2006-1758: SOFTWARE EVALUATION OF AN AUTOMATED CONCEPT GENERATOR DESIGN TOOL

Cari Bryant, University of Missouri-Rolla

CARI BRYANT is a Ph.D. student at The University of Missouri-Rolla, Department of Mechanical and Aerospace Engineering. The objective of her research is to develop design methods and tools that build on existing design knowledge to support the design process, specifically during the concept generation phase of product development. In 2003 Cari received a M.S. degree in mechanical engineering and an M.S. degree in biomedical engineering from the University of Michigan while doing research in the University of Michigan Orthopaedic Research Laboratories. Contact: crb5ea@umr.edu

Eric Pieper, University of Missouri-Rolla

ERIC PIEPER was a senior in the Electrical Engineering Department at the University of Missouri-Rolla and involved with the university Solar Car Team at the time of the reported study.

Brandon Walther, University of Texas-Austin

BRANDON WALTHER received his B.S in Mechanical Engineering from the University of Texas at Austin. Currently, Brandon is a M.S. student studying mechanical design in the Department of Mechanical Engineering at U.T. Austin. He also works at Applied Research Laboratories designing mechanical components for high frequency sonar equipment.

Tolga Kurtoglu, University of Texas-Austin

TOLGA KURTOGLU is a Ph.D. candidate in the Mechanical Engineering Department at the University of Texas at Austin and works as a research assistant at the Automated Design Lab. His research interests include development of computational design tools, design optimization and conceptual design theory. Tolga has an M.S. degree in Mechanical Engineering from Carnegie Mellon University. In his M.S. studies, he specialized in development of sketch based user interfaces for CAD tools. Currently, he is working on creating a computational theory for conceptual mechanical design.

Robert Stone, University of Missouri-Rolla

ROBERT STONE is an Associate Professor in the Basic Engineering Department at the University of Missouri-Rolla. He joined the department in January 1998 after completing his Ph.D. in Mechanical Engineering from the University of Texas at Austin. Dr. Stone’s research interests lie in design theory and methodology, specifically product architectures, functional representations, and design languages. Contact: rstone@umr.edu.

Daniel McAdams, University of Missouri-Rolla

DANIEL MCADAMS is currently an Associate Professor of Mechanical Engineering and the Associate Chair for Graduate Affairs in the Department of Mechanical & Aerospace Engineering at the University of Missouri-Rolla. He joined the department in October of 1999 after receiving his Ph.D. from the University of Texas at Austin. He teaches undergraduate courses in machine element design and introduction to design and graduate courses in product design and dynamics. Dr. McAdams' research interests are in the area of design theory and methodology, concept generation, product architecture, design for manufacturing, tolerance design, and modeling for design, with specific emphasis and applications in product design.

Matthew Campbell, University of Texas-Austin

MATTHEW CAMPBELL is a faculty member of the Manufacturing & Design program of the Mechanical Engineering Department. He has served on the College of Engineering faculty since

2001. Dr. Campbell's research is focused on the area of computational design synthesis. Dr. Campbell has been acknowledged with best paper awards at conferences sponsored by the ASME, the ASEE, and the Design Society. His research focuses on computational methods that aid the engineering designer earlier in the design process than traditional optimization would. To date, he has been awarded $1.57 million in research funding, including the CAREER award for research into a generic graph topology optimization method. This research represents a culmination of past computational synthesis research including the automatic design of sheet metal components, multi-stable MEMS devices, function structures, and electro-mechanical configurations.

Software Evaluation of an Automated Concept Generator Design Tool

Abstract

Few computational tools exist to assist designers during the conceptual phase of design where design success is often heavily weighted on personal experience and innate ability. Many well-known methods (e.g. brainstorming, intrinsic and extrinsic searches, and morphological analysis) are designed to stimulate a designer's creativity, but ultimately still rely heavily on individual bias and experience. As a first step toward enabling novice designers to readily reuse design knowledge during a function-based design process, an automated mathematically-based concept generation method was created to generate new solutions from existing product knowledge housed in a web-based repository. The algorithm was developed into software using Java code. The software, currently in the initial stages of development, accepts a chain of sub-functions describing the product's desired functionality. The software then uses matrices describing component functionality and component compatibility to build and rank chains of feasible concept variants based on historical data. A designer can then explore and evaluate the returned concepts for further development as design solutions. In an effort to help evaluate the current software and establish research goals for further development, four undergraduate engineering researchers from the University of Missouri–Rolla and University of Texas at Austin executed a qualitative study of the software's effectiveness at producing useful design solutions. The students engaged in several activities designed to test the capabilities of this early version of the software. The students reported on the results of their analyses and described the benefits and disadvantages of the software as they viewed it at this stage of development. Their experiences were used to help identify avenues for further development of the design tool.

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. Often, few records are kept cataloging a designer's rationale during the decision making processes that lead to the embodiment of a successful design solution. Additionally, although many successful designs are prevalent around us, often it is unclear why or how an existing design is successful without prior experience dissecting or designing a similar product. Although it is difficult, if not impossible, to retrieve and store existing design knowledge capturing decision rationales or unsuccessful designs, research has shown that successful component configurations in the form of existing products can readily be dissected and stored for reuse.[1,2]

In reference to their study investigating snap judgments that web users make within 50 ms of viewing a website, Lindgaard describes a societally pervasive tendency to 'jump to conclusions'. The article points to the desire to be right, part of a 'cognitive bias', as a phenomenon that causes users to continue to use a website that gave a good first impression, thus helping to 'prove' to themselves that they made a good initial decision.[3] Lindgaard also relates this phenomenon to the shown tendency of doctors to make a diagnosis following their initial hunches from a patient's most immediately obvious symptoms. Putting this in the context of making design decisions, even though experience in the form of design knowledge may be accessible to an inexperienced designer, (s)he may feel compelled to select a concept to embody based on a subconscious desire to validate an initial 'gut feeling.' So, the challenge becomes finding innovative ways to guide an engineer toward the best solution(s) by building on existing design experience while simultaneously discouraging tendencies to make choices or evaluations based on hunches or biased methods—a challenge made especially difficult when encouraging young engineers-in-training to engage in specific design methods designed to enhance creativity and build on existing design knowledge.

