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MEMIC: An Interactive Morphological Matrix Tool for Automated Concept Generation

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Abstract

Advancement in product design is usually made by building on previous experiences and learning from past successes and failures. However, knowledge transfer in the broad field of product design is often difficult to accomplish. Research has shown that successful component configurations, observed from existing products, can be dissected and stored for reuse; but few computational tools exist to assist designers during the conceptual phase of design. Many well-known manual concept generation methods (e.g. brainstorming, intrinsic and extrinsic searches, and morphological analysis) rely heavily on individual bias and experience and are generally laborious tasks that may not draw upon a wide enough solution space. This research presents an automated design tool that augments traditional activities during the conceptual phase of design. The interactive morphological matrix (or MEMIC, the Morphological Evaluation Machine and Interactive Conceptualizer) draws on knowledge contained within a repository of existing design solutions to quickly produce numerous feasible concepts early in the design process, which each satisfy the functional requirements for a design problem. By quickly presenting numerous concepts from products that have already been developed, this design tool provides a broader set of initial concepts for evaluation than a designer may generate alone when limited by his/her personal experiences.

Keywords
concept generation, design automation, component configuration, design repository implementation

1. Introduction

The creative nature of design generation demands skills from a designer that must be developed and refined through practice. Advancement in technology is usually made by building on previous experiences and learning from past successes and failures. However, this knowledge transfer in the broad field of product design is often difficult to accomplish. Many tools exist that specialize in certain aspects of the product design space. For example, CAD tools allow designs to be visualized and moved to production, while Finite Element Analysis (FEA) packages allow for specific components to be structurally analyzed. While many design packages exist for the CAD and FEA space of product development, few software packages are geared toward the pre-form space of product design. This paper builds on previous concept generation techniques explored at the Missouri University of Science and Technology (formerly the University of Missouri-Rolla) and presents an interactive concept generation tool aimed specifically at the early concept generation phase of the design process.

Previous research into automated concept generation design tools led to the creation of two distinct design tools: a web-based automated morphological matrix generator [1] and a computational concept generation algorithm [2]. A hybrid method of both the automated morphological matrix and concept generation algorithm yields an interactive concept generator that allows the user to build complete solutions of physically compatible components that solve the desired functionality. The interactive morphological matrix approach presented here (hereafter referred to as MEMIC or the Morphological Evaluation Machine and Interactive Conceptualizer) combines the component functionality and compatibility information from the concept generation algorithm while enabling creative decisions to be made more easily by presenting more solutions simultaneously as the web-based morphological search does. This paper begins with a review of related work in Section 2, followed by a description of the MEMIC design tool in Section 3. A preliminary assessment of the impact that MEMIC has on individual creativity during concept generation is presented in Section 4. Finally, Section 5 discusses this research and future work that has been identified.

2. Review of Related Work

Some challenges in creating useful design theories include finding both innovative and useful ways to guide an engineer toward the best solution(s). These challenges are especially difficult when encouraging young engineers-in-training to engage in specific design methods designed to enhance creativity and draw upon design knowledge external to their realm of personal experience. Yang [3] concludes that, in the context of student design teams, it is both important to generate and solidify a large number of ideas as well as begin prototyping a design early in the design process. Designers traditionally have a limited number of options available to them for generating multiple feasible design solutions to evaluate. Available options may include drawing on personal experiences or the experiences of coworkers, utilizing patent searches to find other approaches or similar designs, and reverse engineering existing products to evaluate how either the current design or a redesign could be used to meet the design goals. All of these methods are potentially limited or biased by a designer's experiences. In addition, patent searches and reverse engineering are potentially time intensive, laborious tasks and may not catch solutions that seem unrelated but are, in fact, analogous.

