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Component-Function Templates To Aid Engineering Design Education*

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A new design instrument, component functional templates, has been developed to assist design engineering education. The templates attempt to link the functional basis and component taxonomy into one coherent visual form that can be used by novice designers as a functional modeling training tool. This paper presents the approach, derivation, and valid examples of template groupings that result from the analysis. Principal components analysis is used to extract historical data from consumer products whose information has been stored in an online repository. An application of the templates is presented where they prove to be sufficient to begin the modeling process that accurately describes the subsystem's functions.

Keywords: conceptual design; design education tools; product modeling

1. INTRODUCTION

THE OBJECTIVE of this project is to develop an educational tool to assist engineering students learning how to create functional models for their design projects. This paper is the collective result of research that has been devoted to establishing a diagrammatic link, such as the spring template shown in Fig. 1, between functional descriptions and the physical components that embody them, which can be applied to any general design problem in many different fields. Functional modeling skills are important in that well-developed models help to describe systems at a conceptual point in the lifecycle of a product when every detail has not yet been determined, to provide some kind of framework. This practice is performed at many different levels including industrial applications.

The group Team X, at NASA Jet Propulsion Laboratory (JPL), designs and analyzes space missions within a short time frame to meet space program mission development and structure planning needs [1, 2]. The interdisciplinary team of subsystem experts translates customer needs into complete mission designs in a matter of days. In previous work aimed at improving and incorporating current methods used in designing these missions, a distinctive functional approach to describing systems or sub-systems was created [3]. A limited set of templates were defined to describe the functional background of typical mission subsystems such as electrical power, sensors, communications, debris control, structure, thermal control, nuclear power, solar power, propulsion, and science instruments. The function template of a solar power subsystem developed for Team X is shown in Fig. 2 as a characteristic example of the basic foundation on which such systems are built. As an aid to Team X, these templates may "help initiate the process of functional modeling," [3] but they are presented as highly specialized models of extremely unique systems, and therefore are little to no use for designers outside of Team X.

Additionally, it was demonstrated in the class work of university level students that there was a clear misapprehension in the functional modeling process when assignment models were submitted that represented physical components instead of the functions that they provided [4]. A survey aimed at determining a solution to this problem was implemented where it was collectively agreed that a tool linking physical components to functions that could be used as a starting point to building functional models would be quite useful. The component functional templates aim to address the common needs of students and working engineers concurrently by prefabricating, to an extent, a visual form of the function-component link that is easily modifiable if it is not in the needed structure already. Information that the user needs to know is limited to the component taxonomy term of the physical component that they are trying to model.

The strategy for developing the component functional templates includes gathering historical information from a repository, using principal components analysis to identify design relationships, and then putting that information in a visual, easy-to-use form. The teaching of new technology is not limited to the integration of novel hardware and software into the engineering curriculum. It is also important to teach the next generation of engineers decision-making skills that build upon the current level of expertise in the

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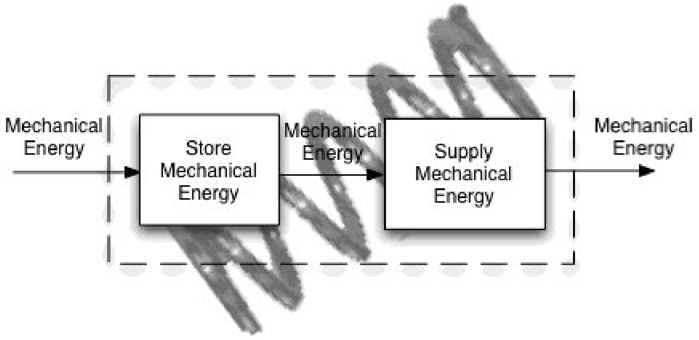


Fig. 1. Spring component functional template.

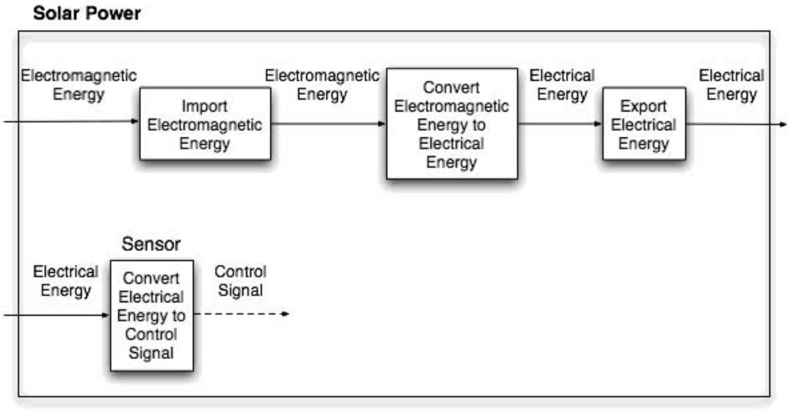


Fig. 2. Solar power function template from Team X.

workforce. Therefore, it is imperative that new technology also be used to prepare the engineers of tomorrow and help teach how to analyze and understand engineering systems by conveying the knowledge associated with years of corporate experience during their undergraduate studies. The results of recent undergraduate functional modeling design applications as well as student surveys enforce the need for an engineering educational tool for the functional modeling method such as the component functional templates [4]. The teaching strategy proposed to utilize this experience via historical function-component relationships is a hybrid problem-based and just-in-time inductive teaching method. Built on several engineering design tools currently used in other related research, a database of component functional templates has been developed and is presented here along with the generative approach. To establish credibility of the concept, a case study is performed on a subsystem of a bicycle.

