Design Flexibility and Agile Product Development: Inferences on Design Education and Industrial Practice

Kristin L. Wood, Ph.D.
Cullen Trust Endowed Professor in Engineering and
University Distinguished Teaching Professor
The University of Texas
Dept. of Mechanical Engineering
ETC 4.146B, M/C C2200
Austin, TX 78712-1063
wood@mail.utexas.edu

I. Motivation and Overview

The ability to invent, create and innovate is at the very core of engineering and product development. It provides a forum for designers to apply creativity and contribute their personal flair. It also represents the time when technology is chosen or developed to fulfill customer and societal needs. This article discusses innovation and creativity in the context of product design research and educational initiatives at the University of Texas at Austin. These initiatives are centered within the Manufacturing and Design Laboratory (MaDLab, http://www.me.utexas.edu/~madlab/) and Laboratory for Freeform Fabrication (LFF, https://utwired.engr.utexas.edu/lff/). Both laboratories are integral components of UT's Advanced Manufacturing Center (AMC, http://www.engr.utexas.edu/amc/).

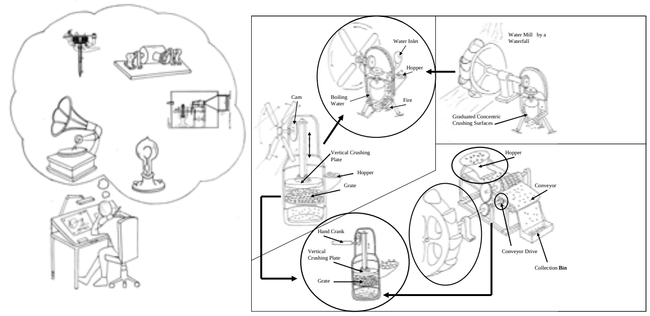
An interweaving theme of design research at UT is design flexibility and agile product development. Design, or product, flexibility is the degree of responsiveness (or adaptability) to the multimodal needs of customers and for any future change in a product. A product must include flexibility to adapt to future and as yet unknown changes in architecture and technology. The product development process must also be agile to address flexibility in cost, schedule, or performance requirements for product evolution and new product development. This agility manifests in the ability to address frontier design problems and customers. It also manifests in varying partitioning strategies for design methods and prototyping and in the ability to rapidly manufacture changing or customizable product components and configurations.

Figure 1 illustrates a range of design research and educational initiatives in design flexibility and agile product development at UT. Figure 1(a) shows a prototype of a flexible training and trail shoe product. This prototype represents the application of design flexibility principles to the evolution of a training shoe for other applications with minimal changes to the original product.

Figure 1(b) shows the results of an experimental study in the area of concept generation. The focus of this research is on an understanding of the underlying scaffolding needed for effective concept generation, especially in the area of design-by-analogy.

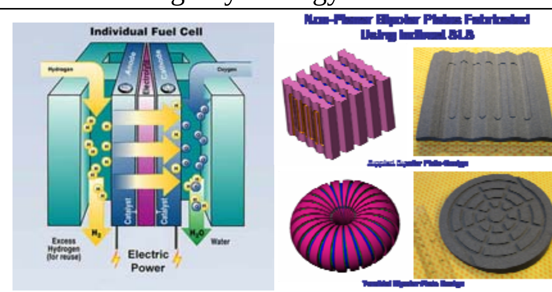
Outsole Module – top and bottom views

(a) *Product Flexibility*: flexible training and trail shoe

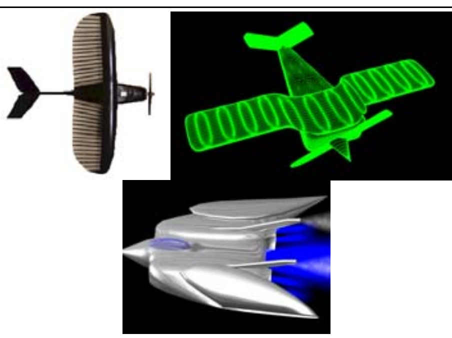


(b) *Design Synthesis:* advances in concept generation and design-by-analogy methods

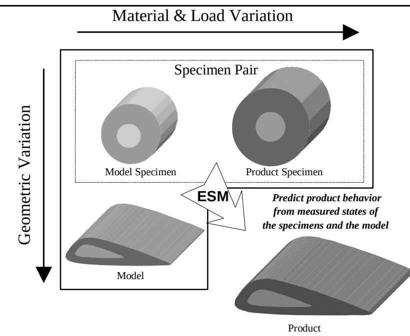
(c) *Product Usage Context*: Dental Chair for Remote Environments



