AC 2008-885: MEASURING THE IMPACT OF COMPONENT FUNCTIONAL TEMPLATES IN A SOPHOMORE LEVEL ENGINEERING DESIGN CLASS

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Measuring the Impact of Component Functional Templates in a Sophomore Level Engineering Design Class

Abstract
This paper describes one experiment to test the utility of component functional templates as a functional modeling instruction aid. Previous research by the authors has shown that problems exist with students describing functional representations of a system or subsystems. *Component functional templates* were derived as a means of addressing this ongoing problem. The experiment was performed on a section of sophomore level undergraduate students and consisted of both a pre and post-test. During the pre-test, the students were divided into small groups of two or three and given the task of creating a functional model for a small consumer product. The lesson prior to the task was based only on a review of the functional modeling lesson taught in a freshman design course. After the pre-test, another lecture was provided that covered the use of the component functional templates. Next, for the post-test, the students were again asked to create a functional model of the same product. It was hypothesized that the use of the templates would provide better results in the quality and accuracy of the models when compared to the models produced without the use of the templates. The results of the experiment confirmed the hypothesis that the component function templates assist novice design students to create higher quality functional models and offer a foundational basis for further experimentation and evaluation.

1.0 Introduction

The marriage of product form and function has long been a critical problem faced by practicing designers and engineers. "By mapping customer needs first to function and then to form, more solutions may be systematically generated to solve the design problem[1]." More solutions imply a greater chance of an exceptional idea, or combination of ideas that can be built upon to form a better final design. This enhanced solution space is provided by describing a design task in abstract terms through functional descriptions instead of physical components. Decomposing a product or system and determining required functions or objectives, set forth either by a formal statement of the needs of the customer or an analysis of product discussion and associated tasks, is a common design approach used in current university courses and texts[1-5].

Function independent of form has many diverse relevant engineering applications including process modeling[6], automated concept generation[7], searchable design knowledge databases[8], modular design[9], multi-level risk analysis[10], and also business modeling with risk assessments[11], among others. More recently, student teams in a graduate level modern product design course at a nationally recognized engineering university were assigned tasks of developing robot models for an intelligent ground vehicle competition and also for retrieval and disposal of explosive ordinance devices utilizing the functional modeling methodology. The resulting models provided adequate functional descriptions of the systems under question, as indicated by the course instructors, but many of the individual students in the groups performing the analysis were experienced and knowledgeable, well versed in the necessary processes such as gathering of customer needs and function chain aggregation. At least six of the nine students were engineering graduates with Bachelor of Science degrees and the remaining students were bright undergraduates whose related coursework included multiple functional modeling applications and experiences.

Previous research by the authors showed that historical relationships could be found between common electro-mechanical components and their associated functions[12]. A design tool, termed component functional templates, was developed to assist the functional modeling process. The templates are a simplified connection to the physical components with which they are familiar. The idea behind the templates is that they provide novice functional modelers function definition to common components. This should help the students to think of the common components in terms of function. Then, after use, think initially in terms of function. During this learning curve the templates also provide a means to produce more complete functional models.

Since the templates are based on historical relationships between component and function, they provide common functional descriptions for a given component without requiring excessive knowledge about functional modeling. An eight page printed hard-copy collection of the templates has been put together, formed corresponding to the list of components in the newest version of the component taxonomy derived from the initial component basis[13]. During the original analysis, it was found that some of the components lacked sufficient information to generate templates based on historical data. Since a complete database is required for use in industry and the classroom, component functional templates that were not available using a principal components analysis were derived using a qualitative approach from a computational theory for solution generation [14]. A collection of classroom experiments is needed to assess the templates as a functional modeling instructional tool. This paper presents one of a collection of experiments.

It is hypothesized that combinations of multiple templates, morphed together with minimal effort will produce more accurate and detailed representations of a system under consideration when compared to similar models created without the use of the templates in a classroom.