2. BACKGROUND

The design tools and methods used throughout the creation of the component templates in order to sort through large amounts of data and make statistical correlations between design mechanisms are described and discussed in this section. Common engineering design methods like the functional basis and component taxonomy were used as a foundational layout to build the templates. Subsystem functional templates have been observed in similar work, along with specific applications of principal component analysis in the engineering design field.

Inductive teaching methods, those that start with specifics and infer rules and principles, will be used as the premise to develop component functional templates that build up students ability to think in terms of product functionality rather than component solutions during the conceptual design process. The primary type of inductive teaching that should be used with the component function templates is problem-based learning—using complex, authentic (real-world), open-ended problems to provide context in the form of product design problems

3. DESIGN TOOLS AND METHODS

The conceptual design stage is a crucial step in the lifecycle of any product due to the importance of the influential decisions that are made during this process. Determining and defining as many variants of products at the conceptual stage

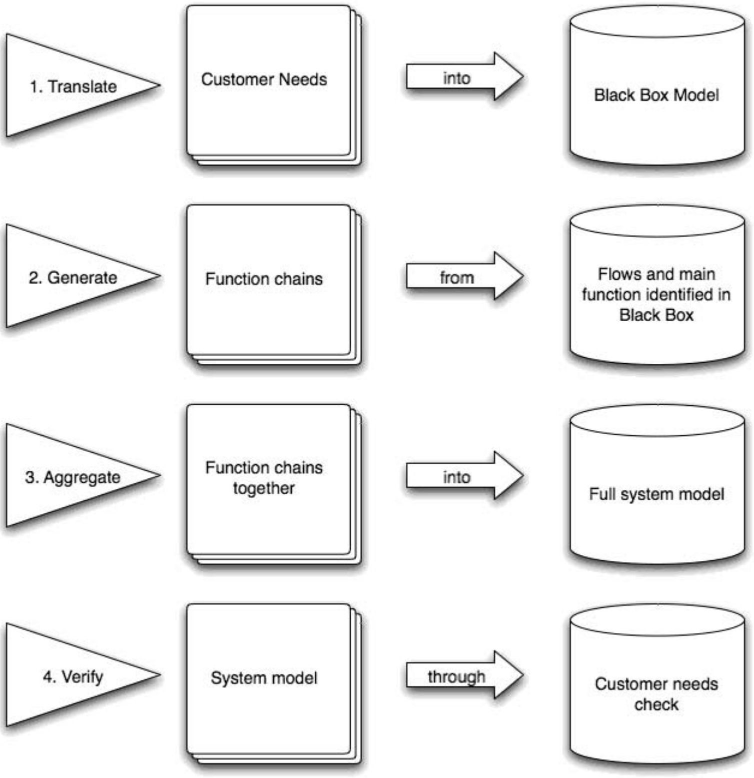


Fig. 3. Schematic representation of functional modeling process

provides a beneficial frame of reference when selecting the best possible solution for any given problem. However, without a scientific approach to the design method, there is an increased possibility that the best solution might not be selected as the final design or that it might not even be found at all.

The functional approach to design is a generally descriptive and structured methodology where Stone and Wood identify the function structure, consisting of both functions and flows [5]. Thinking in terms of the functions that are performed by a product gives the designer an advantage of not being limited to how that function should be encapsulated physically. Alternatively, designing from actual components or subsystems during conception will drastically hinder other creative possibilities. A fundamental understanding of the most basic concepts of any design can be gained through an application of the functional modeling method [6], which could help explain why many modern texts, some used in college level courses, present the functional approach to the art of design [7, 8, 9]. Just like any other scientific process, there is a step-by-step procedure, which can be seen in Fig. 3 that is commonly followed to create a properly formatted functional model. Fig. 3 is a graphical representation of the necessary steps in the functional modeling process. The four triangles on the left represent the main action that occurs in each step while the other shapes show what conversion is taking place in that specific step.

The first step in constructing a functional model is to create the system's black box model, which is translated from the customer needs. Inside the black box is the main function of the system as a whole and entering and exiting the black box are the material, energy, and signal flows. Then, every unique flow is observed from the entrance into the system, defining any relevant functions that might be encountered while interacting with the system, and eventually to where they depart from the system. Once the separate chains have been generated, they are morphed together, adding or removing functions as necessary, to develop the overall functional model of the system. The final step consists of a simple check to make sure that all of the needs set forth by the customers in the first step are catered to. An example of a functional model for the controls of a combine is shown in Fig. 4. The section lines with letter designations connect to other parts of the system functional model.

