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Development of an expert system to aid engineers in the selection of design for environment methods and tools

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ABSTRACT

Despite the importance of the matter and significant research efforts extended, adoption of the sustainability tools and methods to design and produce more sustainable products is slower than desired. This has been attributed to the extensive and complex nature of the relevant knowledge landscape, which also makes it harder on non-expert engineers to select appropriate tools. As a response to this problem, a sustainability tool and method adviser (GREENESYS) is developed. In the paper, we provide the rationale, methodology, and application steps of this expert system development along with an evaluation of it. Our results point to the efficiency and effectiveness contribution of this expert system in design settings, where the designer answers a few simple questions about the design task and GREENESYS recommends appropriate sustainability tools and methods. GREENESYS can also be used as an educational tool by disclosing the selection process; and as an indicator to identify design tasks that have not been addressed by sustainability researchers.

1. Introduction

The use of Design for Environment (DfE) methodologies has gained momentum as new legislation on product development requires companies to design and manufacture for a lower carbon footprint, and society in general acknowledges the need to actively protect the environment. Accordingly, design engineers have the important role of adopting environmental considerations in their design process in order to design products that are less harmful to the environment. This adoption might involve various DfE strategies including minimizing resource consumption, selecting low impact resources and processes and optimizing product life (Vezzoli & Manzini, 2008).

One clear example of minimizing resource consumption category is the solar cooker, an easy to build and inexpensive cooking system. It is made of a parabolic reflective panel and a plastic bag. In areas with high insolation index, it can save up to half of the fuel (e.g., petrol, biomass) consumption; and if firewood is used as fuel, it can reduce deforestation (Vezzoli & Manzini, 2008). Another example is the i-Magic Fortius, an exercise bicycle that stores energy to a power network ready to be utilized by any electric device such as a computer or television.

Designers working on selecting low impact resources and processes have created devices that utilize non-toxic (e.g., renewable, no-emission) energy. For example, Seiko wristwatches use the kinetic technology, which is powered by human movement. Any arm movement is transformed into a magnetic charge and then stored into a rechargeable battery capable of running up to 5 months Vezzoli and Manzini (2008). Another example worth mentioning is the hydrogen powered FIAT Panda. Unlike other potentially harmful fuels such as gasoline or diesel, the use of hydrogen in this automobile does not produce contaminants or emissions harmful to the environment.

Despite these good examples of DfE applications, there are multiple factors keeping a majority of companies from fully adopting sustainable design practices (i.e., DfE methodologies and tools). Boks and Pascual (2004) suggest that these obstacles are mostly non-technical (i.e., not related to the execution of the method or tool), relating more to the management aspects (i.e., who decides what methods to use). Confirming this, various other researchers have analyzed the integration of DfE methodologies and tools into the design process (Handfield, Melnyk, Calantone, & Curkovic, 2001; Johansson, 2000; Lindahl, 2003, 2006; Mathieux, Rebitzer, Ferrendier, Simon, & Froelich, 2002; Tukker et al., 2001) and suggested that the obstacles and success factors lie on the "soft side of eco-design", pertaining to who decides what methods to use, or how is that decision made.

When a designer decides to improve the sustainability characteristics of a design, he/she will find a variety of tools in the DfE literature. How can a designer select the most appropriate tool for the design at hand? Experienced designers will know the answer,

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or at least, where to start looking for it. Inexperienced designers will have difficulties since (1) many options may be available, (2) the descriptions may be too general or unclear, even with explicit application examples, and (3) it may be difficult to translate the tools to a practical context. Learning and applying any DfE tool has its challenges, but one cannot reach this point before first selecting a tool. Selection and application of the most appropriate tool is made difficult by the vast availability of tools and not having the necessary knowledge or experience (Reyes & Rohmer, 2009; Telenko, Seepersad, & Webber, 2009). This appropriate tool selection difficulty has implications for the performance of the design process as the tools need to be incorporated to it.

According to Telenko et al. "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" (2008). Consequently, there is a need to synthesize methodologies to provide existing, emerging, and future DfE guidelines in a useful way to engineers and designers. Artificial intelligence provides approaches to transform observed expertise into accessible knowledge. The first expert systems were created to capture the stored experience of a single subject matter expert. Since that time, more approaches have been developed that can be used when aggregating knowledge from a variety of subject matter experts in any area of research or practice.

This paper presents the GREENESYS, GREen ENgineering Expert SYStem, an expert system framework prototype for the selection of DfE methods and tools. As previously mentioned, integration of DfE methods and tools into the design process is not complete and there is a need for this type of a tool to help novice designers. The objective of the proposed expert system tool is to fill this void by providing expert advice on DfE methods and tools to improve the design process.

For our development effort, we adopt Syamil, Doll, and Apigian, (2004)'s motto and assert that by improving the process performance (in this case the design process) through the implementation of GREENESYS, we intend to improve the outcomes. Accordingly, in the paper, we also present a utility analysis of GREENESYS focusing on two performance measures: (1) efficiency of the process, and (2) effectiveness of the process. In the following sections, we first present the methodology with which we have developed the GREENESYS, and provide extensive details for each development step. Utility analysis precedes the conclusions.

2. Expert system development methodology

How does a designer know which DfE techniques and tools to use? The answer is expertise, either from their own experiences, or borrowing that expertise from somebody else by soliciting advice. An expert DfE designer considers many factors in selecting DfE techniques and tools including: (1) application type (automotive, mechatronic, electronic, etc.), (2) design process step (conceptual, embodiment, detail), and (3) product life cycle target to improve (production, distribution, use, and disposal). A human expert will consider other non-technical aspects before imparting advice such as: designer's background, resources allocated (time, personnel, software, hardware, etc.), management's priority, and even the designer's preferences. A good expert system should be able to mimic this behavior to a large extent.

The development process for the expert system (GREENESYS) followed three steps, which are displayed in Fig. 1. The first step is to characterize the knowledge and create a conceptual map that identifies the elements involved, their relationships, and the sequence of the process. The conceptual map represents an understanding of the expert's knowledge in simple terms. This conceptual map is then translated into a logical model to ensure that contradictions and redundancies are identified and cleared. This step shapes the software architecture, and hence is the intermediate step for its programming implementation. The logical model is then implemented physically using a programming language.

In order to represent the knowledge, there exist three main approaches: (1) relational tables, (2) case-based reasoning system, and (3) knowledge-based reasoning system. The knowledge could be represented as relational tables (RT), for which a database management system is most appropriate. For success with this approach, knowledge must be readily available in the format of succinct, specific, segments that can be organized by topic along with defined relations among segments. An additional advantage of *Relational Tables* is that updating and adding information is easy. Relational tables are not recommended for complex relations among elements, such as hierarchies or networks (Gorman, 1991).