2.1. Manual Concept Generation Methods

Several manual concept generation methods have been created to help stimulate designer creativity and encourage exploration of the solution space beyond an individual designer's personal experience (e.g., the 6-3-5 method [4], catalog design [5], and the Theory of Inventive Problem Solving, or simply TRIZ [6].) The morphological matrix introduced by Zwicky is a now a classic technique for use in conceptual design [7]. This method provides the design engineer with a simple, albeit manual, means for bookkeeping potential physical solutions and their corresponding functionality. A morphological matrix is traditionally created by listing all of the subfunctions for a design and brainstorming solutions to each subfunction, listing the solutions as columns and the subfunctions as rows (e.g., [8]). In a manual engineering design context, the morphological matrix is limited to the concepts generated by the engineer, although the morphological matrix is one technique that can be used in conjunction with overall design processes such as the 6-3-5 method. Each of the previously described manual conventional engineering design methods are intended to spur creativity and thus assist the engineer in generating a large number of candidate design solutions. The fundamental challenge that each of these methods attempt to address is that of identifying a suitable set of design alternatives to later exploit and prune based on evaluation.

2.2. Automated Concept Generation Methods

The fuzzy front end of the conceptual design process has seen few attempts at automation. Non-computational methods exist (e.g. the techniques described in Section 2.1) but do not employ any automated tools to help guide a designer. Furthermore, redesign tools (e.g. Quality Function Deployment [9] and Life Cycle Analysis [10]) may prove initially confusing to an inexperienced designer. Computational tools that support the conceptual stage of design do exist, but often these tools address areas that support initial requirements gathering (e.g. organizational tools such as the TikiWiki project [11]), or the creation of function structures (e.g. the function grammar tool developed by Sridharan and Campbell [12]) or optimization of well-established concepts (e.g. [13]) rather than the generation of design solutions from existing design knowledge. One notable exception is the A-design approach to conceptual design [14]. This approach employs a sophisticated algorithm to produce multiple conceptual configurations based on evolving user preferences within the electro-mechanical domain. However, at this stage of development, the concepts produced seem restricted to flows of energy or those components for which a bond graph can be readily utilized.

Conventional CAD programs are not designed to foster interactivity and creativity during the early stages of design [15], and suitable computational tools that support the fuzzy leading edge of the conceptual phase are still relatively young and underdeveloped. One area of research explores the development of computer tools that enable 2D designer sketches to be quickly transformed into 3D parameterized models, which can then be evaluated for the given design problem. Hearst, et al. [16] state that computerized sketching research seeks to create an environment that encourages collaboration and modification in contrast to current computer interfaces that feel too formal and precise to stimulate creativity. However, computerized sketching tools (e.g., [17][18]), although potentially useful, seem geared more toward capturing a designer's ideas for further development early in the design process and do not seem to address the origination of the ideas to sketch. Other computer-aided conceptual design tools apply function-based associations to graphically describe the elements of a mechanical assembly [19][20]. Often, though, function and flow semantics are only assigned to a conceptual design after the structure has been chosen for manipulation by the software, thus diluting any benefits that may be gained by first abstracting a problem (e.g. the Multiuser Groups for Conceptual Understanding and Prototyping (MUG) research platform [21]).

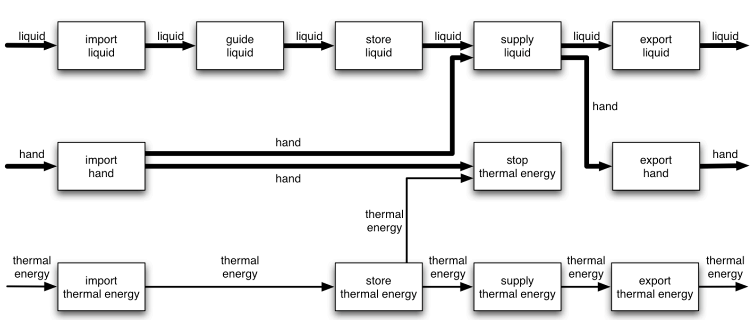
With these notions in mind, the overall purpose of an automated concept generation design tool is to spark (viable) ideas early in the design process. The goal is to quickly give a designer a set of potential solutions that may then be used to help explore the design problem. MEMIC, the design tool presented here, seeks to alleviate some of the drawbacks of two previously presented automated tools: a web-based morphological search [1] and the static list output of an automated concept generator that utilizes a list-based output [2]. This hybrid method, described next in Section 3, presents a designer with a large interactive matrix of design solutions that a designer may then tinker with to produce complete and feasible solutions for a set of functional requirements.

