 2 primary answers

Select energy resources that reduce dangerous emissions during usage (10 points)
Select energy resources that reduce dangerous residues and toxic and harmful waste (8 points)
Use renewable energy sources (8 points)
Life Cycle Assessment (5 points)
Select energy resources with high second-order efficiency (6 points)
Selection of non-toxic energy sources (5 points)
MET Matrix (3 points)
Total points 45

Question 3 primary answers

Life Cycle Analysis (10 points)
MET matrix (8 points)
Eco-indicator 99 (6 points)
Total points 24

Principle	Sub principle						
Minimizing Resource Consumption		**Reduce material**	**Product specification (Geometry)**	**Substitute hardware for software**	**Reduce design complexity**		
	Minimizing Material Content	Avoid over-sized dimensions Reduce thickness	Dematerialize the product or some of its components Apply ribbed structures to increase structural stiffness	Digitalize the product	Miniaturise Avoid extra components with little functionality		
		Reduce material	**Packaging minimization**				
	Minimizing Packaging	Apply materials only where absolutely necessary	Avoid packaging Design package to be part of the product				
		Diminish resource consumption	**Maintenance**	**Recycle**			
	Minimizing Materials Consumption During Usage	Design for the efficient consumption of operational materials Design for the more efficient supply of raw materials Design systems for the consumption of passive Facilitate reducing materials consumption for the user Set the product's default state at minimum materials consumption	Design for the more efficient use of maintenance materials	Design for the cascading of recycling systems			
		Material selection	**Product specification (Design intent)**	**Reduce materials**	**Diminish resource consumption**	**Packaging minimization**	**Reduce energy consumption**
	Minimizing Energy Consumption	Select materials with low energy intensity Select local materials and energy sources	Define accurately the tolerance parameters Design compact products with high storage density Scale down the product weight Design attractive products for collective use Engage digital dynamic support systems Program the product's default state at minimum energy consumption	Scale down the weight and dimensions of all transportable materials and semi-products	Design concentrated products Design/engage highly efficient engines	Equip products with on-site assembly Scale down the packaging weight Scale down the weight of transportable goods	Design for energy-efficient operational stages Design for energy efficient maintenance Design systems with the consumption of passive energy sources Engage highly efficient energy conversion systems Design/engage highly efficient energy power transmission Design for localized energy supply Design energy recovery systems Design enegy-saving systems Design dynamic energy consumption systems for differentiated operational stages

Table A-1: Guidelines vs. Approaches

Selecting Low Impact Resources and Processes		**Material selection**	**Product Specification (Standard)**
	Select Non-toxic and Harmless Materials	Avoid toxic or harmful materials for product components Avoid materials that emit toxic or harmful substances during pre-production Avoid materials that emit toxic or harmful substances during usage Avoid materials that emit toxic or harmful substances during disposal	Minimize the hazard of toxic and harmful materials Avoid additives that emit toxic or harmful substances Design products that do not consume toxic and harmful materials
		Energy Resource Selection	
	Select Non-toxic and Harmless Energy Sources	Select energy resources that reduce dangerous emissions during pre-production and production Select energy resources that reduce dangerous emissions during distribution Select energy sources that reduce dangerous emissions Select energy sources that reduce dangerous residues and toxic and harmful waste	
		Material Selection	
	Select Renewable and Bio-compatible materials	Use renewable materials Avoid exhaustive materials Use recycled materials, alone or combined with primary materials Use biodegradable materials	
		Energy Resource Selection	**Product Specification (Design intent)**
	Select Renewable and Bio-compatible Energy Resources	Use renewable energy sources Select energy resources with high second-order efficiency	Engage a cascade approach