DfE knowledge can be also represented as a collection of cases in a case-based reasoning system (CBR). Cases are an efficient and practical learning tool. Their disadvantage is determining how to index (i.e., organize) the cases for retrieval. Another challenge is populating the system with a wide variety of cases. CBR approaches are only as useful as their indexing system (Aamodt & Plaza, 1994; Kolodner, 1992).

Finally, DfE knowledge can be represented using a series of if-then rules in a knowledge-based reasoning (KBR) system. A definitive characteristic of the KBR system is the applicability of the rules; if the rules are too strict, the system will unnecessarily reduce possible advice. If the rules are too general or relaxed, the system will provide too many answers possibly defeating the purpose of the system (Brachman, Levesque, & Reiter, 1992; Kaufmann, 1993; Vargas-Hernandez, Shah, & Lacroix, 2002).

Given the disadvantages of case-based and knowledge-based systems, as it will be seen in the following sections, the conceptual model for the expert system indicates that the relational tables (RT) are the most appropriate approach to represent the expert knowledge. The development methodology steps are explained in the next section.

3. Application

The development steps identified at the macro level are further detailed below.

3.1. Knowledge analysis

During the knowledge analysis step, the landscape of the DfE knowledge domain is studied through prominent review papers, followed by characterization of tools and methods, and definition of the knowledge flows (i.e., the sequence of steps and their inputs and outputs). These activities are summarized below.

Ramani et al. (2010) presented a classification of research papers according to life cycle stages, shown in Fig. 2. Research work surveyed focuses on each stage of the product life cycle (Design, Manufacturing, Supply Chain, End-of Life). When investigated deeper, however, it is seen that even when papers are classified as relating to latter stages in product or system production, they also are a fundamental concern during initial design (e.g., Design for Sustainable Manufacturing, Design for Green Supply Chain, Design for Sustainable EOL). This relation is shown in Fig. 2 with the dash lines going from the later stages of design to the main design box (Design/Life cycle design).

3.2. Techniques and methods

Vezzoli and Manzini (2008) define Design for Environmental Sustainability as the inclusion of product life cycle processes and

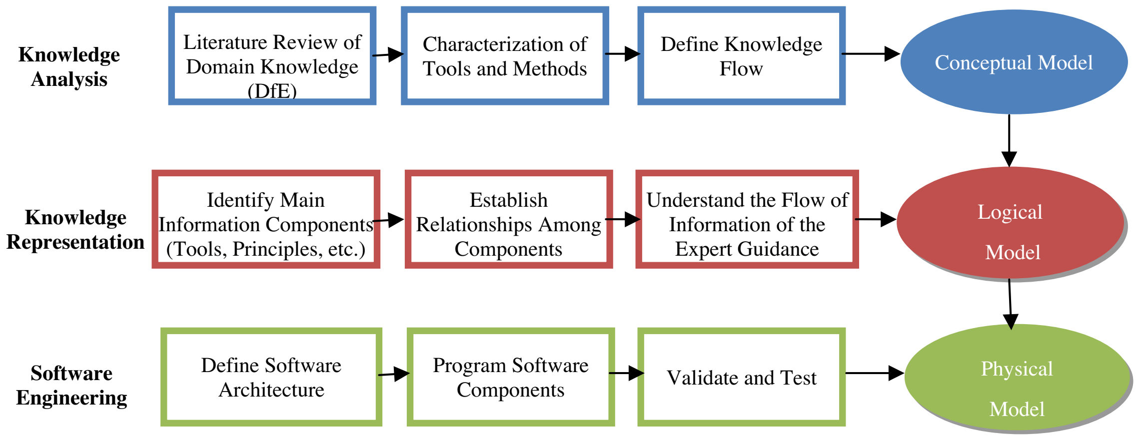

Fig. 1. Expert system development roadmap.

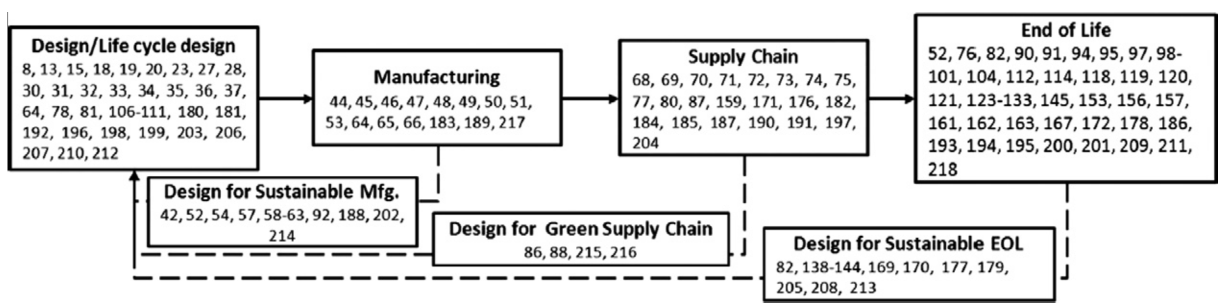

Fig. 2. Classification of research papers according to life cycle stages (Ramani et al., 2010).

life cycle assessment into the design process. DfE considers future life cycle processes during the design process; these are usually divided into preproduction, production, distribution, use and disposal. Five principles to implement sustainable measures into a product are suggested (2008):

- 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 the different potential applications in more depth. Principles provide foci and goals, and guidelines refer to specific applications to achieve the specific goals.

There are additional techniques and tools that aid in the sustainable development when designing a product. These tools can either be employed at the beginning of the design process or whenever a preliminary solutions has been obtained. These techniques and tools have proven to be relevant to users, and have been grouped into five sections (Bhamra & Lofthouse, 2007) as shown in Fig. 3.

