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Automating Environmental Impact Assessment during the Conceptual Phase of Product Design

Karl R. Haapala, Kerry R. Poppa, Robert B. Stone, and Irem Y. Tumer

School of Mechanical, Industrial, and Manufacturing Engineering
204 Rogers Hall, Oregon State University, Corvallis, OR
Karl.Haapala@oregonstate.edu, poppak@engr.oregonstate.edu,
Irem.Tumer@oregonstate.edu, Rob.Stone@oregonstate.edu

Abstract

Product environmental impact reduction efforts largely focus on incremental changes during detailed design. Application of automated concept generation using a design repository and integral life cycle assessment approach is explored to evaluate and reduce environmental impacts in the conceptual phase of product design.

Introduction

Current efforts to reduce product environmental impacts across the life cycle are largely focused on the analysis of incremental changes to the product design, manufacturing process parameters, and supply chain configuration. Thus, existing product environmental impact assessment approaches are most beneficial to implementing changes during the detailed design phase. In addition, impacts due to materials choices, manufacturing processes utilized, and transportation of an existing product can be evaluated and reduced. It has been recognized, however, that transformative change in product design, especially for life cycle cost reductions, can be effected by implementing strategies for automated concept generation early in the product design. In this way, the basic product requirements and desired functionality are elucidated, and the design is ensured to meet those critical requirements, while reducing the focus and importance of non-critical requirements and superfluous functionality.

Similarly, a focus on reducing life cycle environmental impacts in the earliest stages of design is expected to lead to creative, possibly unforeseen engineering solutions that simultaneously meet customer requirements and sustainability performance goals for the product or system. By automating generation of concepts and evaluation of the generated concepts in terms of life cycle environmental impacts, life cycle costs, and other attributes, the set of potential design alternatives can be rapidly pared down. This more manageable subset of competitive product families can then be further investigated by the design team. Automated concept generation and environmental impact assessment are discussed below, and then a methodology to integrate the two approaches in support of sustainable product design is introduced.

Background

Automated concept generation techniques utilize archived design knowledge and a description of the desired product to automatically synthesize potential solutions. This work focuses on a morphological matrix based approach that operates on information stored in a design repository to output high-level descriptions of possible solutions. The following section describes the data source and concept generation algorithm.

Design Repository

Design repositories facilitate the storage and retrieval of design knowledge at various levels of abstraction during the product development process (Bohm 2005; Szykman et al. 2001a, 2001b). The automated concept generation approach herein utilizes the Design Repository maintained by the Design Engineering Lab at Oregon State University, which contains design information for over 130 consumer electro-mechanical products. Design information in the repository is divided into seven main categories that describe artifact function, failure, physical parameters, performance models, sensory information, and media. The repository includes pictures and CAD models of the products. The repository is the result of collaborations between researchers at Oregon State and UT-Austin (Bryant et al. 2005a, 2005b), Penn State (Bohm et al.,

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2006), Virginia Tech, Bucknell (Shooter et al., 2005), University of Buffalo, Drexel, and Texas A&M. Collaborations have expanded the types of design information and breadth of design tool features within the repository. A standalone application supports information entry and retrieval (Bohm et al. 2007), while a web portal (http://repository.designengineeringlab.org) enables information retrieval on the web.

Automated Concept Generator

Information stored in the repository can be used by automated concept generation techniques to transform a functional description of a desired product into assemblies of components. The concept generation algorithm used in this work, Morphological Evaluation Machine and Interactive Conceptualizer (MEMIC), translates the input functional model into a function adjacency matrix. This adjacency matrix undergoes a series of matrix multiplications that map functionality to solutions and filters out infeasible component-to-component connections based on repository data. The output of MEMIC is a set of concept variants that solve the input functionality (Bryant et al. 2005b). The methodology described below would use an evolution of this tool as its concept generation algorithm. After concepts have been generated, repository data can be used to predict a number of their performance attributes including environmental sustainability metrics.