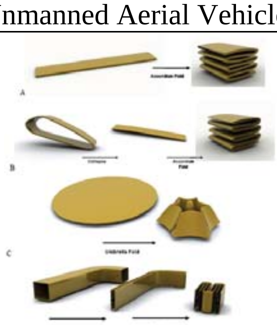
(d) *Rapid Manufacturing*: PEM Fuel Cells



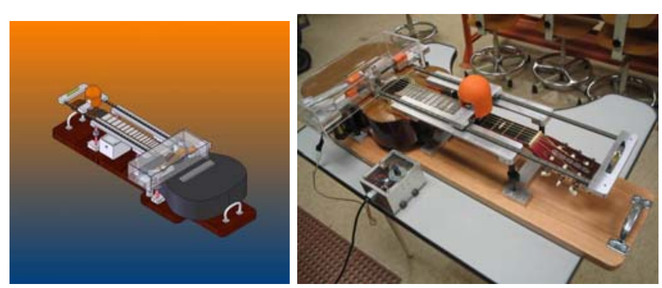
(e) *Product Transformers:* Applications in Unmanned Aerial Vehicles



(f) *Rapid Functional Prototyping*: Empirical Similitude



(g) Rapid, Flexible Manufacturing: *Freeform Fabrication of Large, Deployable Parts*



(h) *Product Development for Persons with Disabilities:* Automated Modular Assistive Guitar

Figure 1. Example of Research in Design Flexibility and Agile Product Development at UT.

Figure 1(c) pictures a dental chair for applications in remote environments, such as third world countries. To develop products such as this collapsible and reconfigurable dental chair, product development teams must gather usage contexts for the product application. Usage contexts address information beyond customer needs, focusing on where, how, and who questions for the product's application circumstances. Figure 1(d) illustrates research results of rapid manufacturing techniques. The application area is PEM fuel cells where 3-D bipolar plates are fabricated using a unique indirect freeform fabrication process. Applications of freeform fabrication greatly expand the potential of rapidly fabricating components with complex geometries and varied material properties.

Figure 1(e) shows three figures of a micro-unmanned aerial vehicle. The figures demonstrate a potential *transformation* of an unmanned aerial vehicle from a reconnaissance mission to a long-distance travel mission. Our research in this area seeks to uncover principles of transformation and to design transformers that will allow products to dynamically reconfigure themselves for varied capabilities. Figure 1(f) shows the concept of Empirical Similitude. This concept seeks to develop functional prototypes of complex products using basic materials and simple geometries. The underlying mathematical framework is then constructed to map testing results of the simplified prototypes to predict the behavior of the more complex product.

Figure 1(g) provides an illustration of the research of Professor Seepersad at UT (http://www.me.utexas.edu/~ccseepersad/). The figure pictures different physical strategies for condensing components during fabrication (such as with freeform fabrication). These condensed structures may then be deployed for much larger and spatially varied applications. Figure 1(h) shows a solid model rendition and picture of a modular automated guitar product. This product is an example result of our research into product development in assistive technologies and, more generally, in the area of low-volume design and fabrication.

II. Research Snippets in Design

Given the variety of UT design research illustrated in Figure 1, the following sections present snippets of selected examples of this research. These snippets present more detail of the research projects of Figure 1. They also provide a foundation to postulate the implications of design research on education (at all levels) and on industrial practice.

II. A. Innovations in Product Flexibility

The strategic objective of this research area is to create, develop, and deploy innovative design methods for flexible product development. Design, or product, flexibility is the degree of responsiveness (or adaptability) to the multimodal needs of customers and for any future change in a product. Three areas compose the field of product flexibility: product portfolios, mass customization, and design for future product evolutions. Product portfolios entail multiple product offerings based on a common platform, such as the Sony Walkman™ and desktop computers. Mass customization refers to product stratagems when "the same large number of customers can be reached as in mass markets of the industrial economy, and simultaneously they can be treated individually as in the customized markets of pre-industrial economies" (Davis 1987). Design for future product evolutions concerns the predictive architecting of a product to accommodate market-driven, future changes in the product over time. Industries are increasingly seeking design strategies for product flexibility. Mass-produced, single offerings of products are becoming more and more rare and specialized. The dynamics of product markets, short-development times, and global competitiveness places a premium on a company's (and product development firms') abilities to be customer centric, to respond quickly to changing needs, to offer wide variety across a marketplace, and to make appropriate decisions that balances these factors. Our work on product flexibility seeks develop fundamental principles and techniques to assist companies in this pursuit.