Environmental assessment tools can help evaluating the performance of a product in sustainability measures 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 strategies provide techniques to gather information regarding the use phase of the product for enhancing the product's architecture. Finally, information provision

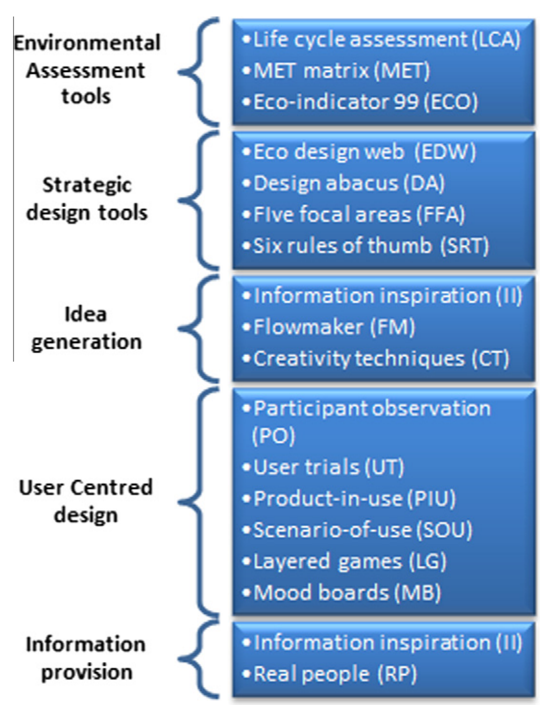

Fig. 3. DfE techniques and tools (Bhamra and Lofthouse, 2007).

techniques are used to learn the user's requirements and preferences in terms of utilizing products (Bhamra & Lofthouse, 2007).

Utilizing principles, guidelines and tools is viewed as favorable to improve a product's quality while reducing environmental

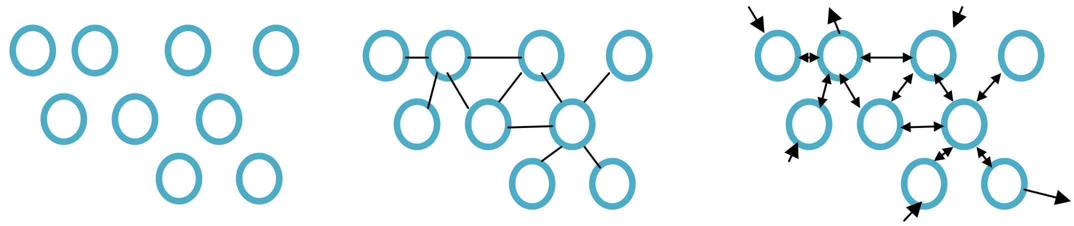

Fig. 4. Conceptual model development.

impact. The principles, guidelines, techniques, tools and methods presented here are representative of the research work done in DfE. These will be the starting point for the expert system as we expect it to evolve in the future to include more of the richness in DfE research.

One critical component of the knowledge domain is incorporation of the sustainability à propos to the designed product life. Product life maximization is driven by durable products that are designed to provide more than one function (e.g., all-in-one printers having fax, scan, copy and printer functions (Vezzoli & Manzini, 2008). Other life-prolonging DfE applications involve the ease of maintenance, for example for engines. Most engines have a modular structure with easy access to key components to facilitate maintenance.

3.3. Knowledge flow and relationships

Mapping the knowledge landscape into a conceptual model requires identification of the entities (elements of information), the relationships among those elements, and the processes (flow of information), as shown in Fig. 4.

Various DfE principles, guidelines, methodologies, techniques and tools exist. The entities (in Fig. 4a) are established as a result of analyzing available literature. Additional entities are defined by the authors as inputs and outputs. Each input entity represents a prompting question posed to the user as follows:

(1) What is your design objective? Extend usage, reduce transportation cost, etc.
(2) What life cycle stage do you intend to impact? Production, distribution, use, etc.
(3) Where are you in the design process? Requirement list, principle solution, etc.
(4) What is your desired strategy? Reduce material, maintenance, etc. (refinement option).
(5) What type of methodology would you choose? Environmental assessment, strategic design, etc. (refinement option).

Questions 1–3 are required to obtain an answer while questions 4 and 5 are refinement options (i.e., the user has the option to answer or not). The outputs are the guidelines and tools that the designer can apply. Choosing a DfE method or tool such as "extend usage guideline" or "lower environmental impact via study" or selecting an approach from 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.

Based on the literature review, 10 different relationships were identified, and are shown in Table 1. The objective of relationship definition is to figure out how the entities relate to each other and what would be the sequence that an expert would follow from input to output. Each relationship represents a relational table that exists in the expert system. The introduction of Type of Methodology, Design Process, Sub-principles, Life Cycle Impact, and Approach and the corresponding relationships are explained in more detail below.

3.3.1. R1: Type of methodology vs. techniques and tools and R2: design process vs. techniques and tools

Sample type R1 and R2 relationships are given in Table 2, where only a segment of each table is shown for brevity. R1 and R2 relationships are between the design process stages and DfE, DfA, and other design for "X" constructs. These *design for* principles and guidelines involve decision making when initiating the design process and usually have a downstream impact (Sutcliffe, Maier, Moultrie, & Clarkson, 2009). The left column entries represent design process stages recommended by Pahl, Beitz, Feldhusen, and Grote (2007) and the right column entries represent techniques and tools provided by Bhamra and Lofthouse (2007). Techniques and tools have been grouped based on type of methodology and catalogued according to the applicable design process stage. The meaning of the acronyms can be found in Fig. 3, which shows categorization of techniques and tools.

3.3.2. R3: Principles vs. techniques and tools

Table 3 depicts relationships between characterization of principles and techniques and methods. Left column shows the five main principles in DfE from Vezzoli and Manzini (2008) and, again, techniques and tools by Bhamra and Lofthouse (2007).

3.3.3. R4: Principles vs. objectives

Table 4 associates DfE principles to higher order design performance criteria. Authors propose three groups of objectives in order to facilitate the organization of principles. The left column shows principles by Vezzoli and Manzini (2008) and the right column relates the objectives to the applicable principles.

3.3.4. R5: Sub-principles vs. objectives

Table 5 indicates how the sub-principles from Vezzoli and Manzini (2008) apply to the applicable proposed objectives.

3.3.5. R6: Life cycle impact vs. sub-principles and R7: principles vs. sub-principles

Athalye, Govindarajan, Lopez, Esterman, and Rothenberg (2009) report the commonly employed methods in design for sustainability such as guidelines focusing on impacting life-cycle stages. Table 6 shows an example categorization including principles, sub-principles and the impacted life cycle stage.

3.3.6. R8: Approach vs. sub-principles, R9: guidelines vs. sub-principles and R10: approach vs. guidelines

Table 7 shows the R8, R9, and R10 relationships between sub-principles, guidelines and proposed criteria (i.e., approach).

Table 1
Identified relationships.

ID	Entity	Entity
R1	Type of methodology	Techniques and tools
R2	Design process	Techniques and tools
R3	Principles	Techniques and tools
R4	Principles	Objectives
R5	Sub-principles	Objectives
R6	Life cycle impact	Sub-principles
R7	Principles	Sub-principles
R8	Approach	Sub-principles
R9	Guidelines	Sub-principles
R10	Approach	Guidelines

Table 2
Excerpt from relationships 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

Table 3
Excerpt from relationship R3.

