Proposed Methodology to Consider Sustainability Impact in Early Design

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ABSTRACT

As it is widely known, early design stages are key to an efficient overall design process, here is were the most substantial changes can be made with less negative impact to the design cycle. Therefore, the inclusion of sustainability factors at the early stages of the design will allow the creation of environmental friendly products, and better control of costs and design cycle duration from the start. Thus preventing high costs corrections of the design, or costly secondary processes at the end of the product lifecycle. Traditionally, early concept evaluation does not consider sustainability in a holistic way; sustainability analysis tools such as Life Cycle Analysis (LCA) and geometry-based carbon footprint calculation are typically applied at later stages of design when full geometric information is present, or full material mass and manufacturing processes has been completely identified. Such requirements limit the capability to integrate sustainability at the early stages of design in a scientific and organic manner. In this work, a methodology is proposed to deal with those limitations by an early estimate of sustainability impact based on product functionality.

Keywords: Conceptual Design, Sustainability, Function-Based, LCA early impact

1. INTRODUCTION

Design is a complex cognitive activity that requires disciplinary and domain knowledge along with experience from the designer. Incorporation of additional requirements to this challenging task is difficult, yet it must be done. Specifically, nowadays it is important to include considerations to reduce the adverse environmental, economic and societal impacts of designs as we customize them for new demands as well as for different geographic locations. Current design methods and tools have not addressed such issues, they are deficient in this regard.

Early design of products and systems proceeds through understanding of the requirements, generating concepts and then evaluating them to select the most appropriate one, or ones. This generation and selection process, in general, does not consider sustainability in a holistic way. For example, while the cost of the design is considered, the implications of the design on the environment are either not taken into account or they are only considered after a conceptual design is selected, which basically provides only limited or local optimization. We propose to transform this design generation and evaluation process by representing product functions as energy-conversion chains and then assigning physical principles and related unit level, scalable energy equations for initial environmental sustainability assessment. Our hypothesis is that availability of an estimate of energy requirement of considered physical principles at early design stages will provide feedback to the designers in terms of the design's sustainability value, thus increasing productivity of the design process and overall sustainability of the selected designs.

The proposed framework to have sustainability factors in early design stages will consists of four steps:

1. Product functional representation as energy-conversion chains.
2. Determination of scalable unit-energy formulation for physical principles of various energy-conversion chains.
3. Aggregation of energy impact indicators of energy-conversion chains and sustainability indicator.
4. Quantification of energy impact for generated concepts and their comparison to concepts developed/selected without the early sustainability impact indicators.

It is expected that the results of the designs generated with the proposed approach, when compared with the results from a typical design process, will have better sustainability considerations across a wide spectrum of sustainability foci because energy use not only relates to cost but also provides an indicator for the human energy to replace chemical and mechanical systems with human energy (e.g., electric bicycle versus human-powered bicycle). Following this methodology designs can be better fit in the context they are being designed for, and thereby contributing to overall efficiency and sustainability.

2. Proposed Methodology

In order to improve the sustainability of any product/system it is required to have knowledge about its level of sustainability in the current state, and any other states, derived in a scientific way. At this time, although Life Cycle Analysis (LCA) analysis and geometry-based carbon footprint calculation methods exist, they either require the full geometric information to be present, or full material mass and manufacturing processes to be identified. These requirements limit being able to integrate sustainability at the early stages of design in a scientific and organic manner. In the work, we propose to eliminate these limitations by an early estimate of product function's sustainability impact (Figure 1)

The steps for the proposed methodology will take the given problem and, after a functional decomposition, will establish energy-based relationships that will provide the basis for initial sustainability evaluation. As various design alternatives are being proposed and evaluated, the proposed sustainability index will be evaluated, resulting in a more appropriate and efficient final design. Specifically:

2.1. Product functional representation as energy-conversion chains

Traditionally, designers generate a functional decomposition that describes the functions as relationships of inputs and outputs of energy, material and signals. There is no specific set of functions to be used and hence the functional diagram is not unique for a given design. Various authors have proposed function ontologies. Kirschman and Fadel (1998) defined an ontology of mechanical design functions. Some authors use repositories (i.e., exhaustive lists) of functions for the user to choose, and matrices to represent the design space (Stone et al., 2000; Stone and Wood, 1999; Kurfman et al., 2000). While these sets of functions seem different, these can be paralleled based on their definitions. Although Functional Diagrams are useful to determine the functionality and flows in a technical system, it is difficult to define a sustainability index at such an early stage to guide the design.

