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COMPARING MATRIX-BASED AND GRAPH-BASED REPRESENTATIONS FOR PRODUCT DESIGN

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1 INTRODUCTION

Modern design problems can be supported with the use of product representations that go beyond geometrical models. Common product representation models can be generally classified as being matrix-based or graph-based models. Two such representations, the High Definition Design Structure Matrix (HDDSM) and the Component Flow Graph (CFG) have been developed independently by the authors. Theoretically, the differences between matrix representations and graphs are minimal because data can be stored and presented in a variety of ways (Lindemann et al. 2009). However, in practical applications in which software tools are being created to support new design methods, we have found that the choice between using a matrix-based or graph-based representation has implications for the way the product information is captured, evaluated, and used. In this paper we explore the benefits and limitations of the HDDSM (a matrix-based model) and the CFG (a graph-based model.) Based on our experiences, we provide a list of questions to guide the selection of an appropriate product representation format for new research in design methodology.

2 USING MODELS IN PRODUCT DESIGN

Engineers use a variety of product representation models during the design process. A formal product model is one that follows an accepted standard. The benefits of using standard models for product representation are to aid in visualization, communication between engineers, and systematic evaluation methods.

The benefits above can be realized with, or without, the use of a computer. For example, the creation of function structures and their evaluation for potential modules within a product can be carried out on paper (Hirtz, et al., 2002). However, using a computer for the collection and evaluation of product representation models may provide additional benefits in terms of 1) design knowledge storage and retrieval, 2) automated search and evaluation of the design space, 3) guided data collection, and 4) greater capabilities for data visualization.

The lifecycle of any product representation model has three main stages. First the model must be created. For product redesign, this stage may involve capturing models of existing products. Second, the model must be evaluated by using heuristics or formal analysis approaches, and by comparing to other models. Finally, the model and results of any evaluation must be used to guide the engineer in developing a better understanding of the product. Many representations build on fundamental mathematical concepts such as matrix representations and graphs. In this paper, we consider two methods that capture nearly identical information. One is based on the concept of a matrix and the other is based on a graph network. The different uses and benefits of the two methods for representing existing product data are explored.

Related work has considered the value of visualizing information as a matrix or as a graph. For example, Jarratt et al. found in their work that large matrix models were difficult for people to absorb (Jarratt et al. 2004). In later work the pros and cons of visualizing information in a matrix or in a graph network were compared (Keller et al. 2005). While this latter study considered the visualization of the same underlying data, the HDDSM and CFG have fundamentally different ways of storing data. These differences provide benefits and limitations that go beyond visualization.

3 THE HDDSM

The High Definition Design Structure Matrix (HDDSM) is a structured nomenclature and process for creating high fidelity representations of electromechanical products (Tilstra et al. 2009). The structured nomenclature of the HDDSM is based on capturing the existence of a set of standard interactions between components of a product. The interaction basis for the HDDSM extends interactions sets used in related DSM research (Pimmler and Eppinger 1994) and in functional modelling (Hirtz et al. 2002). Each type of interaction is recorded in a component DSM that makes up a single layer of the HDDSM. The elements of the HDDSM should be at a very low level of abstraction such that every unique part (or nearly every unique part) of the product is represented. The large number of interactions and large number of elements for a given product may require a significant investment in creating the HDDSM. The HDDSM modeling process reduces the effort required from the examiners and allows the creation of the model to be distributed across many people or completed at different points in time. These benefits are achieved by using a hierarchical systems approach in which the system is divided into groups at the beginning of the model creation process. The system model is created using each group as a single element. Then a HDDSM for each group can be created separately and merged back into the system model. After merging the group HDDSM into the system HDDSM, only a subset of interactions between elements of the group and other elements of the system needs to be reviewed.

The HDDSM process has been implemented in a software package that runs on the MATLAB platform. The software guides the examiner through the process and ensures that the interactions between every relevant pair of elements are considered.

4 COMPONENT FLOW GRAPHS

A component flow graph, or CFG, is the name given to a graph of connected components wherein nodes (also known as vertices) represent the components of a system and arcs (edges) connect components together and include labels of specific energy, material, and signals. While such connectivity graphs are commonly used in engineering systems, the first formal presentation of a component flow graph (CFG) occurred in (Kurtoglu and Campbell 2009). The original intent of the CFG was to formally represent concepts derived from a function structure. While creating such formal representations of a concept could be seen as a hindrance to human designers, the goal was to automate the creation of new concepts by transforming a function structure graph into a CFG through a generative graph transformation grammar. Grammar rules were originally created by hand and more recently by computer by exploring intersections in a particular system's CFG and function structure. Typically one system leads to a dozen or more grammar rules which are then used to create new concepts when presented with a new function structure.