Principles	Techniques and tools		
	Environmental assessment	Strategic design	Idea generation
Minimizing resources consumption	LCA, MET, ECo	EDW, DA, EFA, 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

Table 4
Excerpt from relationship 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

Table 5
Excerpt from relationship R5.

Sub-principles	Objectives		
	Extend usage	Reduce material usage	Reduce maintenance costs
Design for appropriate 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	

Table 6
Excerpt from relationships R6 and R7.

Principle	Sub-principles	Life cycle phase		
		Pre-production	Production	Distribution
Selecting low impact resources and process	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		

Table 7
Excerpt from relationships R8, R9 and R10.

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

Sub-principles and guidelines are provided by Vezzoli and Manzini (2008). The left column represents sub-principles while the right column shows guidelines correlated to proposed criteria according to their description.

Once knowledge elements and their relationships are defined a conceptual map can be constructed. Whenever an input is received from the user the expert system maps through the tables finding appropriate guidelines and tools. The qualifying methodologies are then located and provided to the user. The conceptual map identifies the knowledge elements involved, their connections, and the sequence for identifying appropriate knowledge elements in response to a query. The conceptual map represents an understanding of the knowledge in simple terms. This conceptual map is then translated into a logical model to ensure that contradictions and redundancies are identified and cleared. It also serves as an intermediate step for its programming implementation. The logical model is then implemented physically using a programming language or tool.

The proposed system's conceptual model was developed in an iterative process. Fig. 5 is a representation of the model. An enabling discovery in the creation of this model was that the principles and sub-principles act as pivots (or joints) integrating all elements and connecting input and output entities as shown in Fig. 5.

In Fig. 5, 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

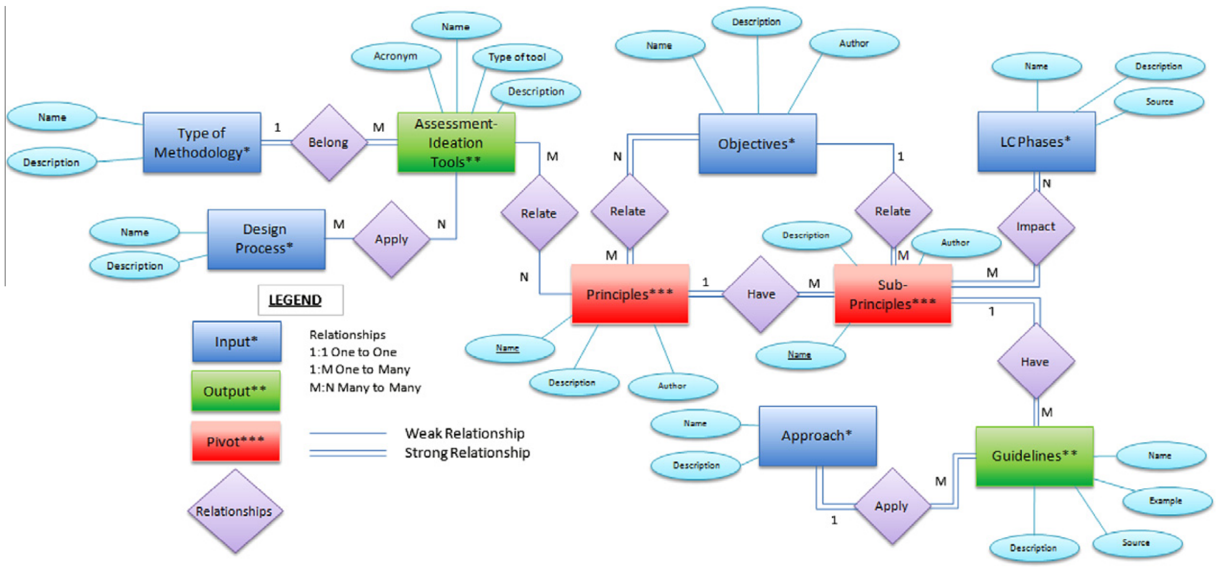

Fig. 5. Conceptual model for the expert system.

techniques or both and guidelines recommended to the user. The output will depend on how the inputs are defined and the relationships between the entities. It is possible to have several recommendations or none at all. For example, if the user wants to know what guidelines (output) to apply, the expert system will ask one or more of the inputs (objective, approach, etc.) and the relational tables will be queried and filtered to identify to select the guidelines that relate to the specific inputs.

3.4. Knowledge representation

In this phase of the expert system development, the conceptual map is transformed into an entity relationship model. According to Dietrich (2001), "The goal of a conceptual data model is to capture the constraint of the enterprise at a higher level of abstraction than the level of implementation".

The Entity Relationship (ER) model, utilizing a graphical notation, is used to represent the activity constraints. The ER diagram can have numerous elements depending on the situation; the one generated for the sustainable expert system is mainly composed of the following elements (Dietrich, 2001): entities, attributes, relationships, cardinality ratios, and participation constrains.

Entities in 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 constraints regarding the number of 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 constraints state whether an entity does or does not need to participate in a relationship and are represented by a single or double line. A 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.

Fig. 6 depicts the logical reasoning of the DfE expert system. This diagram is acquired from subjecting the conceptual model to follow a logical pattern. 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 by the query engine by creating relationships in the relational databases. This process will be explained in the following sections.

3.5. Standard query language (SQL)

In order to retrieve data contained within the databases (i.e., relational tables), standard query language (SQL) was used. SQL is a declarative language that provides tools to retrieve data by means of an algebraic expression (Dietrich, 2001). Following the guidelines on the W3Schools website (2011), syntax was developed to extract information from the databases in response to input from the user. The approach taken was to define a sequence of simple questions that an expert would ask to arrive at the DfE methods and tools in response to an inquiry from someone seeking advice. That sequence was then structured as a series of SQL commands to relate the inputs to the outputs through relational databases, sequentially filtering the possible output. 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 +")"

This query searches for the Design Process vs. Tools table to obtain the Tool(s) that match a specific Design Process (called Label36) and Methodology (called Label33). All these commands were placed into debugging software to allow the software tool to extract data from the databases.