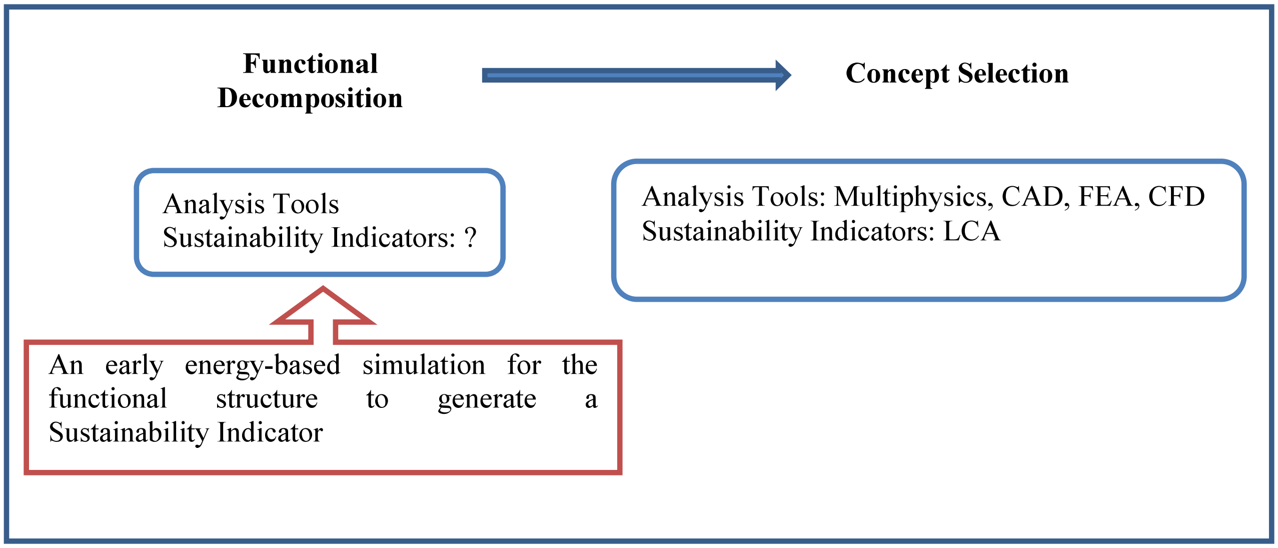

Figure 1. Graphical representation of the proposed methodology.

Our objective is to define a sustainability index using the available information in a functional diagram. The approach is to simulate the energy used (generation, transformation, consumption) at the functional level taking into account the energy sources (human, machine, environment). The eventual challenge is to define the energy independent of a particular concept, and hence independent of a particular domain. As the design process continues, functions are resolved into concepts; when enough information is available, a designer may describe the physical behavior using domain models, for example electrical circuits, pneumatic circuits, mechanical diagrams.. An alternative is to use a multi-domain physics modeling approach such as Bond Graphs (Paynter, 1999). A bond graph is a graphical representation of a physical dynamic system (Wikipedia, 2013). Additionally to bond graphs, exergy analysis will be explored as potential frameworks to represent product functions as energy-chains. Bond graph is a domain-specific behavior representation of technical systems. The representation uses a set of elements connected by energy and signal flows through identifiable ports (Thoma, 1975). Bond graph models provide a common behavior representation for numerous branches of engineering; this level of abstraction allows the combination of typical models such as hydraulics/pneumatics, mechanics, electric/electronics, and thermodynamics in a single domain-less model. For example, the Bond Graph "Resistance" element can represent a mechanical load or a hydraulic valve as well as an electrical resistance.

In the proposed work, we will not only explore theoretical fit of these potential frameworks to represent function in energy-conversion terms but also experiment with relevant software tools to understand their practicality (e.g., Dymola and 20-SIM for Bond graphs)

2.2 Determination of scalable unit-energy formulation for physical principles of various energy-conversion chains

Functionally decomposed product definition will be associated to energy equations for various physical principles. The energy equations to be used will be unit-based and scalable, which requires reanalyzing them for scalability. There exists a variety of software to simulate physical phenomena in various domains, e.g., Abaqus, ANSYS Multiphysics, Code Aster, CFD-FASTRAN, COMSOL Multiphysics, FlexPDE, CheFEM, Elmer, and at different levels of detail, for example, 2D and 3D dynamic simulations, thermo, CFD, FEA, 3D geometry, chemical. Traditionally, these simulations are reserved for later stages of design when more parameters are known (i.e., geometry, pressure, temperature). On the other hand, it is possible to define simple, generic simulations with limited parameters that consider higher level unit levels that can be used to simulate functions and functional diagrams and obtain rough estimates of energy usage to be considered in an early sustainability index.