The concept generation phase of the design process is a particularly difficult stage to resist (or discourage) premature fixation on a single design solution for both inexperienced and experienced designers alike. To help spur creativity at this critical point, designers traditionally have a limited number of options available to them for generating numerous 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.

Additional research has produced structured design methods such as those presented in the textbooks of Pahl and Beitz[4] and Otto and Wood[5] that take a designer through a specific set of steps designed to help dissect a design problem and build conceptual solutions based on the functionality that a product needs to exhibit. Functional modeling methods intend to help a designer abstract the functionality a solution is required to fulfill from any bias that may be introduced from considering specific embodiments early in the development of a solution. This act of abstraction is thought to help a designer generate more creative and complete conceptual solutions and balance design choices between different components with the same functionality.

The Concept Generator software[6] evaluated during the experimental activities presented in this paper relies on user-input generated from these functional modeling methods to automatically produce a ranked list of feasible conceptual designs built from existing design knowledge[1,2] from over 70 consumer products. The Concept Generator, briefly presented in Section 2, uses a matrix-based algorithm to create chains of design solutions for a product design from a given chain of sub-functions using knowledge extracted from the design repository.[7] The algorithm starts with a high level functional description of a product and uses component functionality along with component compatibility to create, filter, and rank concept variants.[8,9] The work presented here describes a qualitative study executed by four undergraduate engineering researchers from the University of Missouri–Rolla and University of Texas at Austin to evaluate the effectiveness of the alpha version of the Concept Generator at producing useful design solutions. The students engaged in several activities designed to test the capabilities of this early version of the software. The students then reported on the results of their analyses and described the benefits and disadvantages of the software as they viewed it at this stage of development. Their experiences were then used to identify avenues for further development of the design tool.

2. The Concept Generator

The following sections briefly outline the details behind the alpha version of the Concept Generator software. The first section gives an overview of the algorithm used to produce a set of feasible concept variants. Next, the Functional Basis and Component Basis are briefly introduced as the taxonomies necessary to communicate input to the software and to translate the component configuration output. Finally, the Java implementation of the Concept Generator algorithm is presented.

a. The Algorithm

The matrix-based Concept Generator algorithm was developed to create chains of design solutions for a product design from a given chain of functional modeling sub-functions using knowledge extracted from a repository of product information.[7] The algorithm utilizes function-component relationships and component-component compatibility from the web-based repository of existing consumer products in the form of function-component matrices (FCM) and design structure matrices (DSM), respectively.[8,10] A visual interpretation of the of the matrix operations can be found in Figure 1. In Step 1, the user generates a conceptual functional model. Step 2 defines the function-component relationships by downloading a FCM from the product repository. In Step 3, matrix multiplication is performed using rows and transposed rows of the FCM to produce the full set of conceptual variants capable of solving the input function chain. Next, in Step 4, the component-component compatibility is defined by downloading a DSM from the product repository. Finally, in Step 5, the full set of concept variants is filtered for feasibility by cell multiplication of the DSM data with the matrices produced in Step 3. For a detailed discussion of the matrix manipulations performed in the Concept Generator algorithm, the reader is referred to Bryant, *et al,* 2005.[7]