Table A-2: Guidelines vs. Approaches

Strategy	Guideline				
		Extend product usage	Product Specification (Design intent)	Material Selection	Maintenance
Product Lifetime Optimization	Designing for Appropriate Lifespan	Design components with a coextensive lifespan	Enable and facilitate the separation of components that have different lifespans	Select durable materials according to the product performance and lifespan Avoid selecting durable materials for temporary products or components	Design the lifespan of replaceable components according to scheduled durability
		Reduce Design Complexity	Product Specification (Geometry)		
	Designing for Reliability	Reduce overall number of components Simplify products	Eliminate weak links		
		Upgrading features	Product Specification (Features)		
	Facilitating Upgrading and Adaptability	Enable and facilitate software upgrading Enable and facilitate hardware upgrading Design products that are upgradable and adaptable Design complimentary tools and documentation for product upgrading and adaptation	Design modular and dynamically configured products to facilitate their adaptability for changing environments Design miltifunctional and dynamically configured products to facilitate their adaptability for the changing of individuals' cultural and physical backgrounds		
		Maintenance	Cleaning	Product Specification (Features)	
	Facilitating Maintenance	Simplify access to and disassembly of components to be maintained Equip the product with easily usable tools for maintenance Design products for easy onsite maintenance Design complementary maintenance tools and documentation Design products that need less maintenance	Avoid narrow slits and holes to facilitate access for cleaning	Pre-arrange and facilitate the substitution of short-lived components Equip products with diagnostic and/or auto-diagnostic systems for maintanable components	
		Maintenance	Product Specification (Features)		
	Facilitating Repairs	Arrange and facilitate disassembly and reattachment of easily damageable components Design products for facilitated on-site reparation Design complementary repair tools, materials and documentation	Design components according to standarts to facilitate substitution of damaged parts Equip products with automatic damage diagnostics system		
		Extend Product Usage	Maintenance	Packaging	
	Facilitating Re-use	Increase the resistance of easily damaged and expendable components Design modular and replaceable components Design re-usable auxiliary Design products for secondary use	Arrange and facilitate access to and removal or retrievable components Design components according to standarts to facilitate substitution	Design refillabel and re-usable packaging	
		Maintenance	Product Specification (Design intent)	Extend Product Usage	
	Facilitating Re-Manufacturing	Design and facilitate removal and substitution of easily expendable components	Design structural parts that can be easily separated from external/visible ones Calculate accurate tolerance parameters for easily expendable connections Provide easier access to components to be re-manufactured	Design for excessive use of materials in places more subject to deterioration Design for excessive use of material for easily deteriorating surfaces	
		Enhance Use	Product Specification (Features)	Diminish Resource Consumption	
	Intensifying Use	Design products and services for shared use	Design multifunctional products equipped with replaceable common components Design products with integrated functions	Design products or components on demand Design products or components on availability	

Table A-3: Guidelines vs. Approaches

		Recycle	**Material Selection**	
Extending the Lifespan of Materials	Adopting the Cascade Approach	Arrange and facilitate recycling of materials in components with lower mechanical requirements Arrange and facilitate recycling of materials in components with lower aesthetical requirements	Arrange and facilitate energy recovery from materials throughout combustion	
		Material Selection	**Product Specification (Geometry)**	**Product Specification (Design intent)**
	Selecting Materials with the Most Efficient Recycling Technologies	Select materials that easily recover after recycling the original performance characteristics Avoid composite materials or, when necessary, choose easily recyclable ones Prefer thermoplastic polymers to thermosetting Prefer heat-proof thermoplastic polymers to fire-proof additives	Engage geometrical solutions like ribbing to increase polymer stiffness instead of reforcing fibres	Design taking into consideration the secondary use of the materials once recycled
		Product Specification (Standard)	**Product Specification (Geometry)**	**Reduce Material**
	Facilitating End-of-life Collection and Transportation	Design in compliance with a product retrieval system	Minimize cluttering and improve stackability of disposed products Design for discarded products' compressibility	Minimize overall weight
		Product Specification (Standard)	**Product Specification (Geometry)**	
	Identify Materials	Codify different materials to facilitate their identification Provide additional information about the material's age, number of times recycled and additives used Indicate the existence of toxic or harmful materials Use standarized materials identification systems Avoid codifying after component production stages	Arrange codifications in easily visible places	
		Product Specification (Design intent)	**Product Specification (Standard)**	**Material Selection**
	Minimizing the Overall Number of Different Incompatible Materials	Integrate functions to reduce the overall number of materials and components	Monomaterial strategy: only one material per product or per sub-assembly Use only one material, but process in sandwich structures For joining, use the same or compatible materials as in the components (to be joined)	Use compatible materials (that can be recycled together) within the product or sub-assembly
		Product Specification (Standard)	**Material Selection**	
	Facilitating Cleaning	Avoid unnecessary coating procedures Avoid adhesives or choose in compliance with materials to be recycled Prefer dyeing internal polymers, rather than surface painting Mark and codify materials during moulding	Avoid irremovable coating materials	
		Material Selection	**Product Specification (Standard)**	**Product Specification (Design intent)**
	Facilitating Composting	Select materials that degrade in the expected end-of-life environment	Avoid combining non-degradable materials with products that are going to be composted	Facilitate the separation of non-degradable materials
		Material Selection	**Product Specification (Standard)**	
	Facilitating Combustion	Select high energy materials for products that are going to be incinerated Avoid materials that emit dangerous substances during incineration	Avoid additives that emit dangerous substances during incineration	

Table A-4: Guidelines vs. Approaches

Facilitating Disassembly

Guideline	Product Specification (Standard)	Product Specification (Geometry)	Reduce Material	Product Specification (Design intent)
Reducing and Facilitating Operations of Disassembly and Separation	Prioritize the disassembly of toxic and dangerous components or materials Design leaning surfaces and grabbing features in compliance with standards Minimize overall number of fasteners Minimize overall number of fastener types	Prioritize the disassembly of more easily damageable components Engage modular structures Divide the product into easily separable and manipulate sub-assemblies Avoid difficult to handle components Avoid asymmetrical components, unless required Avoid difficult-to-handle fasteners Design accessible and controllable dismantling points	Minimize the overall dimensions of the product	Minimize hierarchically dependent connections among components Engage a sandwich system of disassembly with central joining elements Arrange leaning surfaces around the product's centre of gravity Design of an easy centring on the component base Avoid joining systems that require simultaneous interventions for opening Design accessible and recognizable entrances for dismantling