Product Environmental Impact Assessment

Product environmental sustainability is often judged in a comparative manner among competing alternatives based on functional equivalency, e.g., operational life or performance level, using life cycle assessment (LCA) (Haapala et al. 2008). Environmental impacts are based on the type, source, and amount of input materials and energy, as well as concomitant wastes and emissions, for each stage of the product life cycle. Life cycle stages include material extraction and processing, component and product manufacturing, use, and end of life. Often, transport of materials and products is considered as a separate stage. A diagram of the product life cycle is shown in figure 1.

Typically, input/output models are devised to represent each unit process involved at each stage of the product life cycle. Model development can involve significant effort and time, thus, to facilitate analysis, practitioners may focus only on specific life cycle stages, omit processes that are seen as insignificant, or rely upon process databases (Todd and Curran 1999). Once process inputs and outputs are determined, known as the life cycle inventory (LCI), the level of environmental impact for each process is assessed using a variety of methods, e.g., Cumulative Energy Demand and Eco-indicator 99 (Hischier and Weidma 2009). The final phase of LCA is improvement analysis, which identifies the most impactful processes and the parameters that cause the greatest change in predicted impacts. This allows targeted modifications to be made to product or process designs.

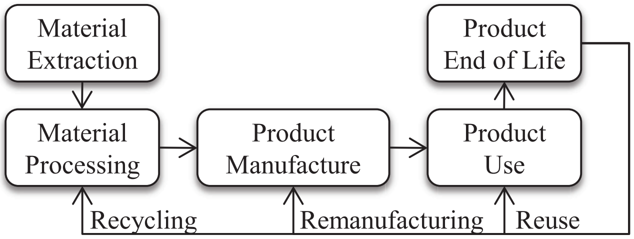

Figure 1 The Product Life Cycle

While LCA is best suited for comparative analyses of existing products or proposed design modifications, product and process information contained within the Design Repository and LCI databases can be used in tandem to evaluate the potential environmental impact of automatically generated, or virtual, concepts.

Related Work in Early Design Life Cycle Assessment

A significant body of existing research focuses on LCA approaches that can be applied early in the design process. Eisenhard et al. (2000) have demonstrated a method in which neural networks are implemented to develop approximate impact assessments during the early stages of design. This approach relies upon parametric LCA models to define particular classes of products. The neural network is then used to find similarities between a new design and existing designs. Kraines et al. (2006) have developed a knowledge-based system that leverages ontologies to merge expert knowledge into a single platform. Kraines' use of ontologies facilitates the transfer of knowledge between disparate disciplines engaged in both the design process and impact assessment.

Park and Seo also make use of a knowledge-based system to approximate life cycle assessments of a particular design (Park and Seo 2006). Their system, the Knowledge-based Approximate Life Cycle Assessment System, makes it easier for designers to implement LCA during early phases of design; however, the input requires CAD representations of the artifacts comprising the overall design. Another knowledge-based approach takes the form of a Decision Support Problem (Bras and Mistree 1991). The DSP technique seeks to suggest more complete design information when a designer specifies an open ended or unstructured artifact.

An approach more similar to the method explored by the authors is shown by Gehin et al. (2007) and focuses on the way component choice determines a product's total environmental impact. They develop an approach using LCA to evaluate end of life impacts that treats the product impact as a sum of component impacts. However, a limitation of their assessment approach is the exclusion of unknown parameters by assuming they are similar for each alternative. Our approach described below would form a more complete evaluation based on stored data from existing products.

Devanathan et al. (2009) have developed a technique that is also similar to our methodology. Their efforts assign life cycle impacts to product functions, focusing designer attention on elements of product function most tied to life-cycle impact. In our methodology, we take the approach that life cycle impacts are primarily determined by the way the specified functionality is achieved, so we estimate the impacts associated with particular component choice. Whether it is best to regard life cycle impact as related to component choice or specified functionality, is still an open question. A third possibility that should be explored in future work is that impacts are properties of the interaction of component type and functionality. More accurate estimates are expected by considering impact as a property of a particular component type performing a particular function rather than as a property of the component type or function alone.

Prior work by the authors evaluating kitchen appliances demonstrated that environmental impacts of virtual concepts are indicative of final product impacts (Bohm et al. 2010). There were several limitations noted, however. The quantity and quality of data available in the design repository directly affected the adequacy of results in representing the final product. In fact, actual products performing the same function were variable in composition. Material data was often reported in terms of bounded volume, rather than mass, raising concern about scaling these measures to an accurate material mass. The data was best suited to cradle-to-gate analysis, since use phase, e.g., energy consumption and failure rate, and end-of-use information was sparse.