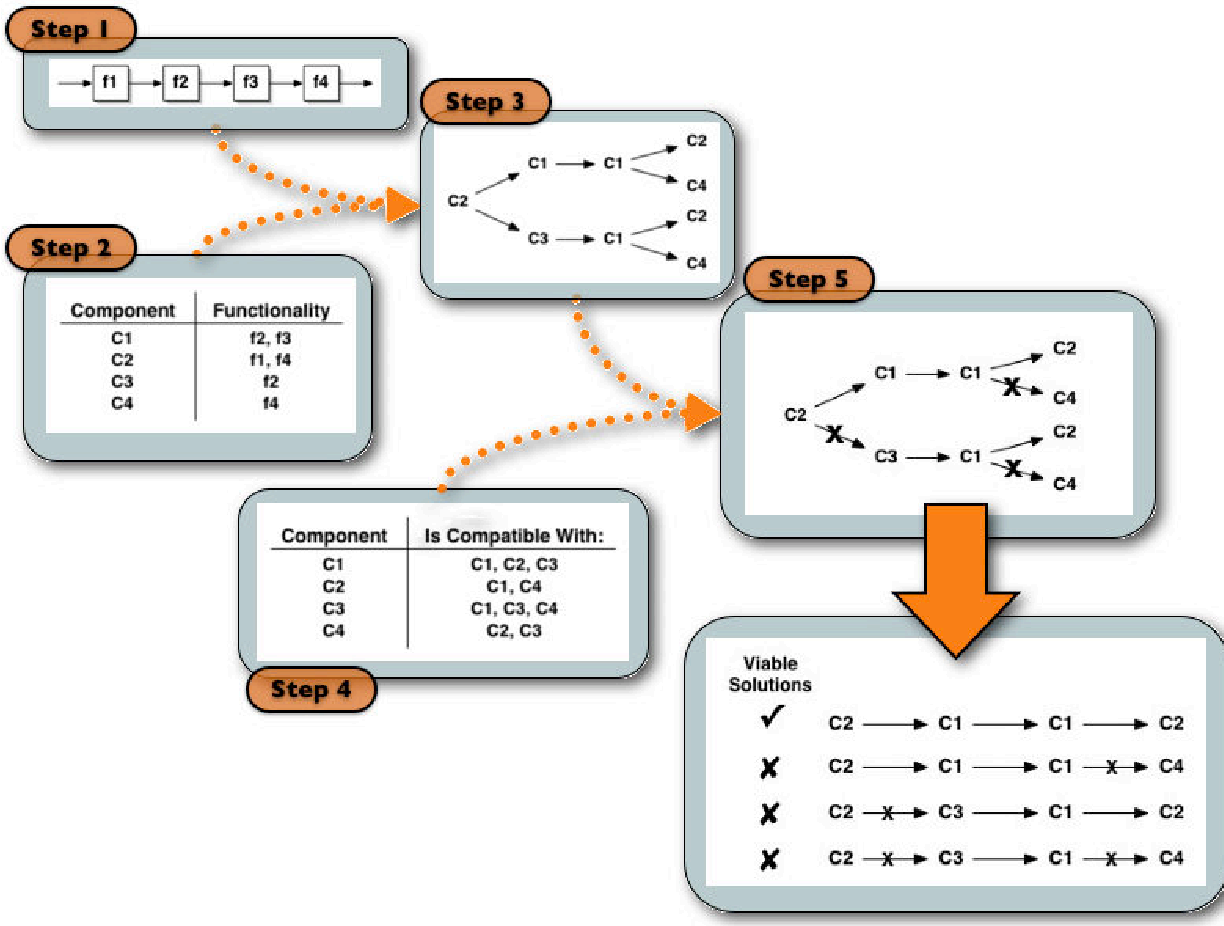


Figure 1: Visual summary of the algorithm used in the Concept Generator. The information shown in Steps 1, 2, and 4 are entered by the user. The unfiltered set of concept variants (Step 3) and set of feasible variants filtered by the component capability information from the DSM (Step 5) are produced using matrix algebra operations.

Product descriptions stored in the database allow access to information such as historical occurrence and failure mode, which can be used to help limit and rank design solutions. At this stage of development, the algorithm restricts the functional model input to a single linear chain of sub-functions and the component configuration output to a corresponding chain of artifacts, with the potential for adjacent functions to be solved by the same component selection.

b. The Functional Basis and the Component Basis

The Concept Generator employs two different taxonomies for accepting input in the form of a chain of sub-functions and displaying the output component configuration solutions—the Functional Basis and the Component Basis.

Tables 1 and 2 show a subset of the Functional Basis, a set of function and flow terms which combined to form a repeatable sub-function description (in verb-object format) of a product.[9,11-16] The Functional Basis taxonomy is arranged hierarchically with the flows (Table 1) and functions

(Table 2) categorized as primary classes (not shown), which are then further specified as secondary and tertiary (not shown) categories within each class.

Class	Material	Signal	Energy		
Secondary	Human	Status	Human	Electrical	Mechanical
	Gas	Signal	Acoustic	Electromagnetic	Pneumatic
	Liquid		Biological	Hydraulic	Radioactive
	Solid		Chemical	Magnetic	Thermal
	Plasma				
	Mixture				

Table 1: Flow classes and their basic categorizations.

Class	Branch	Channel	Connect	Control Magnitude	Convert	Provision	Signal	Support
Secondary	Separate	Import	Couple	Actuate	Convert	Store	Sense	Stabilize
	Distribute	Export	Mix	Regulate		Supply	Indicate	Secure
		Transfer		Change			Process	Position
		Guide		Stop				

Table 2: Function classes and their basic categorizations.

The Functional Basis terms, which are intended to span the entire mechanical design space without repetition, are utilized during the generation of a black box model and functional model in oder to encapsulate the actual or desired functionality of a product, as illustrated in the cup example shown in Figure 2.

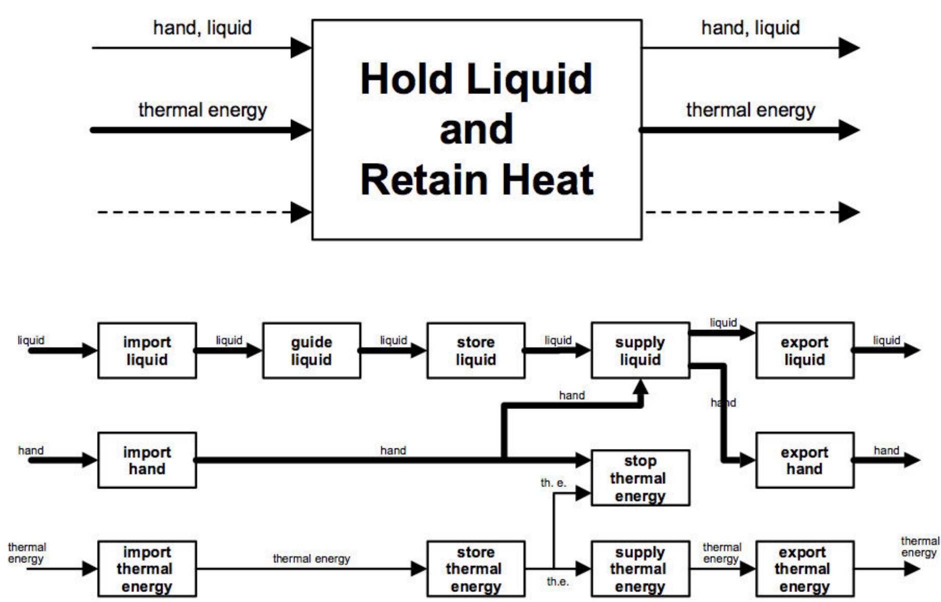


Figure 2: Black box model and functional model of a cup.