3. The Interactive Morphological Matrix

The MEMIC automated concept generator was created to produce chains of design solutions for a product design from a given chain of sub-functions using knowledge extracted from a web-based design repository [22]. MEMIC accepts a user-input, high-level functional description of a design and uses functionality and compatibility information describing partial conceptual solutions or components to generate, filter, and rank full concept variants. The algorithm utilizes the function-component relationships contained in a function-component matrix (FCM) and the component-component compatibility information contained in a design structure matrix (DSM) generated by the repository of existing consumer products.

Beneficial characteristics of a web-based morphological search [1] and a list-based automated concept generator [2] were combined into a hybrid technique in an effort to enhance the usefulness of the automated design tool to a designer. The hybrid technique retains the solution accessibility that the web-based morphological search method provides a user by listing the solutions for each function in a matrix form, while retaining the connectivity information that the list-based automated concept generator utilizes. Thus, a user can more easily choose between multiple solutions for a given function and interactively build a complete feasible solution. The MEMIC software first requests a text file describing a full functional model in the form of a function-adjacency matrix. A function-adjacency matrix, briefly demonstrated using a simple example shown in Figure 1, is a translation of a block functional diagram into matrix form, where a non-zero cell entry indicates a forward connection between the row and column functions. Converting a graphical functional model into this asymmetric matrix form yields an easy and convenient tool for identifying the connectivity between functions, including branching connections and connections that converge into a single function, as well as starting and ending subfunctions (zero columns and zero rows, respectively).

(a)



(b)

	import liquid	guide liquid	store liquid	supply liquid	export liquid	import hand	export hand	import thermal energy	store thermal energy	supply thermal energy	stop thermal energy	export thermal energy
import liquid	0	**1**	0	0	0	0	0	0	0	0	0	0
guide liquid	0	0	**1**	0	0	0	0	0	0	0	0	0
store liquid	0	0	0	**1**	0	0	0	0	0	0	0	0
supply liquid	0	0	0	0	**1**	0	**1**	0	0	0	0	0
export liquid	0	0	0	0	0	0	0	0	0	0	0	0
import hand	0	0	0	**1**	0	0	0	0	0	0	**1**	0
export hand	0	0	0	0	0	0	0	0	0	0	0	0
import thermal energy	0	0	0	0	0	0	0	0	**1**	0	0	0
store thermal energy	0	0	0	0	0	0	0	0	0	**1**	**1**	0
supply thermal energy	0	0	0	0	0	0	0	0	0	0	0	**1**
stop thermal energy	0	0	0	0	0	0	0	0	0	0	0	0
export thermal energy	0	0	0	0	0	0	0	0	0	0	0	0

Figure 1. (a) A simple functional model and (b) the associated function-adjacency matrix.

Next, a user is prompted to load tab-delimited data files of the function-component matrix (FCM) and design structure matrix (DSM), typically generated from a web-based repository of design knowledge. The user interface for uploading the files is shown in Figure 2a. Once each of these three data files is loaded, the “Create concepts!” button may be pressed to generate design solutions.