The learning outcomes, touching on multiple categories of Bloom's taxonomy [10], of a functional modeling lesson include the following:

1) identify the main function of the system in a black-box model;
2) identify flows (material, energy, signal) entering and exiting the system;
3) create subfunction chains that follow the flow as they enter until they exit;
4) evaluate junction points for flow chains that allow interaction of multiple chains;

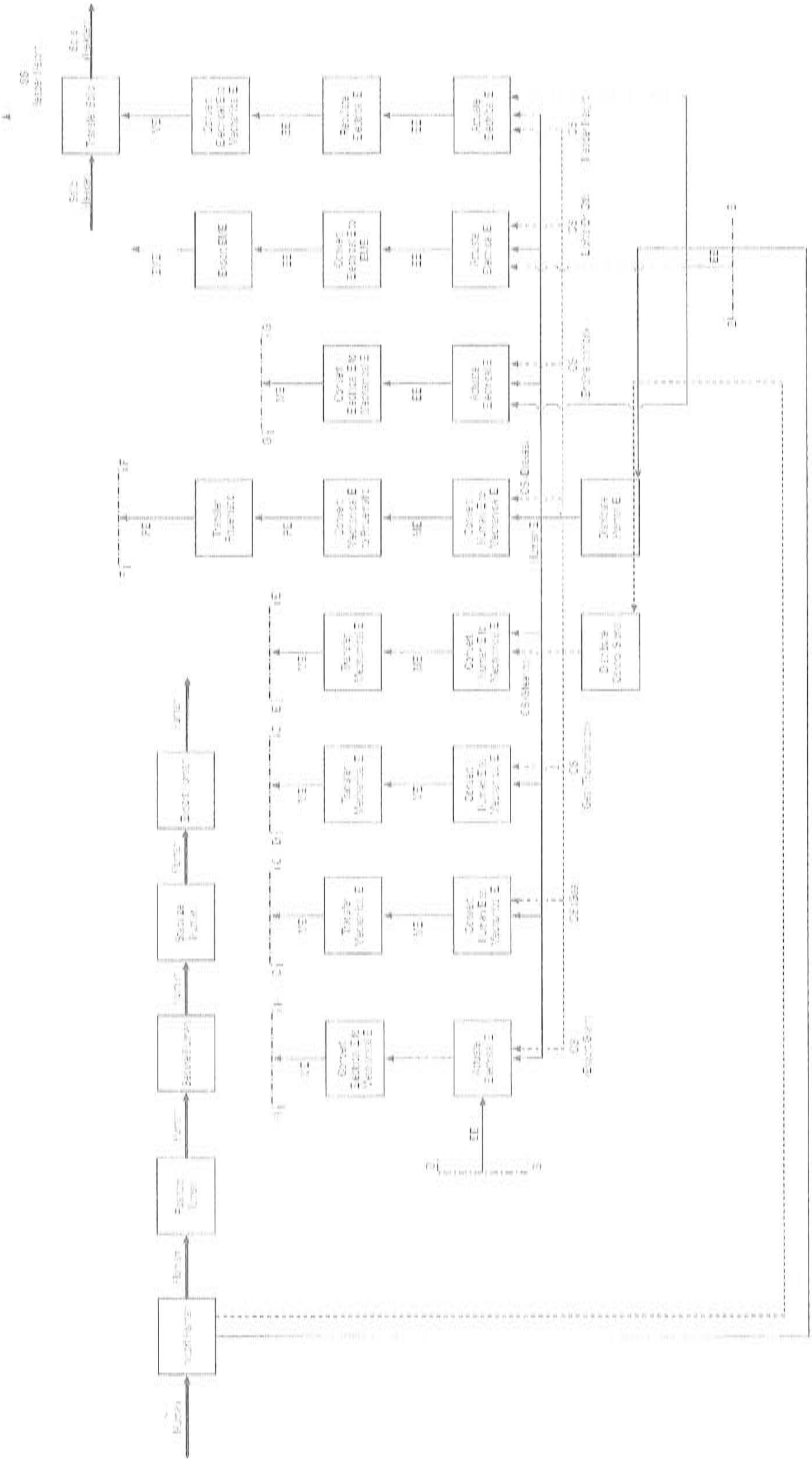


Fig. 4. Functional model of combine controls

5) design function-chain interfaces that preserve conservation of mass and energy;
6) create a connected subfunctional model combined with the black-box model for complete system functional model.

The experience of the authors and other product design faculty at Missouri University of Science & Technology suggest that learning outcomes 1) and 2) are achieved by most students while learning outcome 3) has less mastery than 1) and 2), and outcomes 4)–6) are very difficult for novice engineers to perform.

Creativity between user descriptions of how different objects function (outcomes 3–6) would pose a problem for the functional modeling method were it not for the structured language that is used when building the models. This language is known as the functional basis [11] comprised of function and flow definitions for all electro-mechanical products. As the proper function and flow terms are used, it allows the designer to avoid describing actual physical components and therefore makes it possible for other creative solutions to find their way into the design. The use of the functional basis, while a useful and necessary addition to functional modeling, has not been able to single-handedly improve the mastery of learning (outcomes 3–6).

Even though the functional basis helps to bring some consistency between the modeling approaches of different users so that results can be repeated, another tool is used as a cornerstone in the development of the templates. The component taxonomy [12] is similar to the functional basis in that it is a collection of definitions useful for modeling and analysis purposes, but instead of defining numerous function structures, the taxonomy defines common electro-mechanical components, many of which can be found in everyday consumer products such as toys and robots to tools and cleaning machines. Also, unlike the functional basis, the component taxonomy is an ever-expanding database of new components and definitions, while the basis is a static set.

With the combination of these tools it would be possible to subjectively determine the functions for the templates, but for the purposes of this research it is desired to relate this information to historic design data which can be found in easily accessible database repository systems [13]. This information is extracted from the user interactive products mentioned previously, which have been deconstructed and reverse engineered by trained technicians. Ultimately, the gathering of all of these design-engineering technologies culminates in the development of the component functional templates. Built on the historical information in the repository, the templates link the functional basis and component taxonomy ontologies in a visual form that can then collectively be used to build any general electro-mechanical system's functional model. Ideally, the templates would be used as an introductory tool for novice functional modelers that are having difficulty grasping the fundamental concepts that are needed to functional model properly.