2.3 Aggregation of energy impact indicators of energy-conversion chains and the overall sustainability indicator

As part of this task, unit-level energy indicators will be aggregated. A more important piece of this task is the establishment of an overall Sustainability Indicator (SI). This indicator will serve as an objective comparison tool between alternative designs or concepts. This indicator needs to take into account two essential aspects:

1. A wide spectrum of factors that directly impact sustainability of a product. For the factors or parameters to be considered, it is accepted that there are three areas of impact in the sustainability fields: economics, environmental and societal. For each one of these areas, there have been several reports that provide comprehensive lists of issues that are used to evaluate sustainability impact. These lists, and the factors that each one includes, need to be examined and a subset will be selected to establish the proposed Sustainability Indicator. An additional consideration is the way that the selected factors are evaluated, which basically reflects the type of data that is available – or can be generated – to be used in the evaluation of the selected factors. For some of the selected factors it will be possible to have a closed form relationship that will provide a direct link to the metric being evaluated (e.g., amount of material, energy used by product). In some other cases there will be a need to find a relationship between the available data and the parameter that will be used in the sustainability indicator (e.g., percentage of poverty level, measure of quality of life). The aforementioned option will result in what will be called "technical" and "non-technical" factors. Each one of these categories will have Objective and Subjective factors, with the Technical factors being mostly objective ones, and the non-technical factors being mostly subjective ones.

2. The philosophy and beliefs of the controlling agent of the product. Each designer/client/manager/company has a different view and different goals and ideas when talking about being sustainable. There is no universal goal, there is not a global recipe that will indicate how much more important environmental impact is with respect to economic impact, or vice versa. The propose sustainability indicator needs to be flexible enough to capture the beliefs and goals of each controlling agent. It is being proposed that this adaptability be implemented with the use of weighting factors. There will be a weighting factor that will be assigned to each sustainability factor in the previously selected subset. Based on these two aspects, the proposed Sustainability Indicator (SI) will be calculated with the following relationship:

$$SI_{xyz} = \sum_i W_i\, O_i + \sum_j W_j\, S_j$$

where the O's and S's are the actual, Objective and Subjective values for each sustainability parameter selected, in a normalized fashion. And the W's are the weighting factors assigned to each parameter. The summation of the effects will provide an aggregate indicator. This indicator will be a multidimensional one, meaning that it will be a vector that will provide a number for each one of the pillars of sustainability (i.e., environment, economics, social). The use of these three pillars will give a better representation to the decision–maker using the indicator.

2.4 Quantification of energy impact for generated concepts and their comparison to concepts developed/selected without the early energy impact indicators

Case studies will be used for contrasting the presence and absence of the indicators.

The case study is a research method used in different research domains. Even when their conclusions are not statistically valid, general sample results can validate the models. According to Yin (1984), the case study research method, as an empirical inquiry, investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used (Yin, 1984, p. 23). The purpose is to offer a conceptual framework that can be used in future research. Thus, when a proposed model is investigated through case studies, validation in different domains is recommended.

3. Sustainability Factors - Sensitivity Analysis

There is substantial information reported in the literature to have some indication of sustainability of a product/system. The reported information basically can be classified in three fields: economics, environmental, and social. An initial screening of those reports has resulted on a list of factors and indicators that are considered as adequate for the purpose of this work, i.e., to evaluate the sustainability impact in early design stages. This is an initial list that will be examined, tried, and redefined as new problems and domains are implemented using the proposed methodology.

3.1 Environment Indicators

- Environmental Burden of Disease: By this we mean if the use of the product selected will induce the propagation of any disease in any country (the person must find out in order to give an objective grade)
- Adequate Sanitation: give a qualification on how is the sanitation of this technology, how much waist is produce by using this product
- Air Pollution: Will the use of this product pollute the air, what is the emission rate?
- Sulfur Dioxide Emissions: What are the emissions in this case?
- Water Stress: Does this product pollutes the water and contributes to the water scarcity in the world?
- Effective Conservation Critical Habitat Protection: Does this product affect in any kind of habitat or ecosystem?
- Emissions per electricity generated: What's the energy consumption of this technology and how is this energy produced in the country that this technology will be used?