2.0 Background

2.1 Approach in Design Curriculum

The functional modeling method has been or is currently used in several design related courses at the Missouri University of Science & Technology (Missouri S&T and formerly known as the University of Missouri-Rolla) such as IDE 20 Introduction to Engineering Design with Computer Applications, IDE 105 Design Representations, IDE 106 Design Perceptions, IDE 220 Engineering Design Methodology, IDE 315 Interdisciplinary Design Project, IDE 420 Modern Product Design, IDE 427 Function-Based Risk Analysis, and ME 161 Introduction to Design. Other universities also apply functional modeling techniques such as Penn State, Carnegie Melon University, University of Texas at Austin, Virginia Tech, and Bucknell University. A significant number of students in these courses are not yet familiar with functional modeling. It is expected that these students will find component functional templates as an exceedingly helpful functional modeling tool to meet individual course design goals. Figure 1 is an example of the conveyor component functional template where a material is first stored on the track and then guided to another location with mechanical energy. Collecting a number of these templates and aggregating them together allows conceptual designs to easily be created while only focusing on product or subsystem function. A concentration on electro-mechanical classes dealing with various aspects of design, perhaps in a semester long design project, in interdisciplinary and mechanically related departments can also benefit from the use of the templates due to the generality of the approach that focuses on making component templates that are readily familiar to these specific design areas.

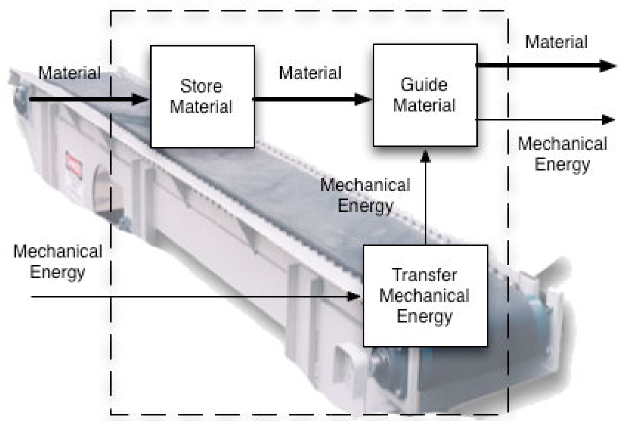

Figure 1: Conveyor Template

2.2 Component Functional Templates

It has already been shown that students struggle with the concept of abstract functional modeling[15]. Surveys given to various levels of Missouri S&T engineering students currently utilizing functional modeling identified a serious lack of understanding of the technique. Instructors also noted lower than expected performance by the students. In functional modeling exercises, rather than describing product function, the students often identify physical components that solve the underlying functions, such as the listing of components “plunger”, “rod”, “circuit”, “motor”, and “ball”. Classroom applications of the functional modeling methods have routinely provided incorrect or insufficient results by students not using the proper format (i.e. incorrect function structure), system misrepresentation, or even providing lists of components. Built on historical data and presented in a simple, visually appealing format, the component functional templates were created to provide a user with a pre-built abstract component functionality derived from common function solutions so that excessive existing design technique knowledge will not be a requirement to successfully use and adapt the functional modeling method to a general situation.

3.0 Experiment

A collection of experiments was designed to test the hypothesis of this study. This paper describes one of the experiments that tests how the component functional templates affect functional modeling results in a sophomore level interdisciplinary design class of twenty-three students. The class focuses on different techniques of representing objects from a design-engineering standpoint. The prerequisite for the class is passing IDE 20. Quality of the models is determined by looking at individual function structures and whole product representations through subsystems. Accuracy is determined by looking at flow representation through a function chain and the number of functions in the model. This experiment included multiple stages to gather information from a control group and compare results from each stage while limiting the amount of noise in the data. These stages included:

1. An introductory lecture on the functional modeling method
2. A pre-template in-class functional modeling assignment
3. A lecture presenting the templates and how to use them
4. A post-template in-class functional modeling assignment

3.1 Stage 1

It is first necessary to determine the current quality and level of modeling skills contained of the student test group. The prerequisite for the course includes instruction on functional modeling techniques. A thirty-minute classroom lecture that reinforced the basics of functional modeling was given to provide as much consistency in the initial amount of knowledge that each student possessed. This lecture was substituted from IDE 20 and covered function structure, the functional basis terminology, gathering customer needs, creating a black box model, generating function chains, aggregating those chains, and verifying that the customer needs are met. Additionally, simple and specific examples were provided that covered how to build a function chain and a step-by-step procedure of creating a functional model for a toy foam-disc launcher. Function chains were developed for multiple flows by the instructors and then morphed together for the final model. This lecture included no discussion or use of the component function templates and was strictly limited to the information that had been previously taught in the IDE 20 class.