3.6. Software engineering

In the physical layer, the conceptual and logical models are converted into tangible information elements. In other words, software applications are utilized to develop the sustainable expert system. The phpMyAdmin (2011) (an open source web-based administrator for MySQL) software tool was utilized to create databases using the conceptual data. The phpMyAdmin was selected because of its simplicity and availability. The logical model provided the structure (i.e., what tables relate to what), and each entity was populated in a table with the corresponding information identified in the literature (e.g., tool, methodologies, objectives). The resulting database and associated queries comprise the expert system. Fig. 7 shows the phpMyAdmin application with the list of relational tables.

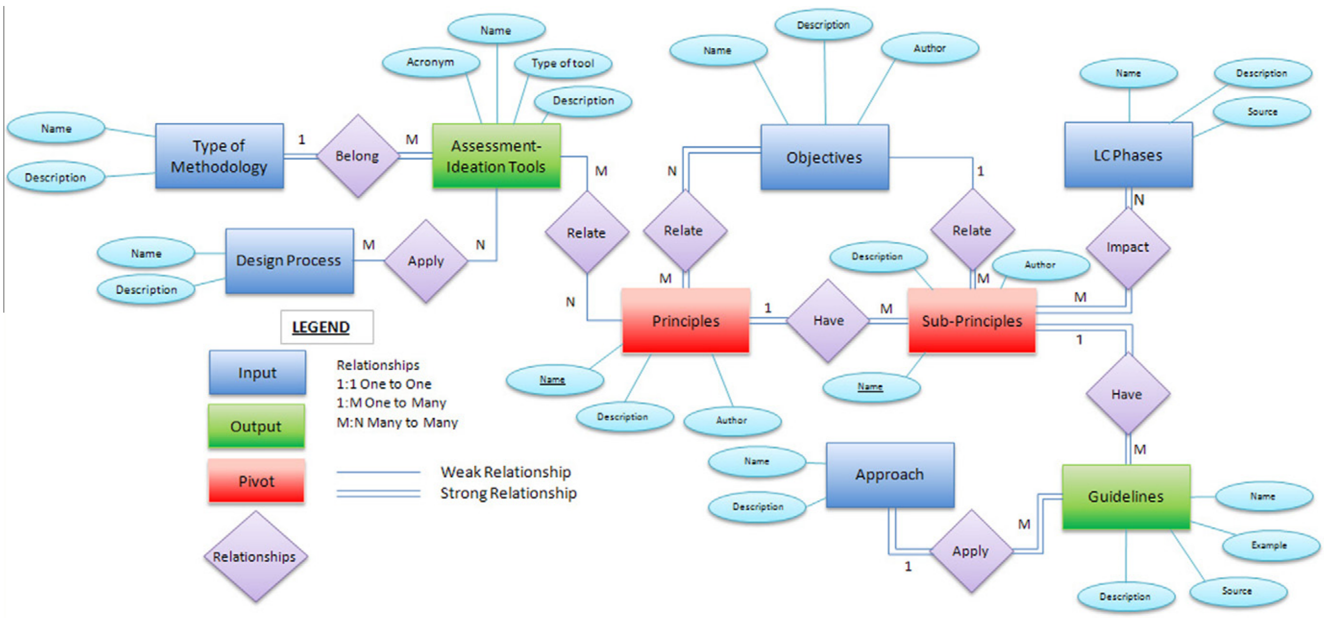

Fig. 6. Entity relationship diagram for the expert system.

The ‘‘Table’’ column in Fig. 7 shows each table created for the expert system. A total of eleven tables were generated and all these tables were connected to the debugging software through an ODBC connector (a standard software interface for accessing the DBMS). Finally, the Visual Studio software was used to create a graphical user interface. Visual Studio (Microsoft) (2011) is a software application that allows designing and deploying windows-based applications through the use of codes. The expert system program was developed as a proof of concept with only the basic functionality features. Fig. 8 shows a screenshot of the application including commands and codes for the expert system.

4. Description of the final product and utility analysis

The final product is a program with a graphical user interface that allows users to rapidly familiarize themselves with the functionality of the software. The objective is not only to provide the expert advice (i.e., outcome), but also to educate the user on the expert reasoning represented. A screen shot of the application is provided in Fig. 9. There are three options available at the start of the selection process; you can either choose guidelines and tools, guidelines only or tools only depending on the situation.

For example, when a user selects ‘‘Guidelines’’, option (1) in Fig. 9, the system asks the first question (2). Based on the answer, the system displays the ‘‘Principles that apply to your objective’’ (3); those can be checked on or off. The second question ‘‘Which product life cycle would you like to impact?’’ (4); depending on the selection, a list of ‘‘Sub-Principles applying to your objective’’ (5). Depending on the sub-principle(s) selected and the selection for ‘‘What is your approach’’ (6), the ‘‘Recommended Guidelines (7) are presented.

The user has the option to access examples associated with each recommended guideline, as shown in Fig. 10.

The utility of the expert system (GREENESYS) was tested in terms of efficiency and effectiveness of providing solutions to three different industrial design tasks with varying green design foci. Efficiency was measured as the elapsed time to arrive at a solution strategy. Effectiveness is evaluated through comparison of the generated solution strategies to the ones gathered from the industrial company sources. Ten undergraduate and graduate engineering student subjects were recruited to partake in the utility testing. The design tasks selected, shown in Table 8, are sustainable implementations completed by selected companies to alleviate the environmental impact on their products. Using the expert system does not require a strong background on design. For the experiment, some students used the expert system while other students used the provided textbooks or another controlled information source (e.g., reference books) as the resource to find a suitable answer. Given access to these knowledge-bases (i.e., GREENESYS and other sources), students were asked to provide an answer for each design exercise, and an answer key was generated containing potential guidelines and applicable tools. Answers were compared to the key to assess the level of correctness.

Elapsed time was measured for providing a solution strategy (i.e., guideline and tool) for each design exercise. During the assessment, students spent a considerable amount of time in familiarizing themselves with the DfE topic. 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 exercises. After the students finished their reading and researching, their time spent was recorded. Students completing the first reading assignment were asked to use the expert system software to answer the same questions and the time elapsed was also recorded.

Table 9 displays elapsed times for each subject as well as averages and standard deviation. Elapsed time recorded for the books column clearly shows higher values than the ones recorded for the expert system column. Students spent more time when using books as resources to search for methodologies. Observations on the use of books spanned the range from 25 min to 43 min. On the other hand, when students used the expert system as the auxiliary tool, results obtained for maximum and minimum values were smaller. Student 1 took only five minutes to propose guidelines and tools while Student 4 spent 24 min. The average time recorded for each student, was significantly different from reading a book than for using the expert system. This clearly depicts that the use of the expert system reduced the time needed to find the solution strategy.