Proposed Methodology

The remainder of this paper discusses our vision for a methodology to integrate LCA into the automated concept generation process, and current work in addressing these limitations initially by focusing on data in the repository; and later through improved data collection and quality, and subsequent data analysis. Efforts will investigate the scalability to better evaluate the correlation of bounding volume and material mass. In addition, product data will be studied to determine key sources and modes of failure. Failed components will cause additional environmental impacts due to production and end-of-use effects and this information can be used to help designers assess tradeoffs between cradle to gate impact and impact due to repair or early retirement of the product due to failure.

We propose and have begun to investigate a five-step methodology for integrating life cycle assessment and automated concept generation, as described below.

Step 1. Functional Modeling

First, the designer develops a functional description of the required product. This description is translated into a functional model that describes the intended products operations on flows of matter, energy, and information. Based on the concept generation tool and design repository used, the functional model must be created using the Functional Basis (Stone and Wood 2000; Hirtz, et al. 2002). An example of such a model for a hypothetical kitchen appliance for heating water is shown in figure 2. A functional model, once generated, is a graph that can be transformed into an adjacency matrix and understood by concept generation software.

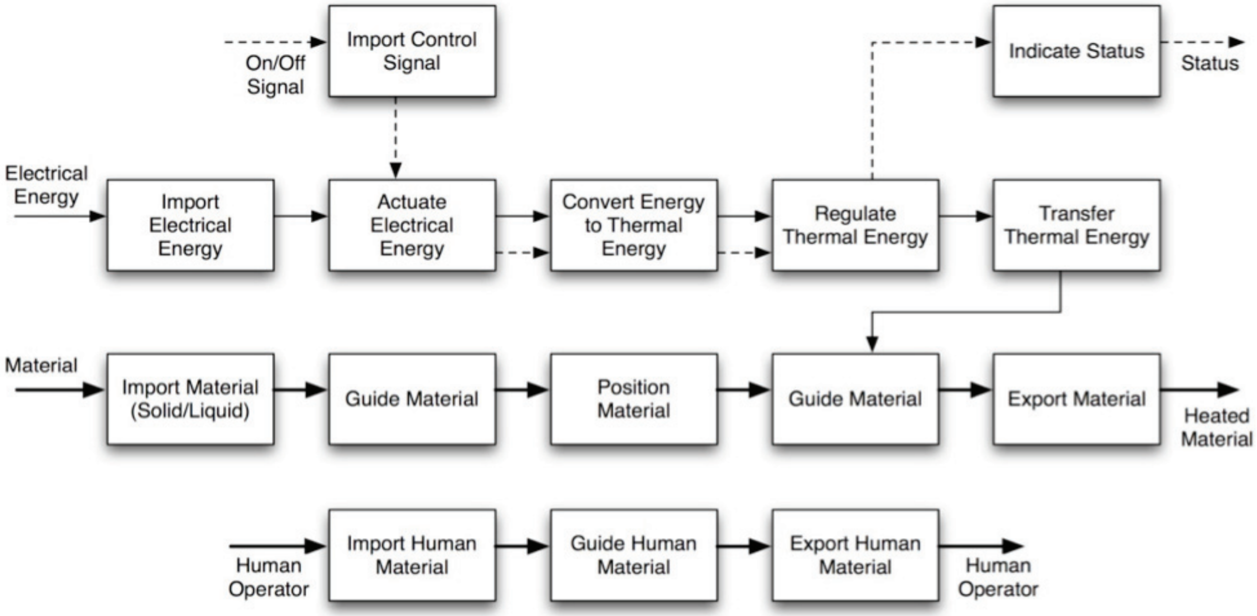

Figure 2 Example Functional Model

Step 2. Automated Concept Generation

In the second step of the proposed method, the designer supplies the generated functional model as an adjacency matrix to the automated concept generator. The tool then performs an automated version of Zwicky's morphological analysis (Zwicky 1969). The tool queries the repository for past instances of products exhibiting the desired functionality and returns all components known by the database to have solved each function. Concepts can then be generated by selecting one element from each row of this morphological matrix. Such an approach necessarily implies a combinatorial explosion of possible solutions, many of which will be infeasible. To reduce the incidence of infeasible solutions, a second query of the database is conducted to assess component compatibility. The tool rejects any solution that is made up of components that are not together in a previously recorded product. Concept generation is halted based on a termination condition that can either be a fixed number of concepts or the drop in concept-to-concept variation below a specified threshold. Concepts are output as component adjacency matrices that can be used to estimate life cycle impacts and failure and reliability concerns.