3.2 Stage 2

After the initial functional modeling review lecture, the students were broken up into nine small groups of two or three. There were five groups of three students and four groups of two students. Each group was assigned an active learning task of disassembling an existing small consumer product (a Bumble Ball) to identify the internal components and subsystems that are present, much like the example provided in the lecture, and creating a functional model based on their existing functional modeling knowledge and stage 1. This set of models serves as a functional modeling pre-test. It will be compared with the functional models generated in stage 4 after the lecture on component functional templates. The activity was performed during the fifty-minute class period and the models were turned in at the end of the session.

3.3 Stage 3

A lecture discussing the component functional templates was given the following class period to the students. The lecture concluded with a bicycle transmission example presented in a Journal of Design Studies article[16]. A set of function chains was created and morphed together to give a good representation of how the templates should be implemented.

3.4 Stage 4

The same groups of students were again asked to dissect the same product and create a functional model of it, except this time using the component functional templates. The time was limited to the same amount that was provided in stage 1. A hardcopy of the templates were provided to the students in an eight-page handout. After gathering the necessary templates, the templates were aggregated together in the appropriate order according to the function chains for the product being modeled.

Of the original nine student groups that participated in the experiment for the first model, only seven of those also participated in producing the second model. The other two pre-template models for Groups 8 and 9 were evaluated but could not be compared to post-template models. Group 3 also did not complete the assignment for the second model and it was effectively a listing of just two templates. Additionally, Group 7 had difficulty grasping how to morph the templates or opted to stop working once they gathered all of the templates because a regurgitation of several templates was turned in as the final post-template model.

A quick glance revealed that several of the pre-template models were riddled with blaring mistakes. Of those original nine groups, seven pre-template models incorrectly represented much of the system by specifying components in the functional model as shown in Figure 2.

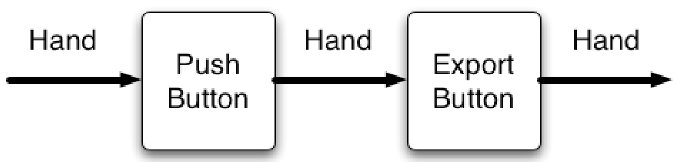

Figure 2: Typical Incorrect Function Representation

This is the same type of result that was alluded to in section 2.2. A simple identification of the components to be used in the design severely limits the opportunity the designer has at determining the best possible solution for that function. Conversion to abstract terms leaves more room for creativity and ingenuity by only specifying the needed function. On the other hand, after the templates were introduced, many of those errors were avoided altogether or corrected and implemented in an acceptable form as shown in the corresponding function chain model in Figure 3, produced by the same student group as Figure 2. Notice the interaction of other flows that were not even taken into account in Figure 2 and the amount of detail present in Figure 3 exceeds that of Figure 2 to a certain degree for the same chain.