3.2 Economical indicators

- Average Manufacturing Hours: Weekly
- Vendor performance: The ability to obtain in the local market or international this product and its parts(if it's the case0
- World wide/Local demand: How is the demand on this product?
- Local/International Permits: Permits or regulations requirement from the local government to use this product?
- Money Supply: Change rate from your local currency in case you need to buy the product overseas
- Consumer Perspective: Positive or negative perspective on the general public perspective on this product

3.3 Social Indicators

- Social Responsibility in manufacturing: What are the manufacturing conditions of this product; where, how and who
- Education Levels: what are the levels of education that a person must have to use this product
- Social Economic levels: What are social classes that a person needs to use this product
- Fitness and health levels: Fitness and health conditions that someone has to have to use this product(what if the user is a person of 67 years)

It is important to highlight that the designer performing the evaluation must rely on a research about each item and the product desired to measure so this index will have as much objectivity as possible. This is a mere tool to help or aid the early design phase, but its up to the person who use it to give it a proper use so it works as its intended.

The index works in this way: for the purpose of this paper we will give each field (Environment, Economic, Social) the same weight but this will not necessary mean that if the weights can be altered if an specific field is more important than the other two according to the project being done.

The Indicators must be grade in a scale from 1 to 10, being 1 the best mark and 10 the worst, this because the idea is to analyze the numbers so at the end the one with the highest score will be the best alternative

Once the sustainability index is calculated, the calculation framework can be analyzed for its sensitivity to guide the design decisions. The proposed methodology has the option to perform sensitivity analysis, in a general case, or "what-if" scenarios, in specific cases. This capability will even allow for optimization studies. The recommended path is to have a focused sensitivity analysis instead of a comprehensive one (i.e., all factors are analyzed). The criterion suggested for the selection of influence factors is based on the following two aspects:

a) Identify the independent factors that have the greatest influence on the Sustainability Indicator. This task will be performed by applying a sequence of techniques that will result in the subset that the designer will consider the most influential according to his/her criteria. The first technique is Screening method that will result in a reduced set of factor to explore, with emphasis on the ones that the designer considers more important. The second technique will be OFAT (one-factor-at-a-time), which performs sensitivity for just one factor, thus neglecting cross-effects, but providing a very good indication of the net effect of each parameter that has been previously screened. The last technique will be variance analysis on the remaining factors.
b) Perform sensitivity based on a factor, or factors, that the controlling agent selects. The situation when specific information about performance change is required for a specific factor is covered here. It contemplates that a controlling agent has the capability to modify specific factors, and needs to decide which one of those will have the greatest impact, which implies that the initial screening has been already performed, and then OFAT and Variance can be applied depending on the request made by the agent in charge.

It is important to note that the sensitivity information will serve as guidelines, and is not being proposed as an absolute path to follow. There are several assumptions and inferences that will be applied, thus making the results good guidelines. The complexity of the problem prevents the designer from using the information for absolute optimization.

4. FUTURE WORK

The next steps in this collaborative project is to fully develop problems in various domains. There is interest in implementing the proposed methodology in the transportation industry (bicycles), injection molding industry, and motorcycle manufacturing. Model application in these enterprises will help us to observe the behavior of the proposed model and make the proper modifications to more accurate evaluation. Completion of these four tasks and their implementation across domains will provide validation and improvement opportunities.

REFERENCES

Kirschman, C. F., and Fadel, G. M., 1998, "Classifying Functions for Mechanical Design", Journal of Mechanical Design, V. 120, pp. 475-482.

Kurfman, M. A., Stone, R. B., Van Wie, M., Wood, K. L., Otto, K. N., "Theoretical Underpinnings of Functional Modeling: Preliminary Experimental Studies", Proceedings of 2000 ASME DETC, Baltimore, MD.

Paynter, H. M., 1961, Analysis and Design of Engineering Systems. The M.I.T. Press

Stone, B., and Wood, K. L., 1999, "Development of a Functional Basis for Design". Proceedings of 1999 ASME DETC, Las Vegas, NV.

Stone, R. B., Wood, K. L., and Crawford, R. H., 2000, "Using Quantitative Functional Models to Develop Product Architectures", Design Studies, 21 pp 239-260.

Thoma, J. U., 1975, Introduction to Bond Graphs and their Applications, Ed. 1, Pergamon Press, London.

Yin, R. K. (1984). *Case study research: Design and methods.* Newbury Park, CA: Sage Publiser.

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