The initial stage of the research focuses on the development of underlying theories and principles to understand enablers for product flexibility. During the last nine months, four Master's students completed parallel work in the development of (1) patent and product search methodologies for product flexibility, (2) procedures for systematically dissecting patents and products to derive flexibility principles, (3) the derivation of principles from initial patent and product searches, (4) the initial development of a lexicon and semantics for stating flexibility principles, and (5) the creation of actual product inventions that employ the preliminary principles. Analysis of an initial set of patents produced 15 distinct flexibility principles and one subset principle, for a total of 16 principles for future product evolution. For consistency, a common form of expressing the principles is desired. This approach means applying a common lexicon to achieve a similar semantic. The current lexicon, or vocabulary, is derived from an analogy to existing principles. Table 1 illustrates selected examples of flexibility principles from our research. We have created a number of inventions from these principles, including a flexible trial and training shoe (Fig. 1(a)), an ambidextrous digital camera, a laser pointer control device, percussion instruments for children w/disabilities, and a modular automotive assistive guitar (Fig. 1(h)). We have likewise developed a technique known as CMEA (Change Modes and Effects Analysis, analogous to FMEA, Rajan, et al., 2005) for performing a predictive analysis of the flexibility that must be included in a product as it is developed. These early research results are exciting and provide momentum for developing a robust theoretical foundation and useful design methods in the area of design flexibility.

Table 1: Product Flexibility Principles (partial)

Number	***Patent***	***Principle***	***Frequency***
Modularity Related:			
1	478, 041, 386, 612, 863, 091, 111, 820, 696, 715, 918, 065, …	Make the device modular.	14
…	…	…	…
3	918, 715, 041, 111, 820, 386, 3179	Place components that are anticipated to change in time near the exterior of the device. Integrate those components into modules.	7
…	…	…	…
Spatial Related:			
5	041, 478, 863, 111, 820, 918, 696, 715, 065	Allow for expansion of current components or addition of new components within the housing or outer structure.	9
…	…	…	…
7	612, 863, 065, 041	Leave unused space within housing and/or modules for storage of current or future modules.	4
…	…	…	…
Interface Related:			
…	…	…	…
11	176, 478, 386	Add the ability to interface modules at multiple locations of a housing or outer structure	3
…	…	…	…
Component Related:			
14	041, 176, 612, 863, 091, 820, 918, 696, 715, 065, 6179	Segment a device to allow relative motion between modules and/or components	11
…	…	…	…

II. B. Innovations in Concept Generation: Understanding the Art of Design

Concept generation methods may be classified, broadly, into two categories: *intuitive* and *directed* (Otto and Wood, 2001). The intuitive category relates to the methods that focus on idea generation from within an individual or group of individuals. The intent of such methods is to remove barriers to divergent thinking so that new connections and features in a product may be visualized. Directed methods, on the other hand, use a systematic, step-by-step, approach to searching for a solution. These methods rely on technical information, expertise, and principles to seek solutions to technical problems or conflicts.

Our research in concept generation focuses on both intuitive and directed techniques. We are working collaboratively with a leading expert in cognitive psychology, Dr. Art Markman (http://www.psy.utexas.edu/psy/faculty/Markman/index.html) at UT. Initial research results from human science experiments demonstrate how enhanced graphical techniques, such as the 6-3-5 method or C-sketch, can greatly increase the number and quality of concepts generated by a product development team. These also provide insights into how these techniques should be taught to enhance and maximize the inherent creativity of the individual team members.

We have taken these findings and considered a focal area in concept generation, known as design-by-analogy. Design-by-analogy, analogies to nature, analogous products and design reuse, are noted methods for conceptual design (e.g., Pugh, 1991; Pahl & Beitz, 1996; French, 1996; Otto & Wood, 2001). Visual or functional similarity can be found based in these methods. Figure 3 illustrates a number of interesting design-by-analogy examples such as a lamp being aesthetically similar to the shape of a flower or a hydra. The Sydney Opera housed is also based on a visual similarity to the yachts in the surrounding harbor (Craig, 2001). Analogy can also lead to innovative functional designs. An analogy based on a snake resulted in an innovative product, the snake lamp (Giesecke, 2004). As a new device is developed, it is frequently based on previous products that serve a similar function. When the first train engines were developed, they were based on an analogous product, the stage coach (Ward, 1995).