Guideline	Product Specification (Geometry)	Product Specification (Standard)	Material Selection
Engaging Reversible Joining Systems	Employ a two-way snap-fit	Employ joints that are opened with common tools Employ joints that are opened with special tools, when opening could be dangerous Use screws with hexagonal heads Prefer removable nuts and clips to self-tapping screws Use self-tapping screws for polymers to avoid using metallic inserts	Design joints made of materials that become reversible only in determined conditions Use screws made of materials compatible with joint components, to avoid their separation before recycling

Guideline	Product Specification (Geometry)	Product Specification (Standard)
Engaging Permanent Joining Systems that Can Be Easily Opened	Avoid rivets in incompatible materials	Avoid stables in incompatible materials Avoid additional materials while welding Prefer ultrasonic and vibration welding with polymers Avoid gluing with adhesives Employ easily removable adhesives

Guideline	Reduce materials	Product Specification (Geometry)	Product Specification (Standard)	Material Selection
Co-designing Special Technologies and Features for Crushing Separation	Design thin areas to enable the break-off of incompatible inserts with pressurized demolition	Co-design cutting or breaking paths with appropriate separation technologies for separating incompatible materials	Equip the product with a device for separating incompatible materials Provide the products with information for the user about the characteristics of crushing separation	Make the breaking points easily accessible and recognizable

Guideline	Material Selection
Using Materials that Are Easily Separable After Being Crushed	Combine materials i.e. metals and plastics, ferrous metals with non-ferrous metals or two polymers with different densities

Guideline	Material Selection
Using Additional Parts that Are Easily Separable After the Crushing of Materials	Keep incompatible inserts in terms of materials easily separable with recycling technologies

Table A-5: Guidelines vs. Approaches

Appendix B

Product Life Cycle vs. Sub-principles Table
Sub-principles vs. Objectives Table
Principles vs. Objectives Table
Principles vs. Tools Table
Design Process vs. Tools Table

Characterize by product development process

Principle	Sub-Principles	*Pre-production*	*Production*	*Distribution*	*Use*	*Disposal*
Minimizing resource consumption	Minimizing material content	x				
	Minimizing packaging			x		
	Minimizing materials consumption during usage				x	x
	Minimizing energy consumption	x		x	x	

Principle	Sub-Principles	*Pre-production*	*Production*	*Distribution*	*Use*	*Disposal*
Selecting low impact resources and processes	Select non-toxic and harmless materials		x		x	x
	Select non-toxic and harmless energy resources	x	x	x	x	
	Select renewable and bio-compatible materials					x
	Select renewable and bio-compatible resources	x			x	

Principle	Sub-Principles	*Pre-production*	*Production*	*Distribution*	*Use*	*Disposal*
Product lifetime optimization	Designing for appropiate lifespan				x	x
	Designing for reliability		x			
	Facilitating upgrading and adaptability	x			x	
	Facilitating maintenance	x			x	
	Facilitating repairs	x			x	
	Facilitating re-use			x	x	
	Facilitating re-manufacturing	x				
	Intensifying use				x	x

Principle	Sub-Principles	*Pre-production*	*Production*	*Distribution*	*Use*	*Disposal*
Extending the lifespan of materials	Adopting the cascade approach		x			x
	Selecting materials with the most efficient recycling technology		x			x
	Facilitating end-of-life collection and transportation	x		x		x
	Identifying materials	x				x
	Minimizing the overall number of different incompatible materials		x			x
	Facilitating cleaning		x			x
	Facilitating composting					x
	Facilitating combustion					x

Principle	Sub-Principles	*Pre-production*	*Production*	*Distribution*	*Use*	*Disposal*
Facilitating disassembly	Reducing and facilitating operations of disassembly and separation	x	x			x
	Engaging reversible joining systems	x		x		x
	Engaging permanent joining systems that can be easily opened	x	x			x
	Co-designing special technologies and features for crushing separation		x		x	x
	Using materials that are easily separable after being crushed					x
	Using additional parts easily separable after crushing of materials					x