4. FUNCTIONAL MODELING TOOLS

Pahl and Beitz's original development of function structures [14] has instigated an expansive growth of many conceptual design related areas including function-based risk and failure analysis [15, 16], 3D concept generating aids [17], as well as tools and methods to aid in properly describing the functional elements that are apparent in any given system. Some methods attempt to use modern computer aided techniques that allow complete and accurate functional representations of physical systems. The graph grammar technique [18] is an example of such a tool that is designed to quickly generate functional models based on the limited number of function combinations that can occur and manipulating them via rules that have been determined through research. By analyzing thirty different products, a set of sixty-nine grammar rules have been established that are then implemented in a node-based computer program.

Though the graph grammars help in speedily building function models through a computer program, they, like other methods, are still reliant on specific knowledge of the concept of functions. This leads to difficulties for people who are not familiar with these concepts such as students learning design methods in the classroom as well as experienced designers who have learned to think in terms of physical components and are trying to incorporate new methods into their design process. Also, the merger of the component taxonomy and the functional basis provides a reference for those designers to use the knowledge they already have to build on new information.

The work related to component functional templates is not the first research that has prescribed templates as a tool for functional model development, as was shown in the Team X space mission templates [3]. However, since the Team X templates have been developed for such exclusive applications, a more generalized technique, like the component functional templates, is needed for use in other non-related products and designs.

4.1 PCA-based application

The design information used in this project is evaluated through a statistical analysis method called principal components analysis, which is currently implemented in a diverse range of professional fields such as ecology among many others [19–25] as a means to analyze large amounts of iterative data. PCA is a form of data compression in that it takes a large amount of correlated information and analyzes it to find the most statistically represented information and brings that information to the attention of the analyst. The steps that are required to perform a PCA on the components in the taxonomy are as follows (as applied in [26]):

1) Calculate the mean vector of the Component-Function Matrix (CFM) with m observations/artifacts on n variables/functions:
2) $\overline{CFM} = \frac{\sum_{i=1}^{m} CFM_i}{m}$ (1)
3) Adjust the mean of the CFM to zero by subtracting the mean vector from each of the observations:
4) $CFDA_i = CFM_i - \overline{CFM} \quad \text{for } i = 1 \text{ to } n$ (2)
5) Calculate the variance/covariance matrix of the mean-adjusted CFM:
6) $\sum_{CFM} = \frac{CFDA^T \times CFDA}{m-1}$ (3)
7) Find eigenvectors (principal components) and eigenvalues (percentage of variance in original data) of the covariance matrix from characteristic equation:
8) $\left|\sum_{CFM} - \lambda I\right| = 0$ (4)

The CFM is a simple regurgitation of the component and function historical data that has already been stored in the repository and is output in the form of a matrix that can be manipulated. The first step is computed for each column or function, which is simply the mean of each variable across all of the artifacts in the CFM. Step two decreases each element in an artifact by the corresponding element in the mean vector and repeated for every artifact. A matrix multiplication of the zero mean adjusted CFM with its transpose and dividing by the rank of the CFM yields the covariance matrix. The characteristic equation in the last step can be put into matrix form by:

$$\sum_{CFM} \times V = V \times D \qquad (5)$$

where V is an eigenvector matrix and D is a diagonal eigenvalue matrix.

An application of PCA as used here is very similar to the approach presented in [26] where the steps are used to identify high risk areas based on function-failure matrices provided by the analyst. Data extraction techniques such as this are similar to the concepts of data mining [27–29] that can use probability theory for numerical prediction and association rules, or clustering of data. Also, methods learning chunks of data from design experiences and applying them to novel problems as prescribed in a new mechanism for A-Design [30] might prove a viable alternate method except that the components have already been defined and extra iterative steps are applied that aren't necessary here. Instead, PCA was employed because of its simplicity and ease of implementation using the first eigenvector or function vector as output. The component functional template application presented in this paper uses PCA to identify the functions that will be included in the templates, originating from the CFM. The key for the use of PCA is to statistically represent design knowledge correlating function and components. A simple summation is not sufficient enough to analyze the mass data, which also contains variants in the input and methods of deriving the information. The principal components and eigenvectors describe the statistical correlation between a set of functions to a particular component. The order is significant because the first principal component (PC1) the first eigenvector (linked to the highest magnitude eigenvalue), correlates to the strongest relationship.

5. TEMPLATE GENERATION DEVELOPMENT

This section is dedicated to presenting the template generation development process in detail. Since there are a large number of components in the component taxonomy, it was necessary to develop a recurring process to generate the component functional templates consistently every time an analysis was conducted. The process consists of gathering the necessary information from a design repository, performing a principal components analysis on that information, interpreting the results from the PCA, and then creating the component functional templates.

5.1 Incorporating repository information

The component templates are derived from an historical perspective founded on the data stored in a separate design repository. As a retrievable design information storage system, the UMR Design Engineering Lab's Design Repository [31] was founded as a free Internet-accessible (function2.basiceng.umr.edu) knowledgebase that houses not only functional information but also many other types of design information including geometric and material properties, failure and manufacturing information, etc. of over 170 consumer products. Armed with the component taxonomy terms and a basic understanding of how the UMR specific repository search tools work, the CFMs are generated for analysis. The CFM is a listing of all the artifacts found in the repository with the subsequent functions that have been solved by that component in the past, which are now associated in the form of a simple matrix.