In psychology, three areas of substantial research form a solid foundation for understanding design-by-analogy: analogical reasoning, naïve physics and reasoning with diagrams. A significant amount of work has been carried out in psychology to understand the cognitive processes people use for creating and understanding analogies (e.g., Gentner, Holyoak & Kokinov, 2001; Falkenhainer, Forbus & Gentner, 1989; Gentner & Markman, 1997;

Blanchette & Dunbar, 2000; Hummel & Holyoak, 1997). We have built upon these psychological findings to consider what scaffolding is necessary to develop useful methods in design-by-analogy for real-world design problems. Our initial results show that analogies are a direct conduit for developing ideas and concepts in product design. But it is also clear that the effective results depend on the representation and method of search for analogies. We are currently performing human science experiments and deductive research into effective methods for analogy representation and search. The initial findings are tremendously exciting.

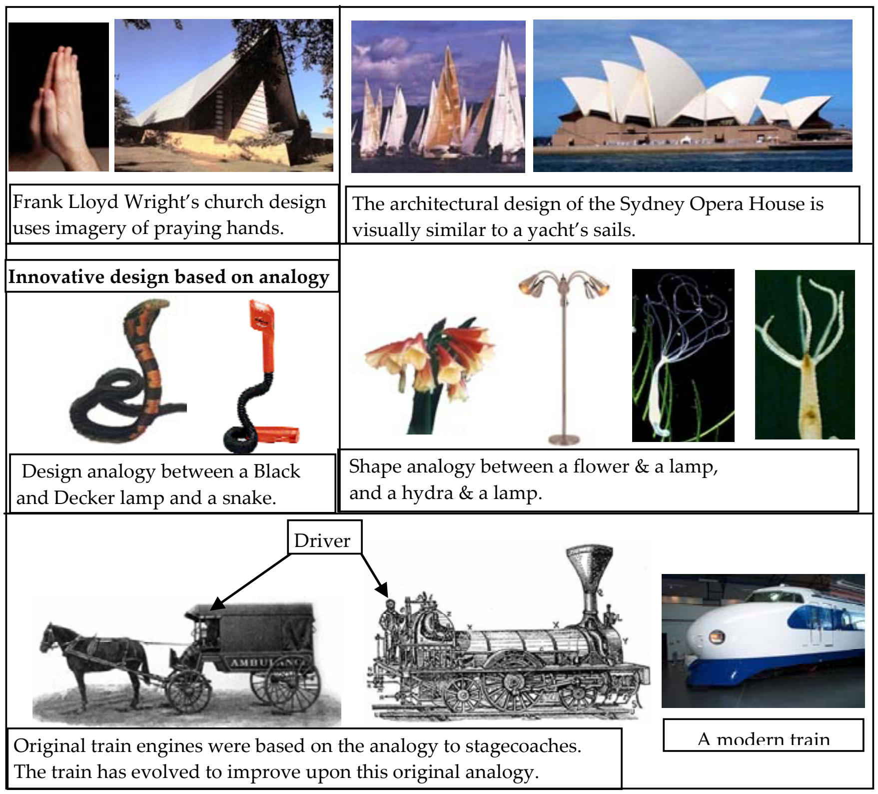


Figure 3. Examples of design-by-analogy.

III. Discussion: Inferences on Design Education, Industrial Practice

This article briefly explores design research at The University of Texas, Department of Mechanical Engineering. While only the highlights of this research are described, a number of inferences may be stated regarding the impact of this research on design education and on industrial practice. Consider the following top-level inferences:

- Design research may be directly transferred to the university classroom. Perhaps one metric of sound design research its ability to be taught at the undergraduate and graduate levels. In any case, the classroom provides a wonderful arena for fine tuning the research, for obtaining experimental validation, and for exposing our students to the state-of-the-art in design.

- Educational research clearly shows that students have a variety of learning styles and personality preferences. Design education and the transfer of design research to the classroom provides a unique opportunity to address these learning styles, especially with hands-on activities and techniques
- Research on product flexibility clearly shows industries' interest in creating flexible products, in investing in regional and rapid manufacturing concepts, and in developing partitioning strategies that recognize the inherent flexibility in requirements instead of just the near-term quarterly financial numbers.
- Analogical reasoning and representation have great potential in the creation of innovative design products. Industry understands the power of analogy and the need to train designers in design-by-analogy methods. Research is needed to develop the underlying foundation for analogical representations and for methods to identify, effectively and efficiently, promising analogical technologies.

Acknowledgements

The work reported in this document was made possible, in part, by the University of Texas at Austin College of Engineering, and the Cullen Trust Endowed Professorship in Engineering No. 1. We wish to acknowledge Dr. Art Markman of the Department of Psychology at The University of Texas. Our discussions with Dr. Markman in the area of design-by-analogy have been illuminating and his expertise in cognitive psychology has greatly enhanced our vision in this area. Any opinions, findings, or recommendations are those of authors and do not necessarily reflect the views of the sponsors.

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