Table B-1: Product life cycle vs. Sub-principles

Sub-Principles	**Objectives**						
	Extend Usage	Transportation costs	Recyclability	Reduce material usage	Reduce maintenance costs	Energy consumption	Environmental impact
Minimizing material content				x			
Minimizing packaging		x					
Minimizing materials consumption during usage				x			
Minimizing energy consumption						x	
Select non-toxic and harmless materials							x
Select non-toxic and harmless resources							x
Select renewable and biocompatible materials			x				
Select renewable and biocompatible resources						x	
Designing for appropiate lifespan	x						
Designing for reliability	x						
Facilitating upgrading and adaptability				x			
Facilitating maintenance					x		
Facilitating repairs					x		
Facilitating re-use	x						
Facilitating re-manufacturing				x			
Intensifying use	x			x			
Adopting the cascade approach				x			
Selecting materials with the most efficient recycling technology			x				
Facilitating end-of-life collection and transportation		x					
Identifying materials			x				
Minimizing the overall number of different incompatible materials			x				
Facilitating cleaning							x
Facilitating composting							x
Facilitating combustion				x			
Reducing and facilitating operations of disassembly and separation	x						
Engaging reversible joining systems	x						
Engaging permanent joining systems that can be easily opened			x				
Co-designing special technologies and features for crushing separation			x				
Using materials that are easily separable after being crushed	x						
Using additional parts easily separable after crushing of materials	x						

Table B-2: Sub-principles vs. Objectives

Principles	Objectives						
	Extend Usage	Transportation costs	Recyclability	Reduce material usage	Reduce maintenance costs	Energy consumption	Environmental impact
Minimizing resource consumption		x		x		x	
Selecting low impact resources and processes			x			x	x
Product lifetime optimization	x			x	x		
Extending the lifespan of materials		x	x	x			x
Facilitating disassembly	x		x				

Table B-3: Principles vs. Objectives

Principles	Tools				
	Environmental Assessment	Strategic Design	Idea generation	Centred design	Information provision
Minimizing resource consumption	LCA, MET, ECO	EDW, DA, FFA, SRT	II, CT	PO, UT	II
Selecting low impact resources and processes	LCA, MET	EDW, FFA, SRT	CT		
Product lifetime optimization		EDW, FFA, SRT	FM. CT	UT, PIU, SOU, LG,	RP
Extending the lifespan of materials	LCA	EDW, DA, FFA, SRT	II, FM, CT	UT	II, RP
Facilitating disassembly	MET, ECO	EDW, DA, FFA	FM, CT		II

Table B-4: Principles vs. Tools

Design process	Tools				
	Environmental Assessment	Strategic Design	Idea generation	Centred design	Information provision
Task	LCA, MET	DA, FFA	FM	UT, PIU, SOU, LG, MB	
Requirements list	LCA	EDW, FFA	FM	UT, PIU, SOU, LG, MB	
Principle solution	MET	EDW, SRT	II, FM, CT		II, RP
Preliminary layout	ECO	SRT	II, FM, CT		II, RP
Definitive layout	ECO		FM		
Product documentation		DA	FM		