Table 3 shows an excerpt taken from the Component Basis, a recently revamped naming basis to classify product components.[17] Each component is classified under a specific basis name according to a distinct function-based definition. For example, separate components from different products may be assigned varying names by different researchers in the design knowledge repository, e.g. "motor 1", "shaded pole induction motor", or "dc motor", leading to an infinite number of naming possibilities. Using the updated Component Basis naming scheme, each of the of these artifacts would be identified as similar and tagged as an "electric motor". Using this basis standard allows for well-defined function-based groupings of artifacts to be used in the creation of FCMs and DSMs, helping to maintain matrices of manageable size and eliminating artifact redundancies that may not be immediately evident due to variations in user-dependent artifact naming. By eliminating these redundancies, a larger variety of unique and more abstract concept variants can be quickly generated and evaluated using these matrix-based design tools. After concept variants are selected using the generalized Component Basis names, individual artifacts classified under the chosen Component Basis names can be inspected to spur more specific concept variant ideas. For example, if a returned concept variant included an "electric motor", the repository could be accessed to provide the designer with the specific examples "motor 1", "shaded pole induction motor", or "dc motor".

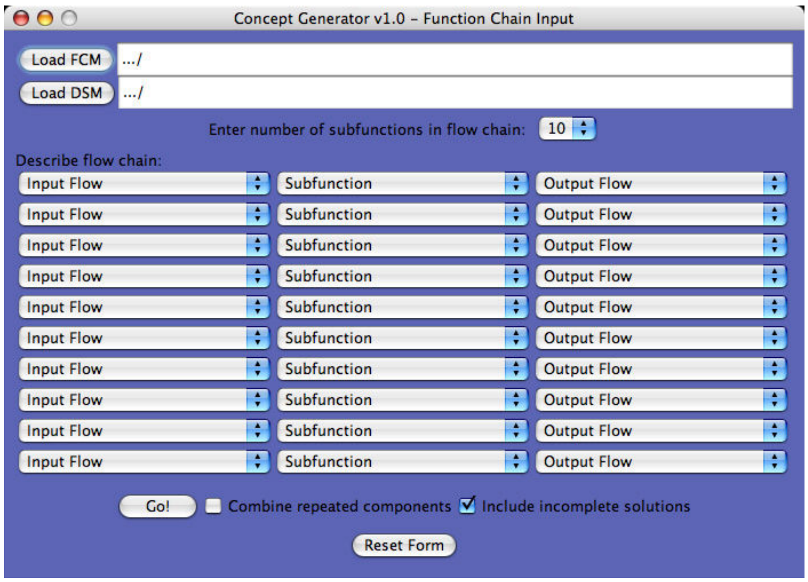
Name	Synonyms	Definition
Acoustic Insulator	silencer	The material that provides the condition of being isolated by non-conductors to prevent the passage of sound, or vibration.
Agitator	stirrer, mover	A mechanical device used to maintain fluidity and plasticity, and to prevent segregation of liquids and solids in liquids, such as concrete and mortar.
Airfoil	wing	Each of the limbs or structures by which an animal or manmade craft is able to generate a lifting force.
Axle	stub axle, beam axle, axle shaft	A supporting member designed to carry a wheel that may be attached to it, driven by it, or freely mounted on it.
Battery		A device that produce a direct current by converting chemical energy to EE. Mostly used to store EE.
Bearing	journal bearing, thrust bearing	Any part of a machine or device that supports or carries another part that is in motion in or upon it, such as a journal bearing or thrust bearing.
Belt	strap, girdle,band,restraint,strip	An flexible band made of leather, plastic, fabric, or the like that is used to convey materials or to transmit rotary motion between shafts by running over pulleys with special grooves.
Bladder	baloon, inner tube, membrane	A device resembling any of various sacks found in most animals and made of elastic membrane.
Blade	cutting edge,knife,razor,scraper	The broad flat or concave part of a machine that contacts the material to be

Table 3: An excerpt taken from the Component Basis definition set.[17]

c. The Concept Generator Software

Using the algorithm described in Section 2a, a Java-based program was created to automatically produce a ranked list of concept variants for a user-input functional model chain.[6] The user interface, shown in Figure 3a, firsts prompts the user for the location of the function-component matrix (FCM) and design structure matrix (DSM) data files generated from the web-based design repository from which the new concepts will be created. Within the repository, the FCM and DSM design tools permit the user to select any subset of products in the repository from which to generate these matrices, allowing the designer to select the group of product knowledge to build new concepts from.

(a)



(b)