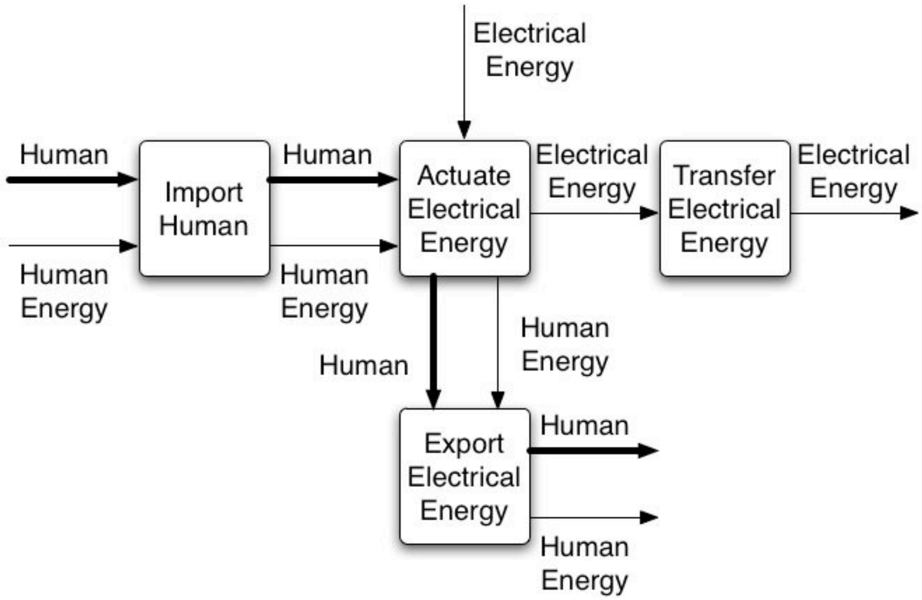

Figure 3: Typical Post-Template Function Chain

Both Figures 2 and 3 have been converted into a digital format from the original hand-drawn models for clarity but remain true to the natural presentation of the models provided by the students.

4.0 Measuring the Impact

In order to effectively analyze and interpret the data from this experiment, a set of evaluation criteria is needed to define the quality of the models and how that quality will be measured. The criterion for this experiment is proper function structure, appropriate number of functions, flow representation through a chain, and accurate product representation. Using these quality-characterizing criteria, each model (both pre- and post-template) was evaluated and scored. The results are compared to determine if the component functional templates, as an instructional aid, improve the quality of the models.

4.1 Function Structure

Proper function structure means that a function is described by a verb and object pair, but should also avoid referencing a particular physical solution. The verb is the function, or action that is taking place on the object. The object in the function pair is the flow that is being acted upon. Any function description in both the pre and post tests that does not follow this format or references physical components is considered incorrect.

There were forty-three examples of improper function structure through reference to physical components that appeared in the pre-template models. Group 1's pre-template model contained only seven functions, but even with so few functions that were incorporated, every single function structure listed identified a physical component. This was the most excessive occurrence of a single type of mistake when considering the total number of functions present in any individual model. The same group's post-template model still contained references to physical components but this time with only five occurrences in twenty-six functions. This was an overall decrease of physical component references of 80%. The limited error occurrences were due to small manual manipulations of the templates during the aggregation step of the modeling process because of the function alterations from the templates, which shows that some sort of check is still needed even after the templates have been used in a manual routine.

Also, another problem that became apparent was the function structure in a conversion process (changing one form of a flow into another), usually from one form of energy to another. Of the original conversion functions that were listed in all of the pre-template models, almost 88% (of them were incorrect by not listing both types of energy (i.e. when converting electrical energy to mechanical energy, the function structure listed was *convert to mechanical energy* instead of *convert electrical energy to mechanical energy*). The conversion function errors were cut by more than 50% after the template lecture. This drop can be attributed to the templates already containing the correct function structure.

Comparing the pre-template models and post-template models, it can easily be seen from Tables 1 and 2 that for the groups creating both models, the percentage of correct function structures increased significantly. The smallest increase was 9% by Group 7 and the largest was 81% by Group 1. It is important to note that each one *increased* and the mean increase was more than 51% and the median was 58% by Group 5.

Table 1: Pre-Template Model Function Structure Results

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Total number of correct function structures	0	3	1	6	2	12	10	2	5
Total number of function structures	7	7	4	16	7	16	11	8	8
Percent of correct function structures	0%	43%	25%	38%	29%	75%	91%	25%	62%

Table 2: Post-Template Model Function Structure Results

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Total number of correct function structures	21	15	6	15	13	18	34
Total number of function structures	26	16	6	15	15	19	34
Percent of correct function structures	81%	94%	100%	100%	87%	95%	100%

Furthermore, as can be seen in Figure 4, the mean number of function structure mistakes per model dropped significantly, almost by a factor of four, after the introduction of the templates. This does imply that further component functional template testing should be performed to determine if and how they directly impact correct function structure.