An effectiveness assessment was also performed after the design exercise was completed. Certain values were given to each

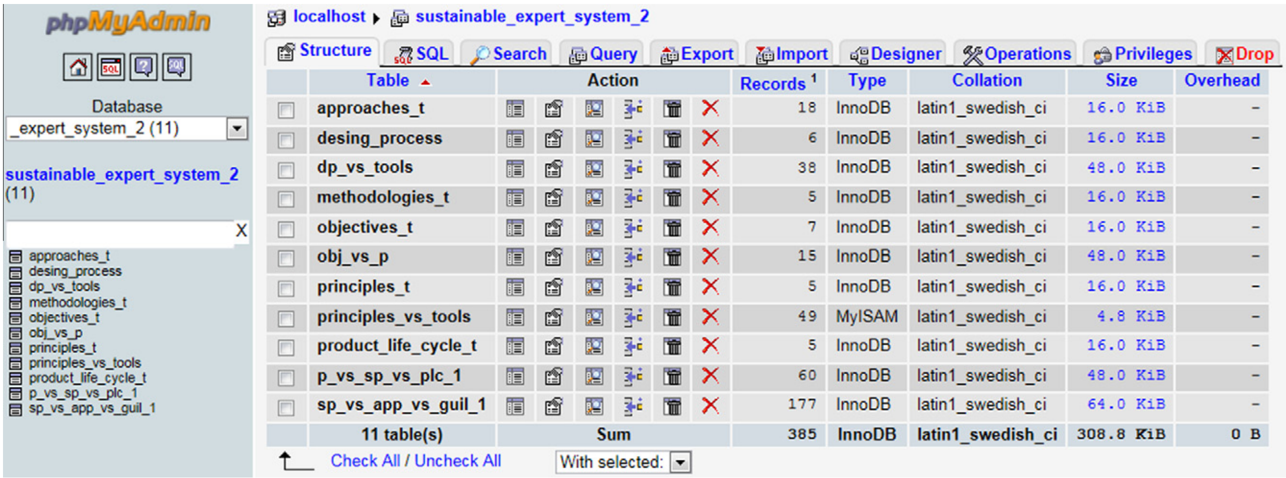

Fig. 7. Expert system application in phpMyAdmin.

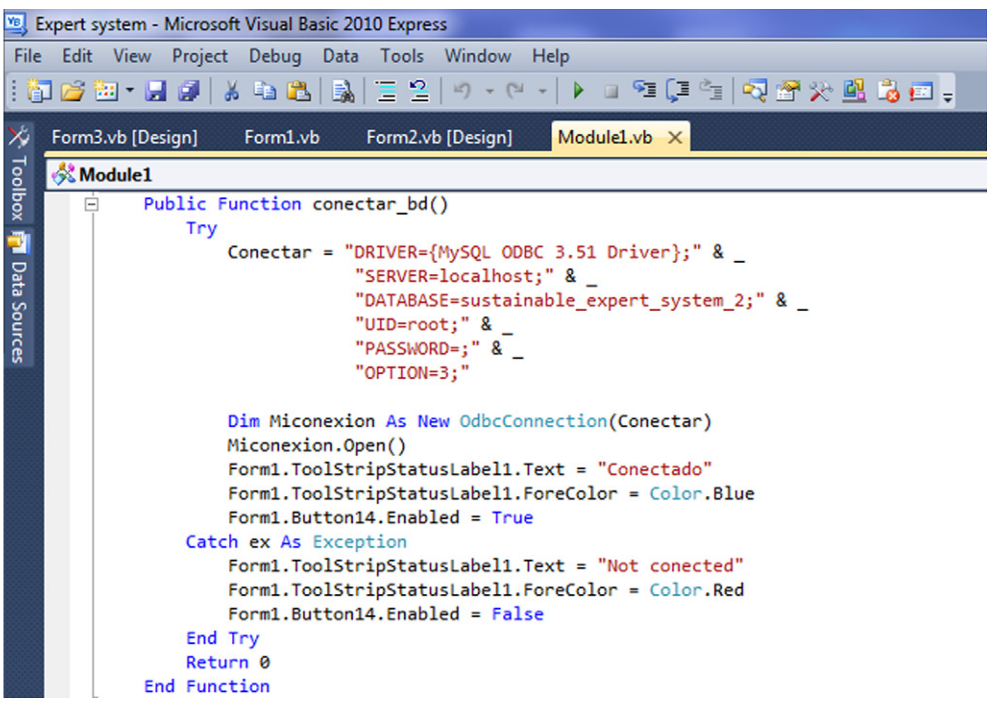

Fig. 8. Visual studio code for the expert system graphical user interface.

question 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. Points awarded for each student across three design exercises are displayed in Table 10.

Points were summed for each question including the calculation of the standard deviation and the average. By simple inspection, it is seen that values registered for the sustainable expert system were higher than the ones recorded for the books. Zeros appear as values where students did not score and this is due to incorrect answers (i.e., guidelines and tools). As for the average for each question, the expert system provided more accurate results on the three questions. The standard deviation for question 2 though was higher for the expert system in question two compared to the one from the books column.

Three separate *t*-tests were done to test the significance of the differences across three questions. In all cases, two-tailed tests were done for a 95% confidence interval. For all three data pairs the differences were significant with *p* values 0.015, 0.023 and 0.05, respectively. Based on these, we state that GREENESYS was effective in increasing the accuracy of the responses.

A post-design task activity was performed with the purpose of verifying the effectiveness of the graphical user interface (GUI) and whole functionality of GREENESYS. Test subjects were interviewed to investigate what aspects of the expert system 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 expert system tool.
- Students would like to choose more than one objective.
- Relationships among entities should be shown somewhere on the expert system GUI interface.