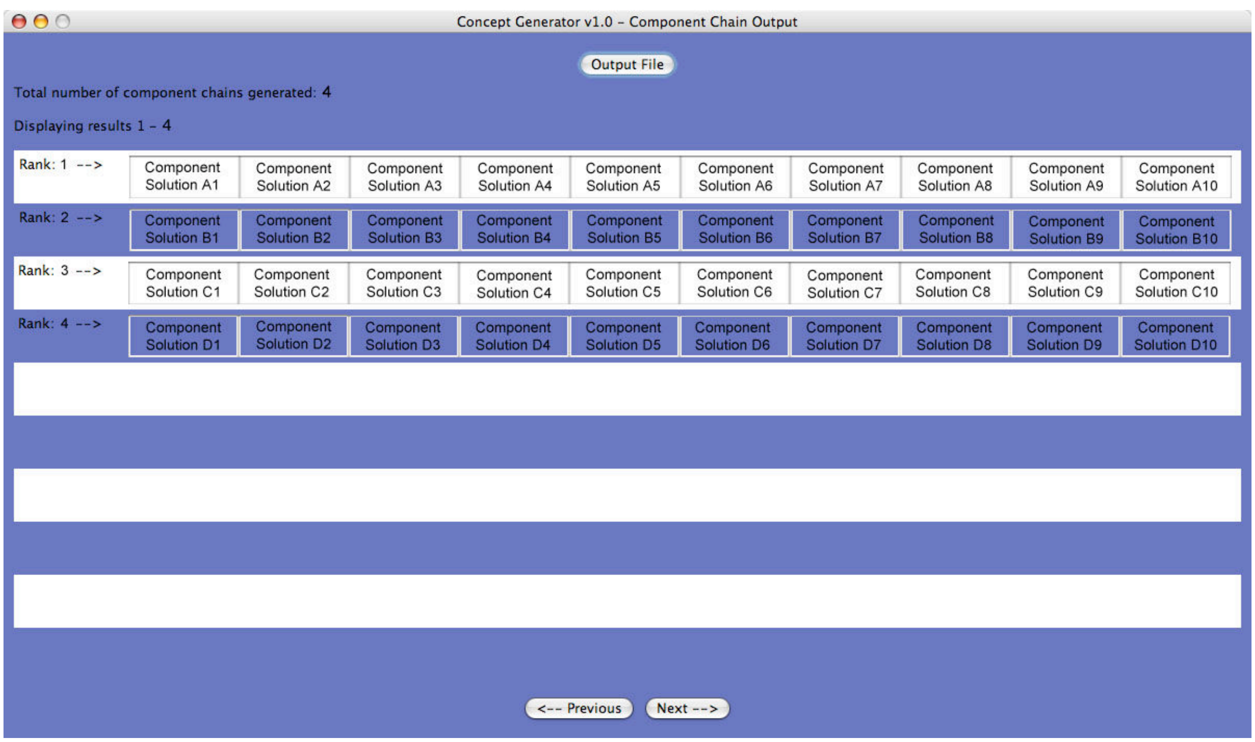


Figure 3: Concept Generator user interface for (a) inputting the FCM, DSM, and functional model for automatic concept generation, and (b) browsing through the list of returned concept variant chains.

Next, the user enters the number of distinct flow chains contained in the conceptual functional model. This initial version of the Concept Generator software limits flow chain entries to a single non-branching flow, requiring the user to break a full functional model up into individual chains prior to entry into the software. The user then selects the number of sub-functions in each flow chain and proceeds to enter the input and output flows and sub-functions for the individual chain. At this point, concepts can be generated and ranked for each flow chain by selecting the "Go!" button. The number of components displayed for each concept variant can be minimized by selecting the "Combine repeated components" checkbox. Under the pretense that a single component has the potential to solve multiple adjacent functions, selecting this option instructs the program to search for repeating series of components in the concept variant chain and collapse them down to a single instance for display.

The option to "Include incomplete solutions" in the ranked returned concepts is also available. This allows the user to decide whether to display concept variant chains that may be incomplete (i.e. not all sub-functions have an associated component solution), since the design repository may not yet contain preexisting solutions for the entered flow/sub-function combination. If selected, incomplete variants will show a question mark in chains where a component solution with known compatibility cannot be found. Once the concept variants are created and ranked, the results are displayed in a separate window, shown in Figure 3b, where the user can either save the results to a text file or browse through the variants using the interface at the bottom of the panel. It is important to note that the alpha version of the Concept Generator employs only a rudimentary method of ranking solutions loosely based on component frequency, and further research needs to be done to implement a more sophisticated and flexible sorting method. By using them as a point of departure for other non-computational creative techniques, e.g. brainstorming, these conceptual design variants can then be further developed and/or modified by the designer to satisfy the design requirements.

4. Research Activities

Four undergraduate engineering students (two from the University of Missouri–Rolla and two from the University of Texas at Austin) engaged in several design activities in order to evaluate the practicality of using the Concept Generator to automatically produce viable concept variants. In a methodological comparison (described below), design solutions produced by the Concept Generator were compared against manually created concepts produced by the students for three original design scenarios and one redesign scenario. Other activities not reported in this paper investigated the robustness of returned solutions against variations in the functional modeling chains used to seed the generation of concepts, including permutations and omissions of sub-functions. The following sections describe, in detail, the design activities that the undergraduate researchers engaged in during the study.

The methodological comparison investigated how the concept variants produced by the Concept Generator compared to concepts that were generated manually by the undergraduate researchers using more traditional brainstorming methods. In order to do this, the students looked at two design scenarios: one investigating concepts produced for an original design, and one investigating concepts produced during a product redesign. The students were instructed to complete the manual concept generation activities for all of the design scenarios prior to exploring the results generated by the Concept Generator software to avoid any unintentional biasing of results. The flowchart in Figure 4 shows an overview of the structure of activities.

Figure 4: Flowchart of the activity structure for the concept generation methodological comparison.

For the original design activities, students generated an original design solution for each of the the design problems described below.

- Hot/cold thermal mug: This design entailed creating a thermal mug to be used either to keep a hot beverage hot or a cold beverage cold. The idea was to create a thermal mug that is superior to ones currently on the market that rely solely on insulating techniques to achieve thermal isolation. In other words, concepts needed to be generated that not only attempted to inhibit the transfer of heat, but also had the ability to add or remove heat to the beverage.

- Human powered power supply: For this original design, the students were instructed to design a human-powered power supply that could reasonably supply enough electricity consistently to power an audio-visual device or that could be used to recharge batteries.