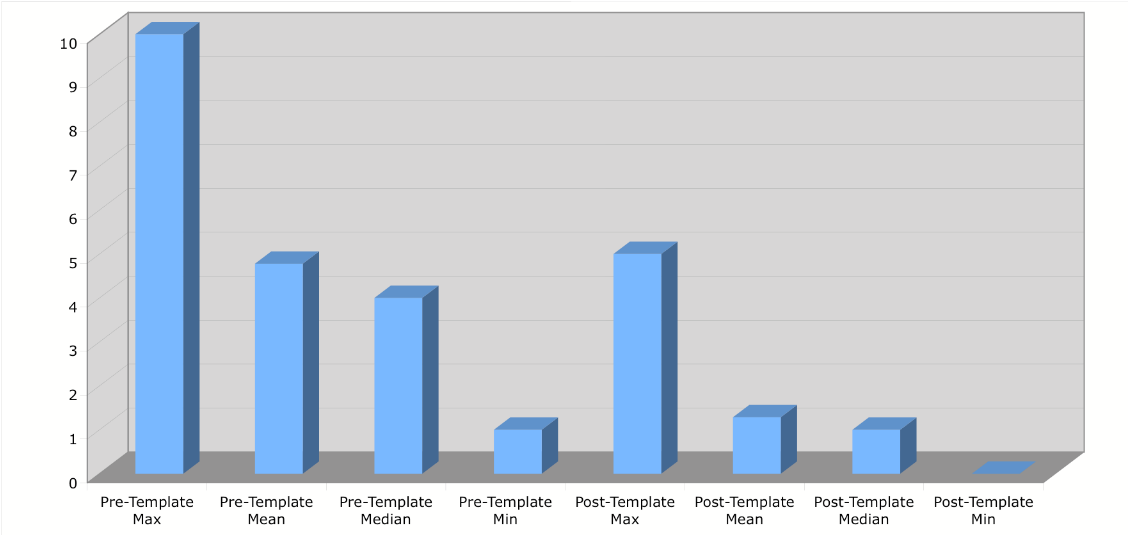

Figure 4: Stats on Mistakes in Function Structure

4.2 Number of Functions

The Bumble Ball, a small child's toy, contained approximately eleven separate types of components when disassembled completely. Since the product already exists, this activity would most likely resemble a redesign activity. The components of the toy are listed in Table 3. The entire system contained a specific number of each of these components, which is also listed concurrently.

Table 3: Child's Toy Component Listing and Quantity

Component Type	**Quantity**
Housing	5
Support	12
Electric Switch	1
Shaft	2
Gear	3
Bearing	4
Spring	1
Fastener	18+
Electric Motor	1
Electric Wire	3
Battery	4

Each of the fifty-four individual components serves a unique purpose or function in the system. Therefore, each type of component should be functionally accounted for at least once. Depending on the student, they may choose not to model multiple instances of the same component type, which is not evaluated in this study. Redundant modeling would be useful in applications such as trying to determine risk from a conceptual functional model so that the more redundant systems there are, the lower the risk, but here it is not completely necessary. A minimum number of functions that should be included in the experimental models are derived from the number of component types, eleven for the Bumble Ball experiment. Therefore, any models that contain fewer than eleven functions are considered deficient. For the evaluation, these eleven functions are not required to be of a certain category or type, just as long as the minimum number has been met. However, the mere counting of functions does not ensure correct modeling, which is why the models are evaluated in other categories as well.

Tables 1 and 2 also display the total number of functions that were used by the students for each model for the pre and post test respectively. Only 33% of the pre-template models contained the minimum number of functions that are needed to address each component type. This percentage increases to 85% in the post test after the template lecture. Although Group 4's post-template model dropped in total number of functions from the pre-template model, it was still acceptable because it still met the minimum. The average number of functions per model can easily be calculated for both pre- and post-template models to get a better understanding of mean group performance without looking at the individual scores, and are displayed in Figure 5.