For the repository, used as it is presented here, the PCA method inherently struggles with components whose artifact populations are low. When this happens, some functions are difficult to determine if they should be included in the templates or not or the values returned by the PCA do not represent the original data well enough to continue on with the generation process. However, as more products are reverse engineered and the artifact

Table 1. General CFM example

	Function 1	Function 2	Function 3	Function 4	Function 5	Function 6	Function 7	Function 8	Function 9	Function 10
Artifact 1	0	0	1	0	0	0	1	0	0	1
Artifact 2	0	0	0	0	0	0	0	0	0	0
Artifact 3	0	0	1	0	1	1	0	0	0	1
Artifact 4	0	0	0	0	0	0	0	0	0	0
Artifact 5	1	0	1	1	0	0	0	0	0	0
Artifact 6	0	0	0	0	0	1	0	1	0	1
Artifact 7	0	0	1	0	0	0	0	0	1	0
Artifact 8	0	0	1	0	0	0	0	0	0	0
Artifact 9	0	1	1	0	0	0	0	0	0	0
Artifact 10	0	0	0	0	1	0	1	0	1	0

information is entered into the repository, the components will begin to converge on a well-defined steady-state function set.

The CFMs produced by the repository generator are binary matrices of component artifacts and functional representations. Each row in the CFM is an observation of the component from the search and each column is a different function that has been found in at least one of the artifacts. The binary values of 0 and 1 indicate either a lack or occurrence of a particular function, respectfully.

Table 1 is a general example of a CFM that is generated by the repository tool. Observe that a search of the stored design information revealed the third artifact found in the repository contained instances of the third, fifth, sixth, and tenth functions while the others were not present in that specific artifact. Likewise, the fifth artifact only had two functions, one and four, associated with it. Once this CFM has been generated, the PCA discussed above ensues. When performing the PCA, the component has already been defined by searching the repository for a specific artifact. It then identifies the functions that should be included in that particular component function template. This process is repeated for each individual component found in the taxonomy.

5.2 Results interpretation

Procedures for interpreting the results of a PCA are as varied as the fields in which PCA is used. In his book, J.E. Jackson [32] reviews and compares several methods of stopping rules for PCA including proportion of trace explained, individual residual variances, scree test, broken stick, average root, and Velicer's method. Similarly, D.A. Jackson [33] compares such stopping methods as Kaiser-Guttman, bootstrapped Kaiser-Guttman, scree plot (same as scree test), broken stick, proportion of total variance, test of sphericity, Bartlett's test of the equality of λ_1, Lawley's test of λ_2, and bootstrap eigenvalue-eigenvector. It was found that while the scree plot method (not including the first point past the cut-off) did not perform best compared to the rest, but it also did not perform the worst. Actually, it fell within the group of methods with average performance. It did, however, consistently overestimate the number of interpretable components, which could be considered a moderate approach in an application of the scree plot such as used in this analysis when determining the function cut-off point as it is used here, instead of the principal component cut-off point as it is used in [33].

All component CFMs were analyzed under the PCA method returning $n \times n$ matrices whose first eigenvector corresponds to the eigenvalue with the greatest magnitude and therefore the function vector of highest statistical correlation.

The component templates are analyzed based on their artifact population size shown in Table 2. As shown in the table, category one is comprised of only 3.26% of the components that had information included in the repository. The other categories included substantially more components but lacked in template robustness.

5.3 Template generation

The functions that are selected for the templates through the PCA method are not organized in any manner when coming directly out of the analysis. Since each component is unique, requiring unique formulation of each template, several general rules that can apply to all or most of the templates are discussed here. Some organization of the functions and flows in the template are critical but also intuitive such as an input function coming before an exporting function along the same flow chain.

Table 2. Template categorical breakdown summary

	Repository Artifact Population	Number of components in category	Percentage of total components per category	Percentage of components per category with repository information
Category 1	pop 10^2	3	1.75%	3.26%
Category 2	10^2>pop 10^1	27	15.79%	29.35%
Category 3	10^1>pop 10^0	62	36.26%	67.39%
Category 4	pop=0	79	46.20%	85.87%

The function and flow order is founded on the function structure and component itself, which to an extent can be derived from the component taxonomy definitions.

Suppose, for instance that the PCA for a particular component returned change mechanical energy and transfer mechanical energy as the functions to be included in the template. The flows are inferred from the PCA results, and in this case the only flow would be the mechanical energy flow. Organizing the functions in the proper order is up to the attributes of the component so that if, along the same flow, the transfer function occurred first, the output of that function would be the input to the following function. Extending the second step in the original functional modeling method [6] from Fig. 3 to apply to the templates, the individual flows are examined as they pervade through the component. This basic routine of connecting functions and flows was adopted for all of the components and was applied as reasonably consistently as possible.