- Wall climbing toy: In this design scenario, a company has begun marketing a wall coating that contains ferrous micro-metal chips. This coating is “attractive” to magnetic devices and walls coated with this product “look” metallic. One potential marketing ploy for the company to increase sales of its coating product is to sell a toy that would operate on the vertical space of the walls (or even the ceiling). Thus, the undergraduate researchers were instructed to generate concepts for toy products that utilize walls covered with the coating as their play space. Since there are numerous types of potential toys for this new application, this call for products is fairly open ended. Broad requirements for the students to exhibit in their design included the ability to direct the toy accurately to specific points on the wall, remain stationary while on the wall, be marketable to a broad customer segment, be lightweight, have a long-lasting power source, and be inexpensive and easy to set up.

Using the design steps shown in Figure 5, the undergraduate researchers produced functional models from the customer needs they established (from customer interviews) for each product.

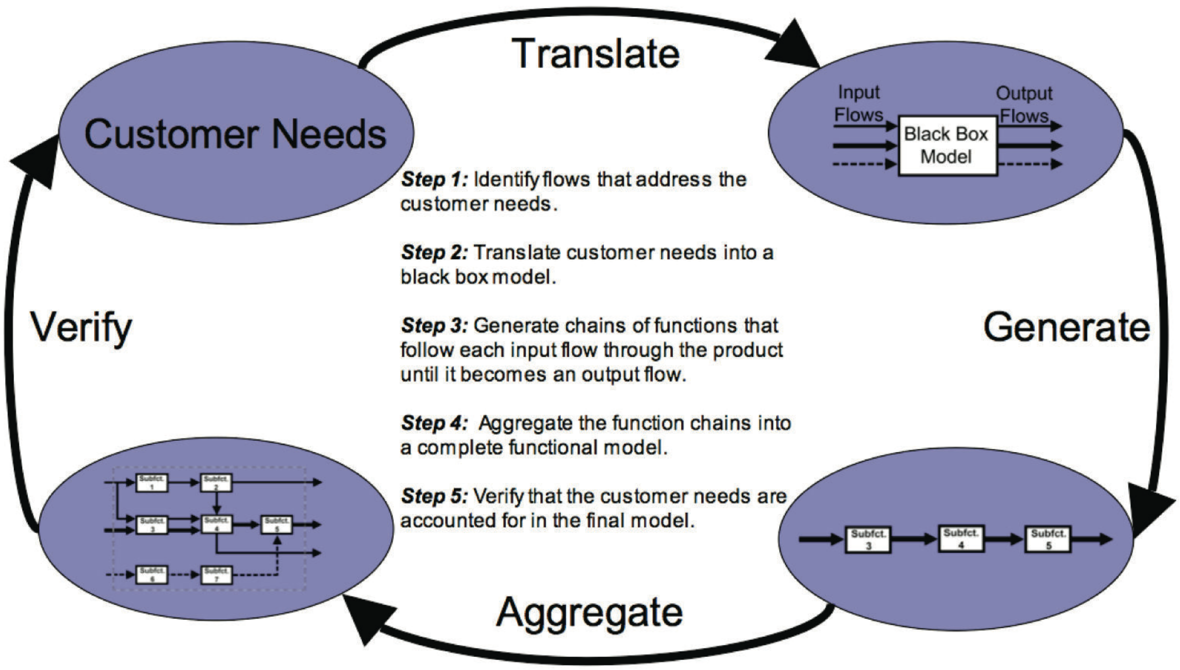


Figure 5: The steps followed to get from customer needs to a functional model.

Once a functional model was generated, traditional techniques including morphological matrices and brainstorming were used to develop concept variants for that product. The students kept records of their conceptual solutions in the form of sketches and verbal descriptions and also generated lists of components comprising each of their designs. Once concepts had been manually generated for the original design problems, the undergraduate researchers performed similar tasks for the redesign scenario before moving on to generate designs solutions using the Concept Generator software.

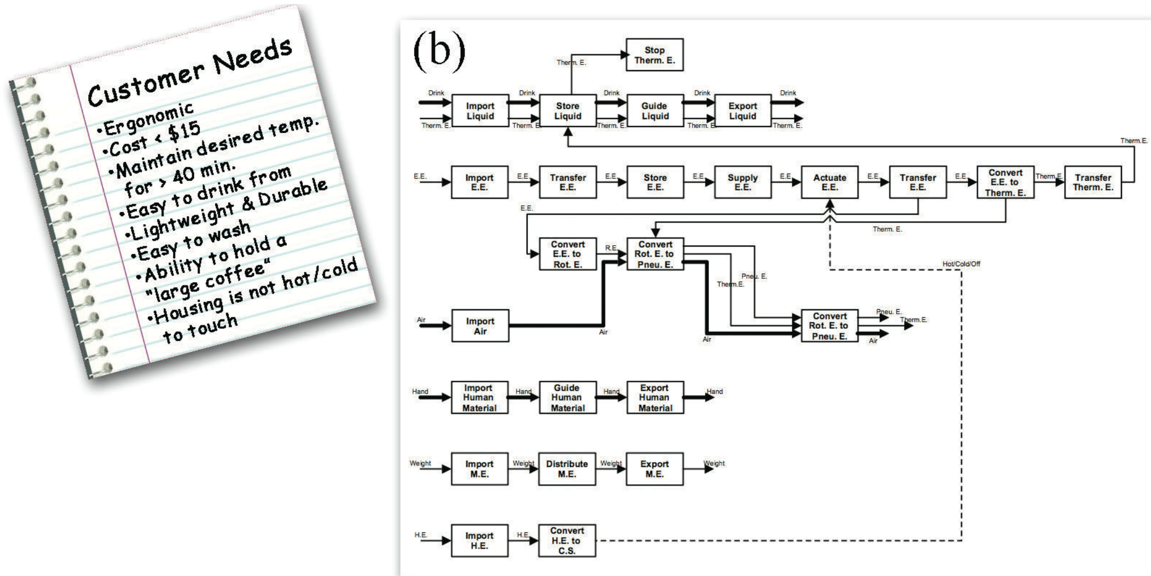
In the redesign activity, students were instructed to select one of the products that they had encountered during previous product dissection activities as a target for redesign. The students chose a snow cone maker device to investigate. A functional model of the existing product had already been generated during the earlier product tear-down activities, so the undergraduate researchers began by establishing any additional customer needs that were not addressed in the existing product. These additional customer needs were then translated into an augmented functional model of the redesign. As in the original design case, traditional brainstorming techniques were next used to produce conceptual variants for the redesign.