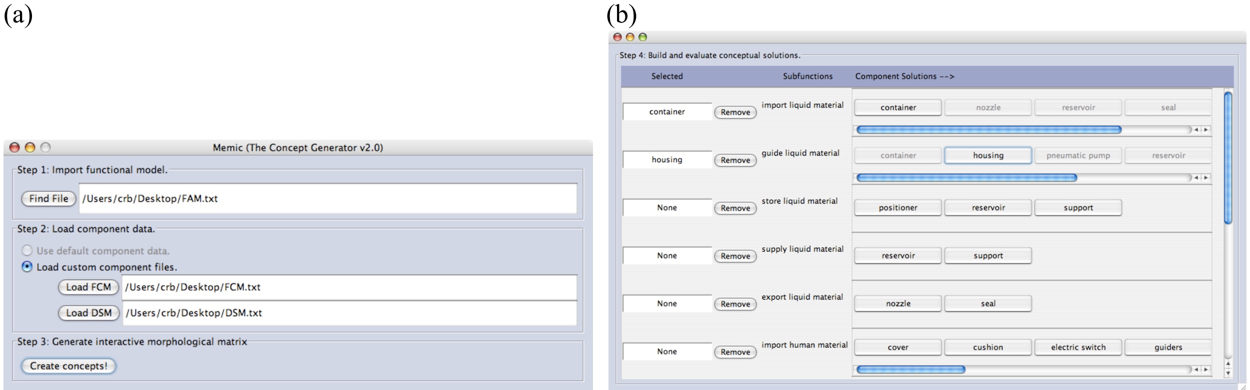


Figure 2. The interactive morphological search user interface for (a) inputting the FCM, DSM, and functional model for automatic concept generation, and (b) interacting with the return conceptual solutions.

When the user indicates that concepts should be generated, the data files are run through the algorithm [2]. The solutions are then returned to the user in the form of a morphological matrix, where the components that may be assembled into a full solution are listed alongside the name of each subfunction in the input functional model. If no compatible solution was found for a given subfunction, a “?” is placed as an indicator that no known solutions were found within the database that was also compatible with the solutions connecting to it.

Once components are returned, the interactive morphological matrix, shown in Figure 2b, allows the user to select components that solve each function in an input functional model. When a partial solution is selected, incompatible solutions are shaded over and the user is no longer allowed to select them. By implementing the concept generator output in this fashion, users can build entire concepts that, based on historical data contained within the repository utilized, are comprised only of partial solutions that can physically be connected together. By using MEMIC, a designer is allowed to tinker with various ideas and virtually assemble a feasible and complete solution.

4. Preliminary Assessment Study

To examine the extent to which the automated concept generator enhances an individual’s creativity, a preliminary assessment involving 19 engineering students at Missouri S&T was conducted. The test subjects were instructed to generate as many complete solution concepts as they could for two different design problems: (1) a device that the elderly and disabled could use to help them transfer heavy cookware into a hot oven from a stove or counter top and vice-versa, and (2) a device that the elderly and disabled could use to help them access the milk contained in a cardboard milk container, which many find difficult to open when lacking dexterity. A pre-test survey was used to gauge the students’ past design experiences, their ability to analyze/repair electro-mechanical devices, and their level of comfort using a computer.

To explore the effect of the use of the automated concept generator in comparison with a commonly utilized, but not specifically design-oriented, search tool (i.e., the Internet), the original set of 19 participants was randomly divided into four experimental condition groups (Groups A-D) as shown in Table 1. Participants in all 4 groups were given 45 minutes to produce concepts from their own experiences (Phase I). Then, for an additional 45 minutes (Phase II), each group either was allowed to use only the Internet or was allowed to use the automated concept generator in conjunction with the Internet as indicated in the table. Three of the 19 test subjects did not complete one or either of the experiments and were subsequently excluded from the analysis, resulting in the following distribution of individuals per group: Group A, n=4; Group B, n=3; Group C, n=4; and Group D, n=5.

Table 1. Summary of Experimental Conditions for Preliminary Assessment

	Design Problem #1		Design Problem #2	
Group	Phase I (45 min.)	Phase II (45 min.)	Phase I (45 min.)	Phase II (45 min.)
A	Personal Experience	Internet	Personal Experience	Internet
B	Personal Experience	Internet	Personal Experience	Concept Generator
C	Personal Experience	Concept Generator	Personal Experience	Internet
D	Personal Experience	Concept Generator	Personal Experience	Concept Generator