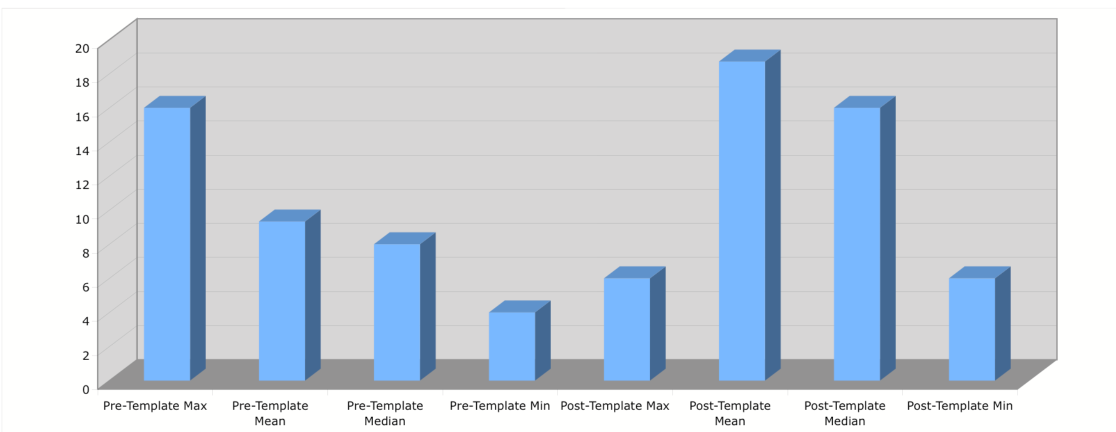

Figure 5: Stats on Number of Functions per Model

The pre-template models average 9.33 functions per model and the post-template models more than double that amount to 18.71 functions per model. By using the templates, the students have shown that it is more likely that a greater number of functions will be included in a model than if the templates are not used. However, the number of functions alone does not determine whether a model is superior. Another factor that influences the quality of a functional model includes flow representation through a chain.

4.3 Flow Representation Through a Chain

Proper flow representation through a chain of functions is critical. If a flow is improperly represented, dismissed or abandoned, it has the potential to cause problems during the design of the product. Therefore, flows entering a function should also exit the function. Material and energy flows must observe the conservation of mass and energy respectfully. Chains of function-flow combinations were analyzed in each of the models to determine if these conservation rules were followed in the correct manner. But unlike the previous two criteria (function structure and number of functions), this one does depend on completed function chains because the flow must be consistent. Groups whose models were not turned in, or templates were not morphed together, were not taken into account when collecting data for both sets of models. Those disregarded included the second round of models for Groups 3 and 7.

Flow representation mistakes were even more prevalent in the pre-template models than were other mistakes in function structure, but not by a large amount. The most common flow representation error was that of a flow not exiting a function after it had entered. Another common mistake was a flow exiting of a function when it did not enter. A smaller number of mistakes occurred due to improper or no labeling. In one case, flow types were confused and misrepresented (i.e. a material flow was mistaken for an energy flow, etc.). Tables 4 and 5 are a summary of the flow representation mistakes found in both pre and post template model sets respectively.

Table 4: Pre-Template Model Flow Representation Results

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Total number of flow representation mistakes	7	1	5	2	3	6	17	3	3
Total number of functions	7	7	4	16	7	16	11	8	8
Percentage of Flow representation mistakes per function	100%	14%	125%	13%	43%	38%	155%	38%	38%

Table 5: Post-Template Model Flow Representation Results

Group	**1**	**2**	**4**	**5**	**6**
Total number of flow representation mistakes	4	1	2	1	1
Total number of functions	26	16	15	15	19
Percentage of Flow representation mistakes per function	15%	6%	13%	7%	5%

Like the function structure mistakes, the total number of functions in each model must be divided into the total number of mistakes to remove a bias that forms when more functions are used. If the number of functions were not divided out, a summation of error types would be lopsided simply from the shear influx of functions and flows present in the post-template models. In three of the pre-template models, there are 100% or more mistakes per function. This happens when there are multiple flow interactions per function and more than one of them are incorrect. These percentages were higher than in two of the three groups because of the lack of detail in the models. Of the groups that could compare both sets of results, only one, Group 4, did negligibly worse. The others dropped the percentage of flow representation mistakes per function considerably by using the templates. The averages in Figure 6 also demonstrate the decrease of the flow representation mistakes.