Table B-5: Design process vs. Tools

Annex

Microsoft Visual Studio Program Code

Visual Studio Program Code

The following codes were used to build the sustainable expert system software tool. Software utilized to create and debug the program was the Microsoft Visual Basic 2010 Express application. The program codes utilize standard query language to extract information, the SQL commands can be found in red. The line codes to create the program are as follows:

```
Public Function Pregunta_5()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.Connection = Miconexion
    comando.CommandText = "select count(*) from objectives_t;"
    misDatos = comando.ExecuteReader
    While (misDatos.Read())
      Form1.Label4.Text = misDatos.GetString(0)
    End While
    Return 0
  End Function
  Public Function Desplegar_obj_t()
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.CommandText = "select Name from objectives_t;"
    misDatos = comando.ExecuteReader
    Dim i, x As Integer
    x = Form1.Label4.Text
    Dim intLeft As Integer = 70
    ReDim objetivos(Form1.Label4.Text)
    For i = 1 To x
      misDatos.Read()
      Dim Rb As New RadioButton
      Rb.Name = "RadioButton" & i
      Rb.AutoSize = True
      Rb.Checked = False
      Rb.Location = New Point(20, intLeft)
      Rb.Size = New Size(50, 23)
      Rb.Text = misDatos.GetString(0)
      Form1.Panel1.Controls.Add(Rb)
      intLeft += 25
      objetivos(i) = Rb
    Next
    Return 0
  End Function
  Public Function desplegar_num2(ByVal Choice1 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.Connection = Miconexion
    comando.CommandText = "select count(*) from obj_vs_p where Objective_name = " + Choice1 + " "
    misDatos = comando.ExecuteReader
    While (misDatos.Read())
      Form1.Label11.Text = misDatos.GetString(0)
    End While
    Return 0
  End Function
  Function desplegar_objectivos(ByVal choice1 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.CommandText = "select Principle_name from obj_vs_p where Objective_name = " + choice1 + " "
    misDatos = comando.ExecuteReader
    Dim i, x As Integer
    x = Form1.Label11.Text
    Dim intLeft As Integer = 70
    ReDim OvsP(Form1.Label11.Text)
    For i = 1 To x
      misDatos.Read()
      Dim Cb As New CheckBox
      Cb.Name = "CheckBoox" & i
      Cb.AutoSize = True
      Cb.Checked = True
      Cb.Location = New Point(20, intLeft)
      Cb.Size = New Size(50, 23)
      Cb.Text = misDatos.GetString(0)
      Form1.Panel2.Controls.Add(Cb)
      intLeft += 25
      OvsP(i) = Cb
```

```
    Next

    Return 0
End Function
Public Function desplegar_num3()
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.Connection = Miconexion
    comando.CommandText = "select count(*) from product_life_cycle_t;"
    misDatos = comando.ExecuteReader
    While (misDatos.Read())
        Form1.Label15.Text = misDatos.GetString(0)
    End While
    Return 0
End Function
Public Function Desplegar_plc_t()
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.CommandText = "select Name from product_life_cycle_t;"
    misDatos = comando.ExecuteReader
    Dim i, x As Integer
    x = Form1.Label15.Text
    Dim intLeft As Integer = 170
    ReDim plc(Form1.Label15.Text)
    For i = 1 To x
        misDatos.Read()
        Dim Rb1 As New RadioButton
        Rb1.Name = "RadioButton" & i
        Rb1.AutoSize = True
        Rb1.Checked = False
        Rb1.Location = New Point(20, intLeft)
        Rb1.Size = New Size(50, 23)
        Rb1.Text = misDatos.GetString(0)
        Form1.Panel2.Controls.Add(Rb1)
        intLeft += 25
        plc(i) = Rb1
    Next
    Return 0
End Function
Public Function desplegar_P_Sp_Plc(ByVal Choice1 As String, ByVal choice2 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.Connection = Miconexion
    comando.CommandText = "select count(*) from p_vs_sp_vs_plc_1 where Principle_name IN" + Choice1 + " and Product_life_cycle_name ='" + choice2 + "' "
    misDatos = comando.ExecuteReader
    While (misDatos.Read())
        Form1.Label22.Text = misDatos.GetString(0)
    End While
    Return 0
End Function
Function desplegar_P_Sp_Plc_t(ByVal choice1 As String, ByVal choice2 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.CommandText = "select Sub_principle_name from p_vs_sp_vs_plc_1 where Principle_name IN" + choice1 + " and Product_life_cycle_name ='" + choice2 + "' "
    misDatos = comando.ExecuteReader
    Dim i, x As Integer
    x = Form1.Label22.Text
    Dim intLeft As Integer = 35
    ReDim PSP(Form1.Label22.Text)
    For i = 1 To x
        misDatos.Read()
        Dim Cb1 As New CheckBox
        Cb1.Name = "CheckBoox" & i
        Cb1.AutoSize = True
        Cb1.Checked = True
        Cb1.Location = New Point(20, intLeft)
        Cb1.Size = New Size(50, 23)
        Cb1.Text = misDatos.GetString(0)
        Form1.Panel3.Controls.Add(Cb1)
        intLeft += 25
        PSP(i) = Cb1
    Next
    'Form1.Panel3.Show()
    'Form1.Button3.Show()
    'Form1.Button6.Show()
    Return 0
End Function
Public Function count_app(ByVal choice1 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.Connection = Miconexion