The final step in this group of activities was to generate conceptual variants for each design using the Concept Generator v1.0 software. Since the software user input is limited at this time, functional models had to first be separated into sequential (non-parallel) chains, with instructions given to the undergraduate researchers to experiment with how they chose to dissect the functional models for entry into the program. The students were instructed to make notes of any thoughts they had on the results produced for the chains they had entered. All design solution chains generated via the software were saved to text files that included the input function chain that was used to generate that set of concept variants. The next section presents a summary of the results produced by the undergraduates during the methodological comparison, with example results from the hot/cold thermal mug design included.

5. Results

For the methodological comparison, the undergraduate researchers manually developed original design solutions for the thermal mug, human-powered power supply, and wall-climbing toy design scenarios and redesign solutions for a snow cone maker device. They began by conducting interviews to collect customer need data for each original scenario. Next, the students used the customer needs to establish a functional model for each product using the method previously summarized in Figure 5. Using the sub-functions from the functional models, the undergraduate researchers manually constructed morphological charts to generate multiple partial solutions for each discrete functional element the design needed to embody using brainstorming techniques. Finally, the students selected a partial solution for each sub-function and sketched a complete concept capable of solving the given design problem. This last step was repeated several times to produce multiple concept variants for each design scenario. Figure 6 gives a summary of the data manually generated by the undergraduate researchers for the thermal mug design scenario described in Section 4.

(a) (b)



(c)

Sub-Function	Brainstormed Solutions				
import liquid	water tank	hose	cap	fountain machine	coffee pot
store liquid	water tank	bubble	cup	baby bottle	sippy cup
guide liquid	hose	cap	chute	levee	nipple
export liquid	water tank	hose	mouth		
stop thermal energy	styrofoam	air pocket			
import electrical energy	plug and cord	lightning rod	generator	thermo-electric device	car adapter
transfer electrical energy	plug and cord	wire	circuit board	terminal block	
store electrical energy	battery	capacitor	electolitic goo [sic]		
supply electrical energy	battery	capacitor	electolitic goo [sic]		
actuate electrical energy	switch	transistor	timer	temp sensor	thermal switch
transfer electrical energy	plug and cord	wire	circuit board	terminal block	
convert electrical energy to thermal energy	thermo-electric device	heating plate	heat exchanger	resistor	heating coil
transfer thermal energy	metal plate	ceramic disc	water	air	cup
convert electrical energy to rotational energy	motor				
convert rotational energy to pneumatic energy	fan	blower			

(d)

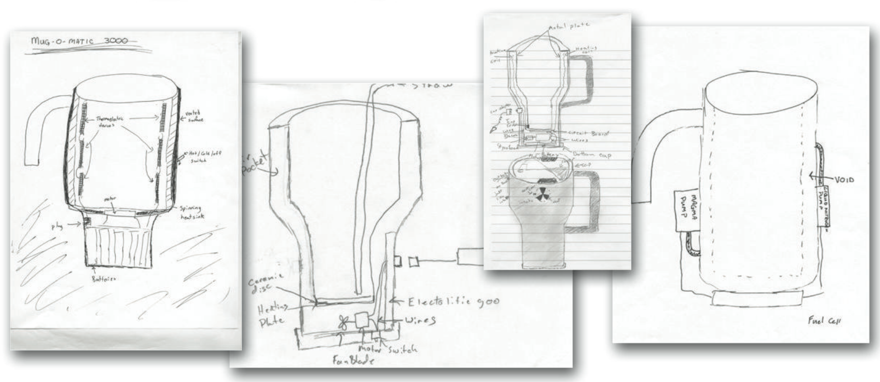


Figure 6: The students began the methodological comparison for the thermal mug by generating (a) customer needs, (b) functional models, (c) morphological charts, and (d) complete concept sketches.

After generating similar sets of data for each of the original and redesign scenarios, the undergraduate researchers divided the functional models they developed during the design process into single non-branching chains of functions and entered the chains separately into the concept generator software. In the case of the thermal mug design, the hypothetical functional model was broken into 8 function chains. Next, they compared the concepts returned by the Concept Generator against the complete concepts they had assembled from their morphological charts. The undergraduate researchers found that every flow chain they were able to gather results from returned at least one concept extremely similar to their manually developed concepts, with most of the matched solutions occurring toward the top of the ranked list of returned component chains. If we first classify the students' brainstormed solutions under the same Component Basis classification scheme that the concept generator uses to return components, the similar matches become identical, as shown in Figure 7. Each of the original and redesign scenarios resulted in successful comparisons that were similar to the thermal mug design example shown.