The creation of both the component flow graph and the function structure are input into the computer using GraphSynth (www.graphsynth.com). Over a dozen small to medium-sized electromechanical products have been disassembled and recorded in this manner. While the nodes currently do not include CAD or shape data, there is a URL in each node that links to a persistent file which includes relevant part data such as mass, material, manufacturing process used, etc. In the example in Figure 1, a hair dryer is shown, both as a function structure on the left and a CFG on the right. The red arrows depict how included data relate the "Convert Electrical Energy to Thermal Energy" function to the "Heating Element" and the "Convert Electrical Energy to Rotational Mechanical Energy" function to the "Motor".

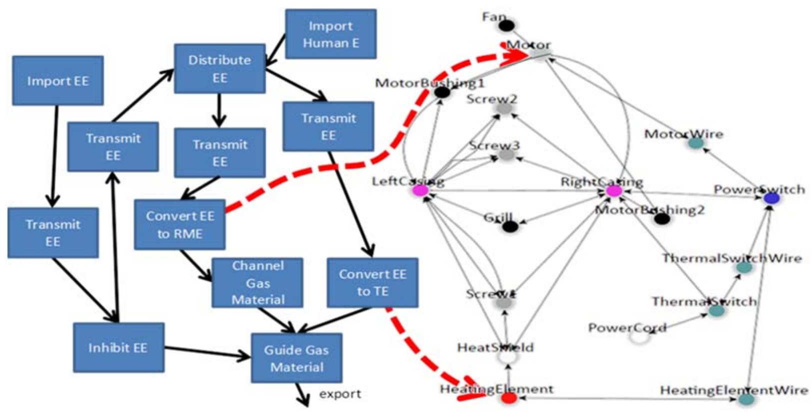

Figure 1: A function structure and a component flow graph (CFG) for a simple hair dryer. Arcs in both graphs include labels on the type of energy material or signal flow between the elements.

5 MODEL USAGE DURING PRODUCT DESIGN

Product representation models can be useful when redesigning a future generation of a product, or when using past product knowledge or analogies in the design of new products. In general the use of product models requires that available information is captured in the model, then the model is evaluated and compared, and finally the results are used to guide the design of the new product. The development of the HDDSM and CFG focused on slightly different, but overlapping stages of the product design process. The HDDSM has been developed with a focus on ensuring objective, repeatable models that can be used for quantitative comparison. The CFG has been developed to aid in the search for design concepts and product embodiment. Figure 2 shows the expected utility of the two product models presented here during the three general stages of product model use in design.

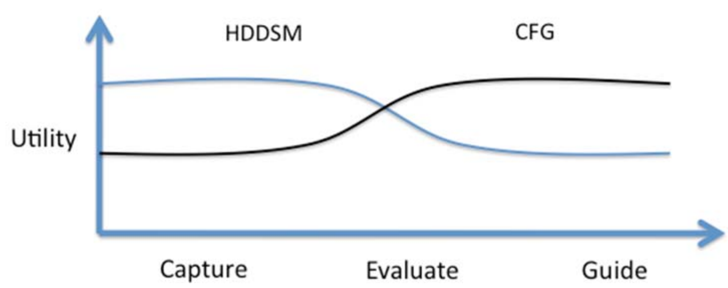

Figure 2: Utility of product models during design

The differences in utility during the redesign process can mainly be attributed to the constraints placed on the designer during the different activities. When capturing a model of a product in the HDDSM, the examiner is guided through the process and is asked to consider each pair of elements in turn. When creating a graph representation, the examiner adds each element as a node, and then considers potential links between the nodes on the graph. The "openness" of the graph can be challenging when working with a large number of element nodes, as the examiner may not be able to view or cognitively process all of the nodes at the same time. During the Guidance step, the focus shifts from creating a 'correct' model of the product to being able to develop insights from the models and see the effect of potential changes. At this point the designer may value the model that allows them to quickly rearrange elements and recognize patterns in connections between elements. Table 1 lists the activities associated with the different steps of the design process and the benefits and limitations of each product model.

The way the data is stored also has an impact during the evaluation activities. The matrix structure used in the HDDSMa allows for simple mathematic analysis. The CFG uses an object-oriented data structure. Although the way data is stored can be transformed if necessary.