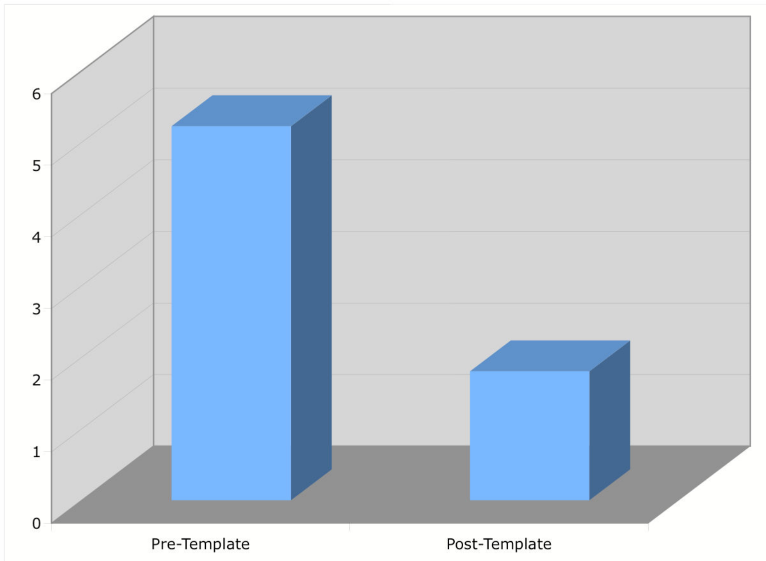

Figure 6: Average Number of Mistakes in Flow Representation

4.4 Product Representation

Correct representation of a product is determined by analyzing the subsystems that have been included. There are five subsystems in the toy that was modeled: interaction with surroundings (human, ground, etc.), power storage, power actuation, power transmission, and physical motion of the product. All of these subsystems are needed to effectively model how the product works internally at a component detail level. This criterion is either pass or fail instead of assigning a numerical value. If all subsystems are included, the model passes, and if not, it fails. For those that fail, insufficiency was either readily apparent or not able to be determined after considerable review and analysis. As was the case with the flow representation mistakes, product representation also depends on completed models or function chains. The same models that were disregarded previously have also been disregarded here. Figure 7 is a summary of the results on effective model representation of the system.

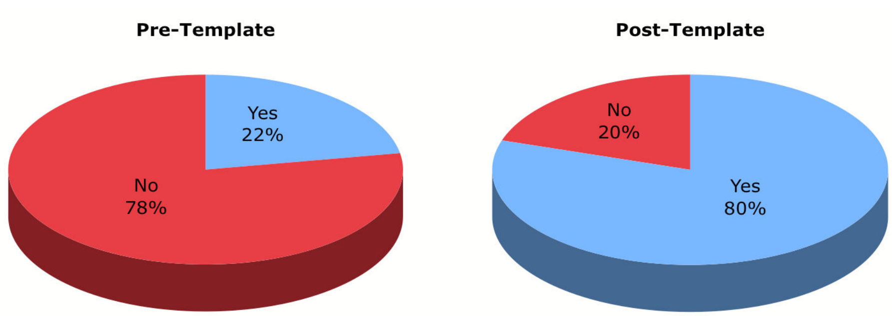

Figure 7: Effective Model Representation of System Results

It was found that an overwhelming majority (seven out of nine) of the pre-template models did not effectively represent the entire system. At least one subsystem in each of these was missing completely. After the templates had been implemented though, the roles reversed and there was only one of the five post-template models that did not include all subsystems. Again, the templates have helped to improve model quality through identification of all subsystems for a good portion of the post template tests.

5.0 Conclusions and Future Work

The application of this experiment shows promise in the use of component functional templates as an aid to novice designers in the development of functional models and verifies the original hypothesis. Overall model quality has been shown to rise in key fundamental areas when the templates are utilized. While a few of the students still failed to grasp some aspects of the method, which was expected to an extent, a fair majority of results improved in overall quality by representing a product in correct and sufficient detail with limited mistakes, which also shows a gain in understanding by the users. It is implied that modeling an already existing product is, in itself, not enough to prove that this approach will indeed help students to produce better designs. However, it does show that there is improvement in the quality of resulting models that have used the templates over those that have not, giving those designers a better grasp of how to functional model in the correct fashion. In the end, this will help those users to develop more complete ideas for themselves and also to communicate those ideas to other designers and engineers as effectively and efficiently as possible.