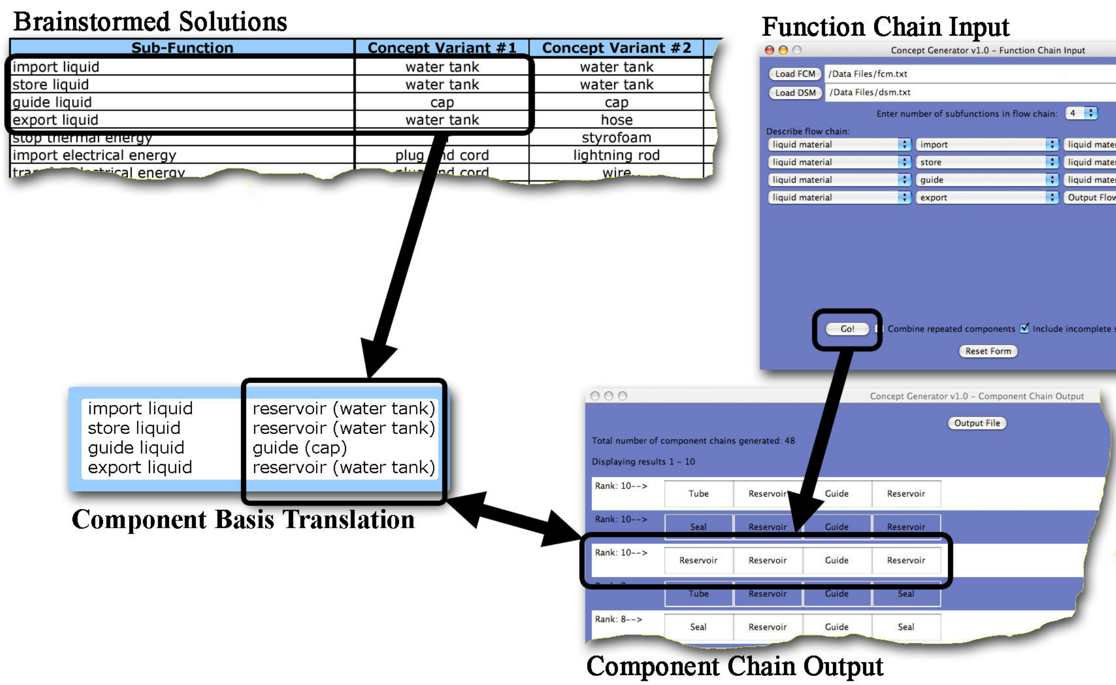


Figure 7: The students found nearly all of their manually generated concepts from their complete design solutions matched up with top-ranked solutions returned by the Concept Generator.

6. Conclusions & Future Work

This paper presents research activities performed by four undergraduate researchers at the University of Texas at Austin and the University of Missouri–Rolla to evaluate a recently developed Concept Generator. Intended to help inexperienced designers choose suitable components for a given function in a redesign or original design situation, the goal of the software 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 software produces a list of feasible conceptual designs quickly and does not require the effort of an entire team of designers.

During the course of their investigation, the undergraduate researchers made several observations and recommendations regarding the user interface of the Concept Generator and the quality of the results returned. The students reported that the Concept Generator works very quickly and returns very feasible concepts for almost all function chains with fewer than 5 functions. For larger chains, the software still returns good concepts, however it takes a significantly longer amount of time, as is expected from the combinatorial nature of the current form of the algorithm. Additionally, the students determined that it would be desirable to save the input function chains so they did not have to be re-entered to generate a new list of concept variants at a later time. They also determined that it would be helpful if the interface allowed the user to simultaneously show all aspects of a sub-function with more than one flow passing through (e.g. a function may *transfer pneumatic energy*, but *thermal energy* may also move along with the air even though no functions are specifically being performed on it.) The undergraduate researchers also indicated that it would be useful to know which product(s) within the repository use(s) a component from the returned variants in the manner described. Finally, one significant drawback of the software identified by the undergraduate researchers is that it does not allow for multiple components to work together to perform one function, although the sharing of adjacent functionality by a single component *is* included.

Areas identified for the expansion of the current software include refining the concept variant display algorithm to reduce calculation time, enabling design generation for full functional models including branching chains, grouping results based on similarity, and establishing sophisticated ranking and filtering measurements to help bubble the most eligible design solutions to the top of the list of conceptual designs returned. Although using the design structure matrix as a first-pass filter eliminates many less useful concepts from the set of design variants, metrics such as measures of failure, manufacturing and assembly costs, quality, recyclability, or some mathematical combination of similar design characteristics could prove to be valuable tools for identifying the most promising variants among the hundreds (or thousands) of potentially viable solutions found. In general, management of the design solutions, including developing useful ranking schemes and grouping similar solutions into sets, will be a key area of development, since this aspect of the software strongly influences a designer's perception of the software's usefulness.

Further areas of expansion may include mapping functional models to assemblies (groups of components) within the design repository as a means to help address the missing capability to map multiple components to a single function. Additionally, by linking the returned Component Basis solutions to the repository, a designer would have the ability to browse through specific examples of each Component Basis term returned in the output concept variant chains. This addition would enable users unfamiliar with the Component Basis to see specific instantiations of the more abstract Component Basis terms. For instance, clicking on the returned component "guide" could produce a list of example repository components classified as a "guide" under the Component Basis, such as a "column", "rail", or "threading fixture". The user would then be able to browse through these examples to gather ideas or more detailed information for a specific concept variant. The ability to automatically create generic component models for visualization and manipulation in a virtual environment is an additional benefit of linking returned solutions to the design repository, which is currently being investigated. Many avenues are available for expansion of the program's functionality. Although basic in its current form, the results support the Concept Generator as a promising first step toward the development of a powerful design tool.

7. References

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