    comando.CommandText = "select count(DISTINCT Approach) from sp_vs_app_vs_guil_1 where Sub_principle_name IN " + choice1 + ""
    misDatos = comando.ExecuteReader
    While (misDatos.Read())
```

```
        Form1.Label27.Text = misDatos.GetString(0)
    End While
    Return 0
End Function
Public Function Desplegar_App(ByVal choice1 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.CommandText = "select DISTINCT Approach from sp_vs_app_vs_guil_1 where Sub_principle_name IN " + choice1 + ";"
    misDatos = comando.ExecuteReader
    Dim i, x As Integer
    x = Form1.Label27.Text
    Dim intLeft As Integer = 30
    ReDim app(Form1.Label27.Text)
    For i = 1 To x
        misDatos.Read()
        Dim Rb2 As New RadioButton
        Rb2.Name = "RadioButton" & i
        Rb2.AutoSize = True
        Rb2.Checked = False
        Rb2.Location = New Point(20, intLeft)
        Rb2.Size = New Size(50, 23)
        Rb2.Text = misDatos.GetString(0)
        Form1.Panel4.Controls.Add(Rb2)
        intLeft += 25
        app(i) = Rb2
    Next
    Return 0
End Function
'dsgfsgdsgfds
Public Function borrar_1eros_objetivos(ByVal choice1 As String)
    Dim y As Integer
    Dim intLeft As Integer = 70
    y = choice1
    Dim a As Integer
    For a = 1 To y
        Form1.Panel1.Controls.Remove(objetivos(a))
    Next
    Form1.Label18.Text = Form1.Label28.Text
    Return 0
End Function
Public Function borrar_objetivos(ByVal choice1 As String)
    Dim y As Integer
    Dim intLeft As Integer = 70
    y = choice1
    Dim a As Integer
    For a = 1 To y
        Form1.Panel2.Controls.Remove(OvsP(a))
    Next
    Form1.Label18.Text = Form1.Label28.Text
    Return 0
End Function
Public Function borrar_plc_t(ByVal choice1 As String)
    Dim y As Integer
    Dim intLeft As Integer = 70
    y = choice1
    Dim a As Integer
    For a = 1 To y
        Form1.Panel2.Controls.Remove(plc(a))
    Next
    'Form1.Label17.Text = Form1.Label28.Text
    Return 0
End Function
Public Function borrar_subp(ByVal choice1 As String)
    Dim y As Integer
    Dim intLeft As Integer = 70
    y = choice1
    Dim a As Integer
    For a = 1 To y
        Form1.Panel3.Controls.Remove(PSP(a))
        Form1.Label29.Text = Form1.Label28.Text
    Next
    Return 0
End Function
Public Function borrar_borara_app(ByVal choice1 As String)
    Dim y As Integer
    Dim intLeft As Integer = 70
    y = choice1
    Dim a As Integer
    For a = 1 To y
        Form1.Panel4.Controls.Remove(app(a))
    Next
    Form1.Label29.Text = Form1.Label28.Text
    Form1.Label30.Text = Form1.Label28.Text
    Return 0
End Function
Public Function count_guide(ByVal choice1 As String, ByVal choice2 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
```

```
    Miconexion.Open()
    comando.Connection = Miconexion
    comando.CommandText = "select count(*) from sp_vs_app_vs_guil_1 where Sub_principle_name IN " + choice1 + " and Approach= " + choice2 + ""
    misDatos = comando.ExecuteReader
    While (misDatos.Read())
        Form1.Label25.Text = misDatos.GetString(0)
    End While
    Return 0
End Function
Public Function Desplegar_guide(ByVal choice1 As String, ByVal choice2 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.CommandText = "select Guideline from sp_vs_app_vs_guil_1 where Sub_principle_name IN " + choice1 + " and Approach= " + choice2 + ""
    misDatos = comando.ExecuteReader
    Dim i, x As Integer
    x = Form1.Label25.Text
    Dim intLeft As Integer = 28
    ReDim guide(Form1.Label25.Text)
    For i = 1 To x
        misDatos.Read()
        Dim lk As New Label
        lk.Name = "Labbel" & i
        lk.AutoSize = True
        lk.Location = New Point(66, intLeft)
        lk.Size = New Size(50, 23)
        lk.Text = misDatos.GetString(0)
        lk.ForeColor = Color.Green
        Form1.Panel5.Controls.Add(lk)
        intLeft += 25
        guide(i) = lk
    Next
    Return 0
End Function
'+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
Public Function Desplegar_b1()
    Dim i, x As Integer
    x = Form1.Label25.Text
    Dim intLeft As Integer = 10
    ReDim b1(Form1.Label25.Text)
    For i = 1 To x
        misDatos.Read()
        Dim B As New Button
        B.Name = "Button" & i
        B.AutoSize = True
        B.Location = New Point(10, intLeft)
        B.Size = New Size(23, 23)
        B.UseVisualStyleBackColor = True
        B.Text = "Example"
        Form1.Panel5.Controls.Add(B)
        intLeft += 25
        b1(i) = B
    Next
    Return 0
End Function
Public Function cero2()
    If Form1.Label22.Text = 0 Then
        MessageBox.Show("No results for the option chosen")
        Form1.Button6.Hide()
        Form1.Button3.Hide()
        Form1.Panel3.Hide()
        Form1.Button5.Enabled = True
        Form1.Button2.Enabled = True
        Form1.Panel2.Enabled = True
        borrar_objetivos(Form1.Label11.Text)
        borrar_plc_t(Form1.Label15.Text)
        desplegar_objectivos(Form1.Label13.Text)
        Desplegar_plc_t()
        ' borrar_subp(Form1.Label22.Text)
    End If
    Return 0
End Function
Public Function method()
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.Connection = Miconexion
    comando.CommandText = "select count(*) from methodologies_t;"
    misDatos = comando.ExecuteReader