Step 3. Estimation of Life Cycle Impacts

The proposed method next estimates the cradle to gate life cycle impact of the generated concepts based on data stored in the repository and values provided by the Eco-indicator 99 impact assessment method. To construct an environmental impact estimate for each concept, the required amount of material used and manufacturing processes utilized must be predicted to produce each of the components used in the concept.

Each component of the products archived in the repository is tagged with the material or materials from which it was constructed. As a baseline, the material of the component used to build the concept can be predicted from this set. The designer would specify, based on the application, whether to estimate the material based on a best, worst, or average case material. In addition to material type, the amount of material required must also be predicted. Mass and volume data are recorded for artifacts in the repository, so an estimate for the composition of the new component can be predicted from prior instances of components of the same type. Again, as for the material prediction, the designer would choose to have the estimates calculated based on a best, worst, or average case.

Estimation of manufacturing process proceeds in a similar fashion, but with a key added complication; the predicted process must be appropriate for the material predicted. Thus, the likely manufacturing processes found for components of the specified type with the predicted material are queried. It should be noted that this process can also proceed in the opposite manner. The manufacturing process can be predicted first, and then the material choice constrained accordingly. We will proceed in the former manner for an initial implementation because much greater confidence surrounds the material data within the repository than in the manufacturing process data.

Predictions must include not only the processes chosen but also estimates of part features related to those processes, e.g., the length of a welded joint, the mass of material machined away, or the length of a bend. At present, this information is not recorded in the repository. The initial implementation of the proposed method will be based on a set of standard values for these parameters that are representative of consumer scale electromechanical products. Combining the manufacturing process – as predicted from the repository in the same manner as mass and material – with standard feature parameters, an estimate of overall impact due to manufacturing process can be calculated using Eco-indicator 99 or similar impact assessment methods.

Finally, the individual estimates for impact due to material and process for each component of the concept can be summed to produce an impact estimate for the concept. The process is then repeated to arrive at estimates for each of the generated concepts. Thus, the impact estimates are representative of the cradle to grave environmental impacts of each concept and form a basis for comparison. Other important factors such as transportation, energy inputs, and use phase impacts are not yet considered, but will be explored in feature iterations of the proposed method.

Step 4. Predictions of Failure Modes

One important additional dimension that can be considered under this method is the reliability of the product. A product whose production represents a small impact on the environment may be a less attractive choice if it is likely to fail earlier and require replacement more often than another alternative. As with material, mass, manufacturing process, and other parameters, the repository can store information about the failure modes of products. The authors have previously used this information to predict likely failure modes in conceptual products (Grantham Lough et al. 2009; Stone et al. 2005; Tumer and Stone 2003). Thus, these methods can be used to predict the likely failure modes and their likelihood and severity for each concept, which in turn can be used to predictively estimate environmental impacts for each alternative on a functional unit basis (e.g., total operational life).

Step 5. Analysis of Results and Presentation to the Designer

The many generated concepts and their predicted environmental impact and failure performance are presented to the designer for further analysis and selection. In practice, the number of concepts will exceed the number a human designer could reasonably be expected to evaluate manually. The proposed method would then employ unsupervised machine learning tools to cluster groups of similar component selection, predicted impact, and failure characteristics. Representative samples of each cluster can then be displayed to the designer to guide their search.

Results generally fall into three categories. First are solutions that are attractive, perhaps because of novelty, but which have poor environmental impact or failure characteristics. Based on the application of the proposed methodology, a designer choosing to pursue these concepts is forearmed with the knowledge of potential problems and can take action during embodiment and detailed design of the concept to mitigate these issues.