6. EXAMPLE RESULTS AND DISCUSSION

The entirety of the following few sections is an in-depth discussion on the different types of results that were obtained from each analysis. Section 6.1 reviews the first category and how the results are analyzed and templates generated. Section 6.2 covers lower populated templates and provides sample results along with how they were interpreted. Section 6.3 is a short overview of the components that were not sufficiently populated to create templates from historical data. The approach detailed in Section 4.1 was followed to generate the PCAs for the components in the design repository. The results from the analysis were first divided into categories based on the dimensions and population of the original CFMs. While the repository contains a vast amount of information on many consumer products covering many different design application areas, it still lacks specific information regarding many individual components in the taxonomy. In fact, of the 172 components that are listed in the component taxonomy, only thirty can be expressed by the templates formulated from the PCA approach due to the populations of their correlating CFMs, and some of those must be manually manipulated. The other 142 component taxonomy terms are either insufficiently populated so that they cannot accurately undergo analysis by this statistical tool or they are not populated at all. From a statistical standpoint, the more information to gather results from the better, due to a larger sample size. But since this data is already supplied and taken directly from a compiled and limited source, we use all of the information that we can by basing the cutoff strictly on orders of magnitude (e.g. 10^1, 10^2, 10^3, etc) of the artifact populations relative to how much information is already in the database. This gives a lower limit of ten artifacts and any components with less than these ten artifacts are insufficiently populated. It is assumed that as the population of the repository database grows consistently over time, the number of artifacts and functions for all components will also grow, eliminating the need for such categorizations in the future.

6.1 Populated and well-defined templates

The first category of component templates has been sufficiently populated in the design repository so that the results of the PCA allow for a direct comparison between the first principal component and the functions that represent the corresponding components without major manipulation or additional subjective interpretation of the information. Only containing a list of three components, this is the smallest group of the four that were observed. The first category components include the *electric wire*, the *gear* and the *housing*. Each of the components in this category had populations with magnitudes on the order of 10^2. Ideally, with higher populations that are consistent with a complete repository database, many more components will fall in categories with several orders of magnitude greater than this. But, even with these lower populations, the three components returned favorable results that did not need to be modified after the analysis in order to create the templates. As was reported in [34], the PCA results only identify functions and do not directly identify flows or temporal order of those functions, but once the functions have been determined, the flows can be inferred from the function structure. The housing component functional template is used here as an illustrative example, and Table 3 presents part of the housing CFM which displays artifact information found in the design repository.

A search of the repository yields a total of 118 artifacts meeting the description of the housing component, presented in the CFM rows. Each of these artifacts has specific functions associated with it, portrayed in the CFM columns. The functions that are present in the artifacts are designated by unity while functions that are not, are designated with a zero. For example, the gun housing 2 in ball shooter artifact displayed the five functions convert human energy to mechanical energy, export human material, guide human material, import human energy, and import human material. All other functions not present in that particular artifact have zero values. After the repository tool generates the CFM, the mean vector $\overline{CFM}$ is calculated and the transpose is found in Table 4. The transpose is purely for presentation since $\overline{CFM}$ is actually a lengthy row vector. Subtracting this mean vector from the CFM adjusts the mean of the CFM to zero yielding the data-adjusted-CFM or CFDA in Table 5. Following the next step, a variance/covariance matrix, Σ_{CFM}, is found via a cross product and dividing by the total number of observation

Table 3. Partial housing component CFM

	actuate electrical	change mechanical	convert electrical to control	convert human energy to control	convert human energy to mechanical	convert mechanical to electrical	couple solid	distribute mechanical	distribute electromagnetic	export gas	export human energy	export human material	export mechanical	export mixture	export mixture to solid	export solid	guide electrical	guide gas	guide human energy	guide human material	guide liquid	guide mechanical	guide solid	guide mixture	import control	import electrical	import electromagnetic	import gas	import human energy to chemical	import human energy	import human material
bottom housing in air purifier	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
inlet grill in air purifier	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
top impeller housing in air purifier	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
paper feed frame in all-in-one printer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
scanner sensor bar holder in all-in-one printer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
side plate in apple usb mouse	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
left housing in b and d circular saw attachment	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
right housing in b and d circular saw attachment	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
left case handle in b and d dustbuster	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
right case handle in b and d dustbuster	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
left housing in b and d jigsaw attachment	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
right housing in b and d jigsaw attachment	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
left enclosure in b and d palm sander	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
right enclosure in b and d palm sander	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
battery case in b and d screwdriver	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
shell in b and d screwdriver	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
bottom case in b and d sliceright	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
upper case in b and d sliceright	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1
gun housing 1 in ball shooter	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1
gun housing 2 in ball shooter	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1
gun housing 3 in ball shooter	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
gun housing 4 in ball shooter	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
housing shell in bissell hand vac	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
left housing in bissell hand vac	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1
right housing in bissell hand vac	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1
body in black 12 cup deluxe coffee	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
basket holder in black 4 cup regular coffee	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
body in black 4 cup regular coffee	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
bottom plastic disc in braun coffee grinder	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