    While (misDatos.Read())
        Form1.Label31.Text = misDatos.GetString(0)
    End While
    Return 0
End Function
Public Function Desplegar_method_t()
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.CommandText = "select  Methodologies_name from methodologies_t;"
```

```
    misDatos = comando.ExecuteReader
    Dim i, x As Integer
    x = Form1.Label31.Text
    Dim intLeft As Integer = 35
    ReDim metod(Form1.Label31.Text)
    For i = 1 To x
        misDatos.Read()
        Dim Rb3 As New RadioButton
        Rb3.Name = "RadioButton" & i
        Rb3.AutoSize = True
        Rb3.Checked = False
        Rb3.Location = New Point(16, intLeft)
        Rb3.Size = New Size(50, 23)
        Rb3.Text = misDatos.GetString(0)
        Form1.Panel6.Controls.Add(Rb3)
        intLeft += 25
        metod(i) = Rb3
    Next
    Return 0
End Function
Public Function contar_p_vs_t(ByVal Choice1 As String, ByVal choice2 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.Connection = Miconexion
    comando.CommandText = "select count(distinct Tool_name ) from principles_vs_tools where  Principle_name IN " + Choice1 + " and Methodology IN( " + choice2 + ")"
    misDatos = comando.ExecuteReader
    While (misDatos.Read())
        Form1.Label34.Text = misDatos.GetString(0)
    End While
    Return 0
End Function
Function desplegar_P_vs_t(ByVal choice1 As String, ByVal choice2 As String)
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    '----cambio4
    comando.CommandText = "select Distinct Tool_name from principles_vs_tools where  Principle_name IN " + choice1 + " and Methodology  =(" + choice2 + ") "
    misDatos = comando.ExecuteReader
    Dim i, x, renato As Integer
    x = Form1.Label34.Text
    renato = 65
    ReDim tolab(x)
    For i = 1 To x
        misDatos.Read()
        Dim tl As New Label
        tl.Name = "label" & i
        tl.ForeColor = Color.Green
        tl.AutoSize = True
        tl.Location = New Point(70, renato)
        tl.Size = New Size(50, 23)
        tl.Text = misDatos.GetString(0)
        Form1.Panel8.Controls.Add(tl)
        renato += 25
        tolab(i) = tl
    Next
    Return 0
End Function
Public Function desing_t()
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.Connection = Miconexion
    comando.CommandText = "select count(*) from desing_process"
    misDatos = comando.ExecuteReader
    While (misDatos.Read())
        Form1.Label35.Text = misDatos.GetString(0)
    End While
    Return 0
End Function
Public Function Desplegar_desing_t()
    misDatos.Close()
    Dim Miconexion As New OdbcConnection(Conectar)
    Miconexion.Open()
    comando.CommandText = "select Name from desing_process"
    misDatos = comando.ExecuteReader
    Dim i, x As Integer
    x = Form1.Label35.Text
    Dim intLeft As Integer = 35
    ReDim dep(x)
    For i = 1 To x
        misDatos.Read()
        Dim Rb4 As New RadioButton
        Rb4.Name = "RadioButton" & i
        Rb4.AutoSize = True
        Rb4.Checked = False
        Rb4.Location = New Point(20, intLeft)
        Rb4.Size = New Size(50, 23)
        Rb4.Text = misDatos.GetString(0)
```

```
            Form1.Panel7.Controls.Add(Rb4)
            intLeft += 25
            dep(i) = Rb4
        Next
        Return 0
    End Function
    Public Function contar_dp_vs_t(ByVal Choice1 As String, ByVal choice2 As String)
        misDatos.Close()
        Dim Miconexion As New OdbcConnection(Conectar)
        Miconexion.Open()
        comando.Connection = Miconexion
        comando.CommandText = "select count(*) from dp_vs_tools where  Desing_process_name  =( " + Choice1 + ") and Methodology =(" + choice2 + ")"
        misDatos = comando.ExecuteReader
        While (misDatos.Read())
            Form1.Label37.Text = misDatos.GetString(0)
        End While
        Return 0
    End Function
    Public Function Desplegar_dp_vs_t(ByVal choice1 As String, ByVal choice2 As String)
        misDatos.Close()
        Dim Miconexion As New OdbcConnection(Conectar)
        Miconexion.Open()
        comando.CommandText = "select Tool_name from dp_vs_tools where  Desing_process_name  =( " + choice1 + ") and Methodology =(" + choice2 + ")"
        misDatos = comando.ExecuteReader
        Dim i, x, renato As Integer
        x = Form1.Label37.Text
        renato = 245
        ReDim dplab(x)
        For i = 1 To x
            misDatos.Read()
            Dim lb5 As New Label
            lb5.Name = "label" & i
            lb5.ForeColor = Color.Green
            lb5.AutoSize = True
            lb5.Location = New Point(70, renato)
            lb5.Size = New Size(50, 23)
            lb5.Text = misDatos.GetString(0)
            Form1.Panel8.Controls.Add(lb5)
            renato += 25
            dplab(i) = lb5
        Next
        Return 0
    End Function
    Public Function borrar_metodo(ByVal choice1 As String)
        Dim y As Integer
        y = choice1
        Dim a As Integer
        For a = 1 To y
            Form1.Panel6.Controls.Remove(metod(a))
        Next
        Return 0
    End Function
    Public Function borrarpvst(ByVal choice1 As String)
        Dim y As Integer
        y = choice1
        Dim a As Integer
        For a = 1 To y