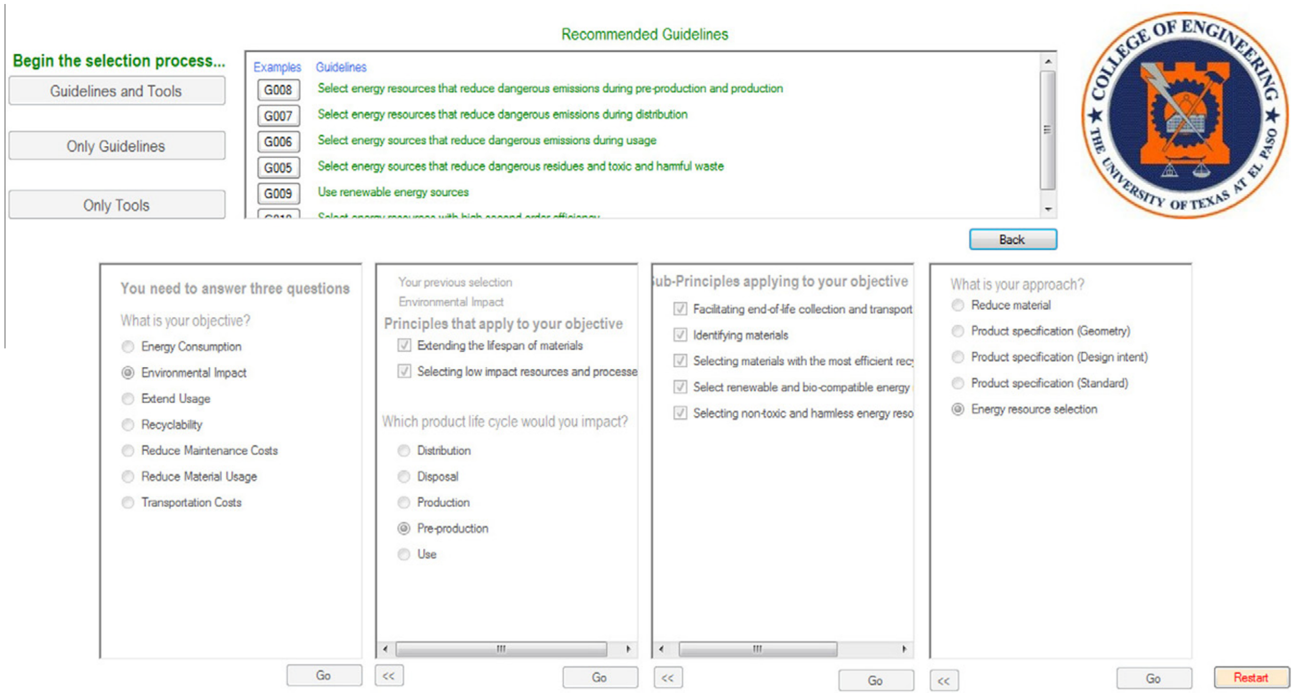

Fig. 9. The sustainable expert system – GREENESYS.

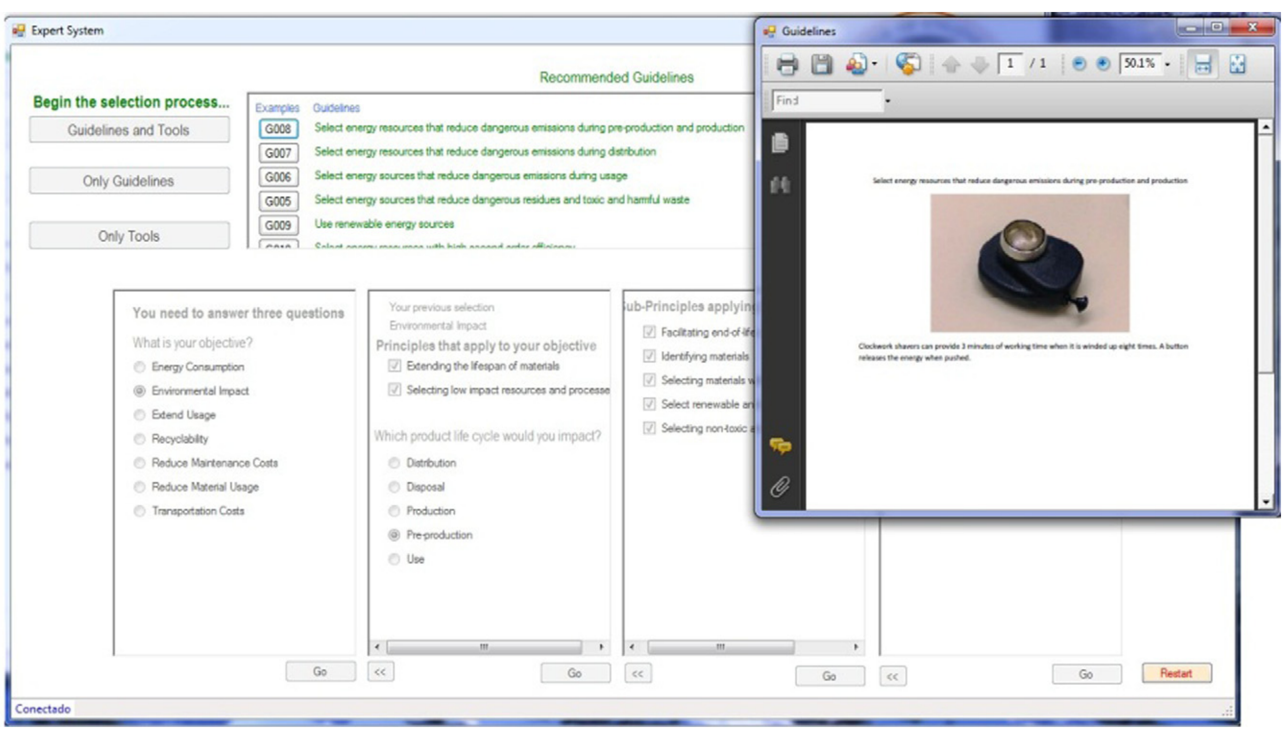

Fig. 10. Guideline example from GREENESYS.

- 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 an interest in the examples provided at the end of the question answering process. The actual examples can help them understand the nature of the guideline as well as stimulate their idea generation while applying 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, similar comments were made on the tools' examples which helped students getting familiar with state of the art DfE tools.

Table 8
Experiment exercises.

Introduction
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 functionality and utility of GREENESYS by using it as a software tool to retrieve applicable methodologies

1. HP Exercise (Hewlet Packard, 2009)
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 GREENESYS, 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. Ford Exercise (Ford Motor Company, 2009)
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 this goal, alternative energy resources must be selected as the main source of energy of a car
Use GREENESYS to find applicable guidelines and tools. These guidelines and tools 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 Exercise (Apple, 2010)
Apple is a growing company continuously developing products utilizing state of the art technology. However, the initiation of any technology can also cause adverse environmental impact although the features on some products are intended to have green aspects. According to Apple's sustainability reports, they have continuously reduced their CO_2 production in all the phases of the product life cycle
Use GREENESYS 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?