A second category is concepts with low environmental impact, but undesirable failure characteristics, or vice versa. The designer, based on application of the proposed methodology is made aware of the potential tradeoffs between impact and reliability and longevity of the product. The tradeoffs can be assessed in light of the designers experience and knowledge of the problem under consideration. As before, the designer is forearmed to take necessary steps to mitigate potential problems during later stages of design.

The third expected category captures solutions that have desirable environmental impact and failure characteristics. These can be presented to the designer as likely candidates for further exploration. Understanding why they have better predicted performance than competing concepts is expected to assist the designer in adapting and enhancing other concepts, especially those deemed more desirable on a functional basis or those that are more attractive from other perspectives (e.g., novelty and aesthetics).

State of Available Data

Before embarking on the development of a tool to implement the proposed methodology, we consider the ability of the data currently recorded in the aforementioned design repository to meet our requirements. The following section summarizes the data available and notes key shortcomings and opportunities for future development.

Material and Process Data

A generated concept is represented as a set of components and their connections with one another. We will estimate the impact of manufacturing a particular concept as the sum of the impacts of its components. Prior work by the authors has has validated that reasonable estimates can be made, but this analysis would require significant manual analysis of the data by the user. To automatically calculate an estimate, the data must correspond to material and processing options with impact values.

We found that, in general, there is good correspondence between the material and process options in Eco-indicator 99 and the materials and processes recorded in the repository. All materials recorded in the repository from previous analysis of kitchen appliances are listed in the Eco-indicator 99 manual, however some are recorded at too abstract a level to be used. For example some artifacts are recorded as simply being metal rather than a particular type or alloy. As a first effort to capture cradle to gate environmental impacts, we propose adjusting the repository schema to use the Eco-indicator 99 list of materials as a fixed vocabulary for future efforts.

Process data is more difficult to use as currently recorded in the design repository and points to necessary changes to its database to accommodate automated estimation of environmental impacts. For instance, processes recorded do not align well with processes identified in the Eco-indicator 99 manual. The current repository records only a small subset of the processes considered by Eco-indicator 99. A major concern is that for the majority of artifacts only a single primary manufacturing process is identified. A reality, reflected by the manual is that real products are produced using a variety of shaping, joining, and finishing processes. The current repository data entry application should be amended to encourage the recording of all relevant processes used to produce each artifact.

Another key data deficiency relates to artifact features. To estimate the impact of a stamped metal part, for example, it is necessary to know the area of material deformed. This data regarding parameters of component features has traditionally not been recorded in the repository, and the current schema lacks a convenient location to store it. For an initial implementation of the proposed method, representative values can be established for use in analysis cases. However, moving forward, the repository schema will have to be amended to add the ability to capture manufacturing process data if reasonable impact estimates are to be automatically calculated.

Many of these results point toward the need for an intelligent data entry tool that can prompt users to supply necessary and appropriate information about artifacts as they are entered. Such a tool could restrict the possible manufacturing processes based on recorded material, or prompt the user to specify correct parameters based on material and process. While such an effort is separate from the proposed methodology; our initial exploration emphasizes the need for such an intelligent data entry tool.

Mass Data and Scaling

A key finding in earlier work was that mass data for many important artifact types was missing. To overcome this limitation, the artifact volume and the density of its constituent materials were used to compute a mass estimate. Recorded volume tended to be represented as a bounding box rather than the actual volume, so a scaling factor was needed. A suitable scaling factor was found for the classes of products studied.

If a suitable scaling factor could be found for other classes of products or components, then the proposed work could proceed without tackling the problem of limited mass data. To asses this possibility, the repository was queried for all components with both mass and volume data. For each component, the actual recorded mass was compared to that obtained by multiplying its bounding box volume (also reported) by the material density. These scaling factors where aggregated to find mean and variance of scaling factor for each component type. Mean scaling factors ranged from 0.01 to slightly less than 3. The inter component data was also characterized by high variance. This analysis suggests that a widely applicable scaling factor cannot be found based on data currently in the repository.