            Form1.Panel8.Controls.Remove(tolab(a))
        Next
        Return 0
    End Function
    Public Function borrar_dp1(ByVal choice1 As String)
        Dim y As Integer
        y = choice1
        Dim a As Integer
        For a = 1 To y
            Form1.Panel7.Controls.Remove(dep(a))
            Form1.Label36.Text = Form1.Label28.Text
        Next
        Return 0
    End Function
    Public Function borrar_dp_vs_t(ByVal choice1 As String)
        Dim y As Integer
        y = choice1
        Dim a As Integer
        For a = 1 To y
            Form1.Panel8.Controls.Remove(dplab(a))
        Next
        Return 0
    End Function
    Public Function borrar_dp_vs_t_b(ByVal choice1 As String)
        Dim y As Integer
        y = choice1
        Dim a As Integer
        For a = 1 To y
            Form1.Panel8.Controls.Remove(bd(a))
        Next
        Return 0
    End Function
```

```
    Public Function borrar_p_vs_t_b(ByVal choice1 As String)
        Dim y As Integer
        y = choice1
        Dim a As Integer
        For a = 1 To y
            Form1.Panel8.Controls.Remove(bm(a))
        Next
        Return 0
    End Function
    Public Function cero3()
        If Form1.Label22.Text = 0 Then
            MessageBox.Show("No results for the option chosen")
            Form1.Button18.Hide()
            Form1.Button19.Hide()
            Form1.Panel3.Hide()
            Form1.Button16.Enabled = True
            Form1.Button17.Enabled = True
            Form1.Panel2.Enabled = True
            borrar_objetivos(Form1.Label11.Text)
            borrar_plc_t(Form1.Label15.Text)
            desplegar_objectivos(Form1.Label13.Text)
            Desplegar_plc_t()
            borrar_subp(Form1.Label22.Text)
        End If
        Return 0
    End Function
    Public Function borrar_guias(ByVal choice1 As String)
        Dim y As Integer
        y = choice1
        Dim a As Integer
        For a = 1 To y
            Form1.Panel5.Controls.Remove(guide(a))
            Form1.Panel5.Controls.Remove(b1(a))
        Next
        'Form1.Label18.Text = Form1.Label28.Text
        Return 0
    End Function
    Public Function cero4()
        If Form1.Label27.Text = 0 Then
            MessageBox.Show("No results for the option chosen")
            Form1.Button20.Hide()
            Form1.Button21.Hide()
            Form1.Panel4.Hide()
            Form1.Button16.Enabled = True
            Form1.Button17.Enabled = True
            Form1.Panel3.Enabled = True
            borrar_subp(Form1.Label22.Text)
            desplegar_P_Sp_Plc_t(Form1.Label18.Text, Form1.Label17.Text)
        End If
        Return 0
    End Function
    Public Function cero5()
        If Form1.Label27.Text = 0 Then
            MessageBox.Show("No results for the option chosen")
            Form1.Button7.Hide()
            Form1.Button4.Hide()
            Form1.Panel4.Hide()
            Form1.Button5.Enabled = True
            Form1.Button2.Enabled = True
            Form1.Panel3.Enabled = True
            borrar_subp(Form1.Label22.Text)
            desplegar_P_Sp_Plc_t(Form1.Label18.Text, Form1.Label17.Text)
        End If
        Return 0
    End Function
    Public Function count_bot1()
        misDatos.Close()
        Dim Miconexion As New OdbcConnection(Conectar)
        Miconexion.Open()
        comando.Connection = Miconexion
        comando.CommandText = "select count(distinct Example) from principles_vs_tools where Principle_name IN " + Form1.Label18.Text + " and Methodology IN (" + Form1.Label33.Text
+ ")"
        misDatos = comando.ExecuteReader
        While (misDatos.Read())
            Form1.Label48.Text = misDatos.GetString(0)
        End While
        Return 0
    End Function
End Module
```

Vita

Pedro Renato Acosta Herrera was born in Hidalgo del Parral, Chihuahua, Mexico. The second son of Pedro Acosta Torres and Angelica Herrera Acosta, graduating from Colegio de Bachilleres #6, Ciudad Juarez, Chihuahua in the fall of 2002 and entered The University of Texas at El Paso in the spring of 2003 completing the required examinations. While pursuing the bachelor's degree in mechanical engineering, he helped his parent in fabricating and repairing boots in his Dad's shoe shop. Later, he was hired by the Union Services to start working as an audio/video technician where he worked for one year until he graduated in the fall of 2007. Afterwards in 2008, he was hired by a transportation electronics company called Stoneridge working for two years as a mechanical design engineer. He attained design experience while enhancing his career experience by developing several products and improving designs. During the second year of his full time position experience, he decided to join graduate school in the fall of 2009 where he started performing research in the area of design. He wrote the paper named: *"An Expert System to Teach Engineering Students Sustainability and Creativity Design Method Selection"* that was accepted in the *118th ASEE (American Society of Engineering Education) Annual Conference & Exposition.*

Permanent address: 535 S Mesa Hills Apt 1415
El Paso, TX, 79912

This thesis/dissertation was typed by Pedro Renato Acosta Herrera.