This experiment is one of several other experiments that will be performed in the pursuit of determining the total usefulness of the component functional templates. These other experiments will implement the templates in different settings and scenarios to include other student levels and knowledge bases (both higher and lower from this experiment), and also industrial applications for practicing engineers. Some of these will attempt to model more complex systems than those considered here in order to engage the templates at the highest level possible and determine if these improved results are sustainable. In the classroom, an experiment in the previously mentioned freshman design course will be aimed at determining if beginning engineering students who have been exposed to the templates will produce higher quality models than those without, except that this experiment will be performed on different groups of students instead of using the same group for both sets of models. This will eliminate any advantage there may have been for the post-template models by being exposed to the information for a longer period of time. Another classroom experiment will be aimed at graduate level courses to determine if the quality of models produced by higher level engineering students will be equal or better than those of lower level engineering students.

Bibliography

1. Otto, K., & Wood, K. (2001). *Product Design: Techniques in Reverse Engineering and New Product Development*. New Jersey: Prentice Hall.

2. Pahl, G., & Beitz, W. (1996). *Engineering Design: A Systematic Approach*. (2nd ed.). London, UK: Springer-Verlag.
3. Dym, C.L., & Little, P. (2004). *Engineering Design: A Project-Based Introduction*. (2nd ed.). Hoboken, NJ.: John Wiley & Sons Inc.
4. Dominick, P. G., Demel, J.T., Lawbaugh, W. M., Freuler, R. J., Kinzel, G. L., & Fromm, E. (2001). *Tools and Tactics of Design*. New York: John Wiley & Sons.
5. Cross, N. (2000). *Engineering Design Methods: Strategies for Product Design*. (3rd ed.). England: John Wiley & Sons.
6. Nagel, R., Stone, R., & McAdams, D. (2006). A Process Modeling Methodology for Automation of Manual and Time Dependant Processes. In Proceedings of IDETC/CIE 2006, DETC2006-99437, Philadelphia, PA.
7. Bryant, C., Stone, R., McAdams, D., Kurtoglu, T., & Campbell, M. (2005). A Computational Technique for Concept Generation. In Proceedings of DETC2005, DETC05/DTM-85323, 24-28 September 2005, Long Beach, CA: ASME.
8. Bohm, M., Stone, R., Simpson, T., & Steva, E. (2006). Introduction of a Data Schema: The Inner Workings of a Design Repository. In Proceedings of IDETC/CIE 2006, DETC2006/CIE-99518, 10-13 September 2006, Philadelphia, PA: ASME.
9. Stone, R. (1997). *Toward A Theory of Modular Design*. (Ph.D. dissertation, University of Texas at Austin, 1997).
10. Grantham Lough, K., Stone, R., & Tumer, I. (2005). Function Based Risk Assessment: Mapping Function to Likelihood. In Proceedings of IDETC/CIE 2005, DETC2005-85053, 24-28 September 2005, Long Beach, CA: ASME.
11. Grantham Lough, K. (2007, December 4). Lecture. Lecture presented to Function Based Risk Analysis course, Rolla.
12. Abbott, D., & Grantham Lough, K. (2007). Representing Historically Based Component-Function Relationships through Design Templates. In Proceedings of ASME IDETC/CIE 2007, DETC2007-35382, 4-7 September 2007, Las Vegas, NV: ASME.
13. Kurtoglu, T., Campbell, M., Bryant, C., Stone, R., & McAdams, D. (2005). Deriving A Component Basis for Computational Functional Synthesis. In Proceedings of International Conference on Engineering Design, IDED05, 15-18 August 2005, Melbourne, Australia.
14. Bryant, C. (2007). *A Computational Theory for the Generation of Solutions During Early Conceptual Design*. (Ph.D. dissertation, University of Missouri-Rolla, 2007).
15. Abbott, D., & Grantham Lough, K. (2007). A Review of Component Functional Templates as an Engineering Design Education Aid. In Proceedings of American Society for Engineering Education Conference, 24-27 June 2007, Honolulu, HI.
16. Abbott, D., & Grantham Lough, K. (2007). Representing Historically Based Component-Function Relationships Through Design Templates. Publication pending, *Journal of Design Studies.*