Table 9
Efficiency 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

5. Conclusions and recommendations for future development

This DfE expert system, GREENESYS, provides a practical solution to a complex problem. The available DfE methods and tools is continuously growing; this by itself is great news, but it makes it more difficult for a designer (current and future) keep up to date. Capturing the expertise makes designers more effective and efficient, in terms of time and effort, as well as the quality of the results. The expert system can be expanded with more DfE information to be included in the tables. Additional functionality can be added by structuring queries. An additional quality of the expert system is the educational functions; the designer will use it to obtain an answer as well as to understand the selection logic.

Table 10
Effectiveness 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
Students	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
Stan. dev.	6.76	8.83	7.94	4.92	13.20	6.78

It is expected that the designer absorbs the expertise and eventually has no need to use it anymore, becoming an expert.

Several improvements are possible, however. For example, educational aspect could be improved by showing a brief explanation of the queries performed. The graphical user interface can be improved by allowing the user to interact with the entity-relationship diagram to define the inputs and display the outputs of the system. Furthermore, the expert system could be enriched by including practical application cases for each DfE principle and tool. Alternatively, the user could explore the expert system through a Case Based Reasoning system to arrive to the DfE principles and tools. In this way, the user can arrive to the DfE principles and tools from the characterized knowledge approach (answering the given questions) and then access the related cases, and similarly, navigating the CBR system using a more practical application approach to arrive to the DfE principles for the selected case(s), and then connect to the characterization of knowledge. Finally, GREENESYS can also be indirectly used to identify areas of opportunity in DfE research when the expert system output is deficient (i.e., few or no outputs) for a given design task.

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References

Aamodt, A., & Plaza, E. (1994). *Case-based reasoning: Foundational issues, methodological variations, and system approaches*. <http://www.iiia.csic.es/People/enric/AICom.html>.

Apple (2010). *iPad: Environmental report*. <http://images.apple.com/environment/reports/docs/iPad_Environmental_Report.pdf>.

Athalye, S.A., Govindarajan, S.K., Lopez, C.A., Esterman, M., Jr., & Rothenberg, S. (2009). Challenges in incorporating sustainability into product development: an exploratory study. DETC2009-87637. In *San Diego: Proceedings of the ASME 2009 international design engineering technical conferences & computers and information in engineering conference*, IDETC/CIE 2009.

Brachman, R. J., Levesque, H. J., & Reiter, R. (Eds.). (1992). *Knowledge representation*. Cambridge: The MIT Press.

Bhamra, T., & Lofthouse, V. (2007). *Design for sustainability: A practical approach*. Hampshire: Gower Publishing Limited.

Boks, C., & Pascual, O. (2004). The role of success factors and obstacles in design for environment: A survey among Asian electronic companies. In *IEEE international symposium on electronics and the environment 2004*.

Dietrich, S. W. (2001). *Understanding relational database query languages*. Upper Saddle River: Prentice Hall.

Ford Motor Company (2009). *Blueprint for sustainability: The future at work*.

Gorman, M. M. (1991). *Database management systems: Understanding and applying database technology*. Wellesley: QED Information Sciences, Inc.

Handfield, R. B., Melnyk, S. A., Calantone, R. J., & Curkovic, S. (2001). Integrating environmental concerns into the design process: The gap between theory and practice. *ISEE Transactions on, Engineering Management, 48*(2), 189–208.

Hewlet Packard, H. P. (2009). *HP standard 011 general specification for the environment*. <http://www.hp.com/packaging/Documentation/gse-2009.pdf>.

Johansson, G. (2000). Success factors for integration of ecodesign in product development – A review of stateof-the-art. In *Eco-efficiency 2000 conference*, June 19–21, Malmö, Sweden.

Kaufmann, M. (1993). *Knowledge representation*. San Mateo. <http://www.cirl.uoregon.edu/research/kr.html>.

Kolodner, J. L. (1992). *An introduction to case-based reasoning*. <http://web.media.mit.edu/~jorkin/generals/papers/Kolodner_case_based_reasoning.pdf>.

Lindahl, M. (2003). Designers' utilization of DfE methods. In *1st International workshop on "sustainable consumption*, March 19–20, Tokyo, Japan.

Lindahl, M. (2006). Engineering designers' experience of design for the environment methods and tools – requirement definitions from an interview study. *Journal of Cleaner Production, 14*, 487–496.

Mathieux, F., Rebitzer, G., Ferrendier, S., Simon, M., & Froelich, D. (2002). Implementation of ecodesign in the european electr(on)ics industry. In *Proceedings of the 9th international seminar on life cycle engineering*, April 9–10, Erlangen.

phpMyAdmin (2011). <http://www.phpmyadmin.net/home_page/>.

Ramani, K., Ramanujan, D., Bernstein, W. Z., Zhao, F., Sutherland, J., Handwerker, C., et al. (2010). Integrated sustainable life cycle design: A review. *Journal of Mechanical Design, 132*.

Reyes, T., Rohmer, S. (2009). The Trojan horse method as a vector of eco-design integration: A case study at a French SME. In *International conference on engineering design* (pp. 7–173), ICED'09, Stanford.

Syamil, A., Doll, W. J., & Apigian, C. H. (2004). Process performance in product development: Measures and impacts. *European Journal of Innovation Management, 7*(3), 205–217.

Sutcliffe, L. F. R., Maier, A. M., Moultrie, J., Clarkson, P. J. (2009). Development of a framework for assessing sustainability in new product development. In *International conference on engineering design* (pp. 7–289), ICED'09, Stanford.

Telenko, C., Seepersad, C. C., Webber, M. E. (2008). A compilation of design for environment principles and guidelines. DETC2008-49651. In *Proceedings of the ASME 2008 international design engineering technical conferences & computers and information in engineering conference*, IDETC/CIE 2008, Brooklyn.

Telenko, C., Seepersad, C. C., & Webber, M. E. (2009). A method for developing design for environment guidelines for future product design. DETC2009-87389. In *Proceedings of the ASME 2009 international design engineering technical conferences & computers and information in engineering conference*, IDETC/CIE 2009, San Diego.

Tukker, A., Eder, P., Charter, M., Haag, E., Vercalsteren, A., & Wiedmann, T. (2001). Eco-design: The state of implementation in Europe. *Journal of Sustainable Product Design, 1*, 147–161.

Vargas-Hernandez, N., Shah, J. J., & Lacroix, Z. (2002). knowledge representation for conceptual engineering design. In *3rd ACIS international conference*, SNPD'02, Madrid.

Vezzoli, C., & Manzini, E. (2008). *Design for environmental sustainability*. London: Springer.

Visual Studio (Microsoft) (2011). *What is visual studio?* <http://www.microsoft.com/visualstudio/en-us/home>.

W3Schools (2011). *SQL tutorial*. <http://w3schools.com/sql/default.asp>.