The experiment was conducted over a two-day period. At the beginning of each experiment, the test subjects were read a script of instructions explaining guidelines for the experimental procedure and were each given a packet of instructions, which included a description of the design problem, a list of customer needs for the design problem, a function structure created for the design problem, and basic guidelines for the prescribed method. The guidelines instructed the participants to generate as many complete solutions as possible in the allotted time. The participants were also instructed to represent their ideas using sketches and/or written words, to place each separate conceptual idea on a separate sheet of paper, and to create conceptual solutions which solved both the customer requirements and the functional requirements specified by the given function structure. When applicable, groups instructed to use the concept generator as a design aid were given additional instructions explaining how to use the software. In these sessions, participants were asked to study the additional material before generating concepts and are instructed that they may use ideas from the concept generation software during the exercise. After Phase II of each design problem was complete, participants were given a post-session questionnaire that asked questions regarding the concepts they generated and the use of the external sources (i.e., the Internet or the automated concept generator) they used to gather ideas.

4.1 Evaluation Metrics

The participants created a total of 132 conceptual sketches (59 for the Oven Helper Device, and 73 for the Milk Carton Opener Device), and three faculty members – experts in function modeling and concept generation – from Missouri S&T's Interdisciplinary Engineering Department judged each concept based on completeness, novelty, and variety:

1. *Completeness*: A measure of the level indicating how much a concept variant addresses the sub-functions depicted in the function structure [23].
2. *Novelty*: A measure of how unusual or unexpected an idea is as compared to other ideas [24].
3. *Variety*: A measure of the explored solution space during idea generation [24].

All three metrics were evaluated using an ordinal scale (1-low to 7-high). The judges assessed each concept produced individually to assign measures of completeness and novelty, whereas the entire set of concepts produced by a single participant was assessed to measure the variety of the individual's concepts. The completeness metric was normalized across subjects to account for differences in the number of concepts produced by each test subject. Each judge was given a shuffled stack of concept sketches, and participant IDs were assigned using random numbers with no indication of the assigned experimental grouping. Pair-wise Spearman rank-order correlation coefficients were calculated to monitor the agreement in scores between judges.

4.2 Experimental Results

Two judges were consistently in close agreement while the third was not. Consequently, the results indicated that there was no statistical effect on the metrics of completeness and variety in either design scenario using a Mann-Whitney U test. While this result was obviously disappointing, a wealth of information was gained to improve the proposed research as discussed next.

5. Conclusions

This paper presents an interactive morphological matrix design tool known as MEMIC (the Morphological Evaluation Machine and Interactive Conceptualizer.) Intended to help designers choose a correct component for a given function in a redesign or original design situation, the goal is to utilize existing design knowledge to rapidly produce a large array of concepts early in the design process. Compared to traditional concept generation methods, the process presented here is quick and does not require the effort of an entire team of designers.

A preliminary assessment of MEMIC investigated the impact of the automated concept generator on individual designer creativity for two design scenarios. Observations made during the experiment indicated that the participants were intrigued by the idea of using the software, but they were generally uncomfortable with the information output from MEMIC (i.e., it was not easy to interpret the textual results like those shown in Figure 2b). This reluctance to interpret the output demonstrates a need for improvements to the output presentation prior to further testing, for instance by adding images or visual schematics. Many of the participants also indicated that the only time that the Internet proved useful for generating designs was when they were able to find a pre-existing solution that was directly addressing the given design problem, which they then sketched as one of their concepts. Application of similar thoughts to use of the MEMIC software suggests that the information retrieved from the concept generator may benefit from being less abstract or by more pointedly demonstrating the pertinence, in order to be perceived as relevant to the design problem at hand. In addition, although the study was designed to exhaust the concepts readily produced from each designer's personal experiences prior to being exposed to external searching options, the researchers observed that many of the participants grew weary of producing ideas and sketches by the time they reached Phase II, increasing their unwillingness to utilize either MEMIC or the Internet. Future experiments will be structured to avoid repetition and minimize fatigue and boredom by making a single pass through the idea generation process. Finally, an experiment studying the impact that MEMIC has on creativity within a team environment, where the abstract conceptual results may be more readily discussed than dismissed, is also planned.

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