Table 1: Benefits and limitations of HDDSM and CFG Graph

Designer Activity	HDDSM	CFG Graph
Capturing	+ Systematically considers of element pairs + Guides xaminer through data capturing process - Can present an overwhelming number of pairs for examination	+ Allows examiner to easily make exceptions - May be difficult to locate and record interactions between nodes on a large graph
Evaluation	+ Matrices can be compared using simple add and subtract operations - Size of matrix increases quickly, making brute force optimization expensive	+ Patterns in graph can be easily located and manipulated automatically - Simple operations, such as counting inputs and outputs must be carried out by a search algorithm
Guidance	+ Matrices can be useful for visually recognizing modules and frameworks in products - Branching flows are difficult to see in matrices - Changes made to the matrix based on the evaluation step may be difficult to see and follow through the matrix representation	+ The visual layout of the graph can be quickly changed and manipulated by a user + Generative grammars and configuration transformations allow automatic insertion or removal of components and connections

6 SELECTING PRODUCT REPRESENTATION

When developing new research tools for design, it will be useful to choose product representation models that fit the needs of the intended research. Therefore the choice of an appropriate format can be determined by considering the preferences of the researchers and the intended goals. To assist in making this decision we provide a list of important questions to ask and suggestions for the appropriate model choice.

Will product models be created by multiple people?

Yes: Matrix-based formats may offer a more systematic and repeatable method for data collection. We have found that when modeling large systems (>50 nodes) it becomes difficult to 'see' the entire graph, which may increase the potential to miss interactions.

Will product models be used for direct analytical comparison?

Yes: When product models are going to be directly compared without interpretation (i.e. Counting the number of interactions in the system or determining the ratio of interactions within modules to those across modules), the regimented structure of the matrix may increase the confidence in the models even when created by different people. Also, the matrix lends itself to easy mathematical analysis.

Will the product model be used as a base for automated system improvement?

Yes: Graphs are amenable to generative grammars and configuration transformations such as automatic insertion or removal of components and connections. The desired transformations are easily defined by the user by drawing a before and after graph grammar.

Will the product model be used for visualizing the system?

Yes: The utility of both forms of product models for visualization depends greatly on the layout of the model. A matrix has one degree of freedom and when the elements are ordered properly, modules and frameworks within the system are easily visualized. However, it is difficult to see branching flows in a matrix. The layout of a graph has two or three degrees of freedom and is regarded as a more appealing tool for visualizing the system. We have found this true especially when trying to communicate with people not familiar with the system.

Will the product model be manually explored and updated?

Yes: The openness of the graph format allows users to quickly make changes in an intuitive manner.

7 CONCLUSION

While the differences between matrices and graphs are small in theory, the selection of a matrix-based or graph-based product representation model should consider how the model will be used in terms of capturing data, evaluating data, and using the data to provide guidance. The difference between the representations and approaches goes beyond visualization, because the way that data is stored and processed is also important, especially in terms interfacing to a designer or multi-disciplinary design team. We presented a list of questions that are intended to assist future researchers consider some possible implications of how a product representation model is implemented. In our work, we have found the formalized structure and systematic process of the HDDSM matrix-based model to be extremely valuable during the capture phase and for mathematical evaluation; whereas, the CFG graph-based model strongly supports automated model transformation and intuitive interpretation for the user.

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REFERENCES

Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., and Wood, K. L. [2002], 'A functional basis for engineering design: Reconciling and evolving previous efforts', *Research in Engineering Design,* Vol. 13, No. 2, pp. 65-82.

Jarratt, T, Eckert, Claudia, and Clarkson, P John [2004], 'Development of a product model to support engineering change management', *Proceedings of the TMCE,* Vol., pp. 1-12.

Keller, R., Eger, T., Eckert, C., and Clarkson, P. J. [2005], 'Visualising change propagation', *International Conference on Engineering Design* (Melbourne, Australia).

Kurtoglu, Tolga and Campbell, M. I. [2009], 'Automated synthesis of electromechanical design configurations from empirical analysis of function to form mapping', *Journal of Engineering Design,* Vol. 20, No. 1, pp. 83 - 104.

Lindemann, Udo, Maurer, Maik, and Braun, Thomas [2009], 'Chapter 3 Methods for managing complex data in product design', *Structural Complexity Management* (Berlin: Springer).

Pimmler, T. U. and Eppinger, S. D. [1994], 'Integration Analysis of Product Decompositions', *ASME Design Theory and Methodology Conference* (Minneapolis, MN).

Tilstra, A. H., Seepersad, C. C., and Wood, K. L. [2009], 'Analysis of product flexibility for future evolution based on design guidelines and a High-Definition Design Structure Matrix', *ASME Design Automation Conference* (San Diego, CA).

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