Given that a consistent scaling factor could not be found for all cases, the possibility that a single scaling factor could adequately represent some clusters of component or material type was then investigated. No strong evidence for such a trend in the data was found, though we suspect that there should be some level of similarity between related components and materials. We surmise that the lack of such a pattern is due in part to the small sample size of some component types in the repository. The absence of an agreeable scaling factor for all artifacts, or even groups of similar artifacts, suggests that the using volume data and density is not a viable solution to estimating component mass. Instead, actual mass data must be used, and greater effort must be placed on ensuring this data is recorded when products are entered into the database.

Availability of Mass and Failure Data

Finally, the availability of sufficient samples of component types was investigated. Of particular concern was ensuring that there was enough mass and failure data for common components to proceed with development of the proposed method and associated tool. Figure 3 shows the state of this data in the repository. The axes show the percentage of instances of each component type with the desired data, while the size of the bubble indicates the population of that component type. While sample sizes are in general small, we find that there is sufficient data to proceed with a preliminary study. Data will continue to be recorded to increase the population of underrepresented components.

Conclusion

Life cycle assessment of automatically generated concepts will enable product development that evaluates and reduces environmental impacts from the earliest stages of design. The proposed approach will allow environmental impact analysis, and ultimately other sustainability considerations, to become a component of automated conceptual design. The method, and a tool to implement it, will enable intelligent aides that enhance the designer's ability to understand risks and tradeoffs related to environmental impact and reliability early in the process. This enables more rapid development of more environmentally sound products with fewer redesign cycles, and facilitates the consideration of important life cycle issues early in design when significant gains can still be made at relatively low cost.

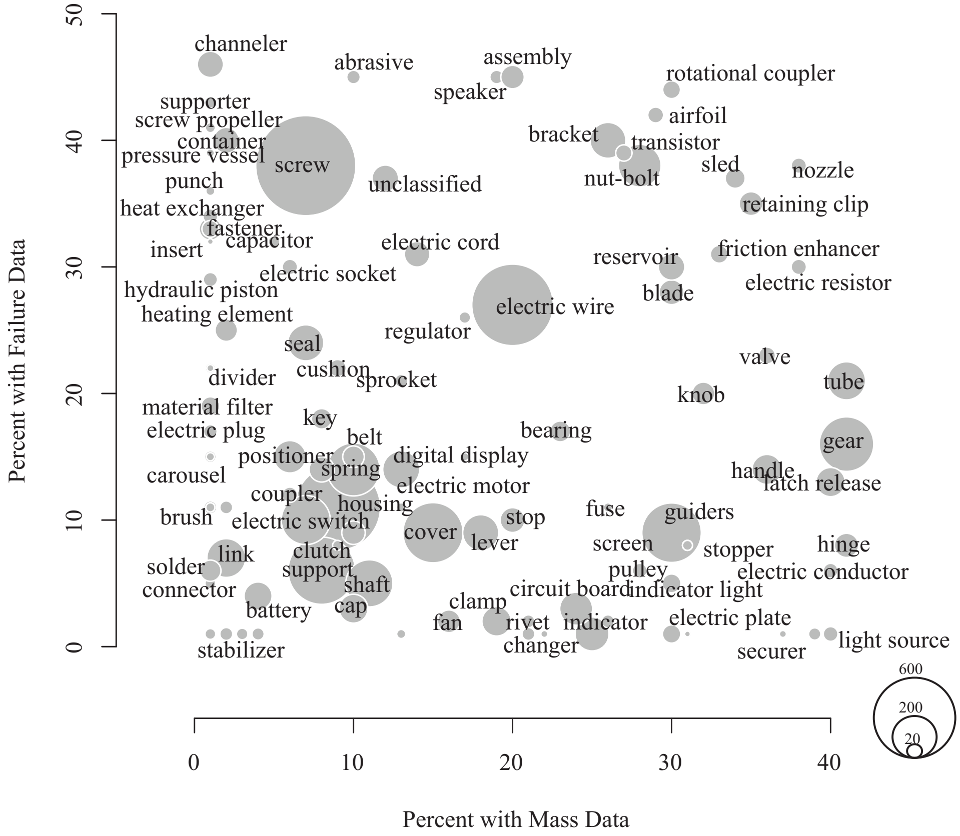

Figure 3 Summary of Available Mass and Failure Data within the Design Repository

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