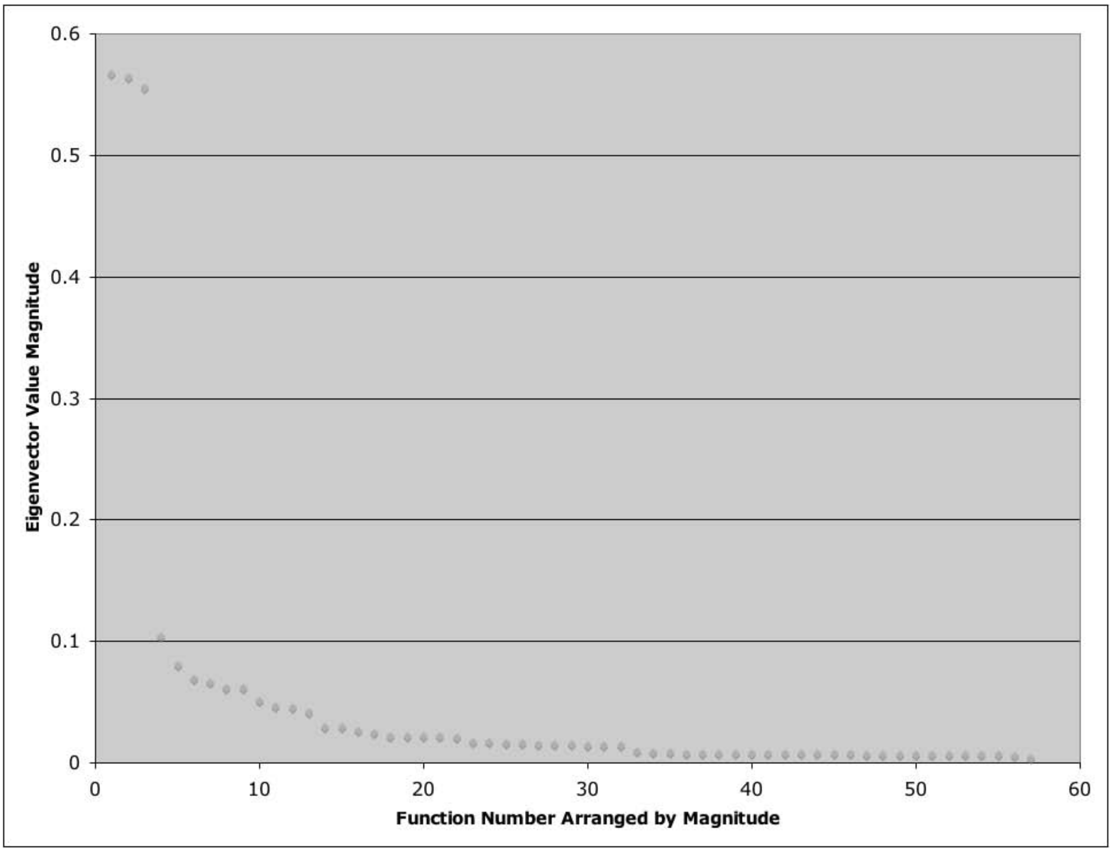


Fig. 5. Example scree plot of first principal component—category 1.

less one. Part of the resulting housing component Σ_{CFM} is listed in Table 6. Table 7 and Fig. 5, which show the first principal component and it's corresponding scree plot.

With a population of 118 artifacts, this was the lowest in the first group, and the first eigenvector identifies the representative functions as *import human material*, *guide human material*, and *export human material*, highlighted in the first principal component. Likewise, the scree plot also clearly identifies the inclusion of the first three functions in the housing template. Comparing these results to a simple summation of the different possible functions through the artifacts verifies that these three functions occur with the highest frequency, which is what was expected. It should be noted here that many of the other functions given in the artifacts are viable solutions to specific design problems, but historically they are not comparatively prevalent enough in the database for the

Table 4. Partial housing component mean vector transpose

0.0085
0.0254
0.0085
0.0085
0.0339
0.0085
0.0085
0.0424
0.0085
0.0678
0.0593
0.3136
0.0254
0.0169
0.0085
0.0593
0.0085
0.0424
0.0593
0.3051
0.0085
0.0169
0.0932
0.0085
0.0169
0.0169
0.0254
0.0085
0.1102

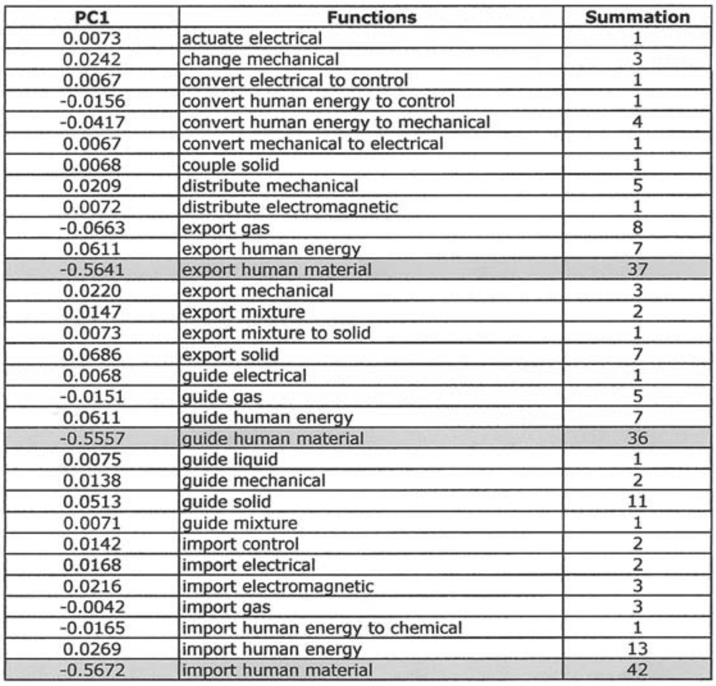
Table 5. Partial CFDA for housing component

-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	0.9576	-0.0085	-0.0678	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	0.9322	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	0.9322	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	0.9322	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	0.9322	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	0.9661	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	0.9661	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	0.9322	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	0.9322	-0.0593	0.6864
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	-0.3136
-0.0085	-0.0254	-0.0085	-0.0085	-0.0339	-0.0085	-0.0085	-0.0424	-0.0085	-0.0678	-0.0593	-0.3136

Table 6. Partial covariance matrix for housing component

0.0085	-0.0002	-0.0001	-0.0001	-0.0003	-0.0001	-0.0001	-0.0004	-0.0001	-0.0006	-0.0005	-0.0027
-0.0002	0.0250	-0.0002	-0.0002	-0.0009	-0.0002	-0.0002	-0.0011	-0.0002	-0.0017	-0.0015	-0.0080
-0.0001	-0.0002	0.0085	-0.0001	0.0083	0.0085	-0.0001	-0.0004	-0.0001	-0.0006	-0.0005	-0.0027
-0.0001	-0.0002	-0.0001	0.0085	-0.0003	-0.0001	-0.0001	-0.0004	-0.0001	-0.0006	-0.0005	0.0059
-0.0003	-0.0009	0.0083	-0.0003	0.0330	0.0083	-0.0003	-0.0014	-0.0003	-0.0023	-0.0020	0.0149
-0.0001	-0.0002	0.0085	-0.0001	0.0083	0.0085	-0.0001	-0.0004	-0.0001	-0.0006	-0.0005	-0.0027
-0.0001	-0.0002	-0.0001	-0.0001	-0.0003	-0.0001	0.0085	-0.0004	-0.0001	-0.0006	-0.0005	-0.0027
-0.0004	-0.0011	-0.0004	-0.0004	-0.0014	-0.0004	-0.0004	0.0409	-0.0004	-0.0029	-0.0025	-0.0134
-0.0001	-0.0002	-0.0001	-0.0001	-0.0003	-0.0001	-0.0001	-0.0004	0.0085	-0.0006	-0.0005	-0.0027
-0.0006	-0.0017	-0.0006	-0.0006	-0.0023	-0.0006	-0.0006	-0.0029	-0.0006	0.0637	-0.0041	0.0213
-0.0005	-0.0015	-0.0005	-0.0005	-0.0020	-0.0005	-0.0005	-0.0025	-0.0005	-0.0041	0.0563	-0.0188
-0.0027	-0.0080	-0.0027	0.0059	0.0149	-0.0027	-0.0027	-0.0134	-0.0027	0.0213	-0.0188	0.2171
-0.0002	0.0079	-0.0002	-0.0002	-0.0009	-0.0002	-0.0002	-0.0011	-0.0002	-0.0017	-0.0015	-0.0080
-0.0001	-0.0004	-0.0001	-0.0001	-0.0006	-0.0001	-0.0001	-0.0007	-0.0001	-0.0012	-0.0010	-0.0054
-0.0001	-0.0002	-0.0001	-0.0001	-0.0003	-0.0001	-0.0001	-0.0004	-0.0001	-0.0006	-0.0005	-0.0027
-0.0005	-0.0015	-0.0005	-0.0005	-0.0020	-0.0005	-0.0005	-0.0025	-0.0005	-0.0041	-0.0035	-0.0188
-0.0001	-0.0002	-0.0001	-0.0001	-0.0003	-0.0001	-0.0001	-0.0004	-0.0001	-0.0006	-0.0005	-0.0027
-0.0004	-0.0011	-0.0004	-0.0004	-0.0014	-0.0004	-0.0004	-0.0018	-0.0004	0.0227	-0.0025	0.0037
-0.0005	-0.0015	-0.0005	-0.0005	-0.0020	-0.0005	-0.0005	-0.0025	-0.0005	-0.0041	0.0563	-0.0188
-0.0026	-0.0078	-0.0026	0.0059	0.0152	-0.0026	-0.0026	-0.0130	-0.0026	0.0219	-0.0183	0.2027
-0.0001	-0.0002	-0.0001	-0.0001	-0.0003	-0.0001	-0.0001	-0.0004	-0.0001	-0.0006	-0.0005	-0.0027
-0.0001	-0.0004	-0.0001	-0.0001	-0.0006	-0.0001	-0.0001	-0.0007	-0.0001	-0.0012	-0.0010	-0.0054
-0.0008	-0.0024	-0.0008	-0.0008	-0.0032	-0.0008	-0.0008	-0.0040	-0.0008	-0.0064	-0.0056	-0.0124
-0.0001	-0.0002	-0.0001	-0.0001	-0.0003	-0.0001	-0.0001	-0.0004	-0.0001	-0.0006	-0.0005	-0.0027
0.0084	-0.0004	-0.0001	-0.0001	-0.0006	-0.0001	-0.0001	-0.0007	-0.0001	-0.0012	-0.0010	-0.0054
-0.0001	-0.0004	-0.0001	-0.0001	-0.0006	-0.0001	-0.0001	0.0078	-0.0001	-0.0012	-0.0010	-0.0054
0.0083	-0.0007	-0.0002	-0.0002	-0.0009	-0.0002	-0.0002	-0.0011	0.0083	-0.0017	-0.0015	-0.0080
-0.0002	-0.0007	-0.0002	-0.0002	-0.0009	-0.0002	-0.0002	-0.0011	-0.0002	0.0154	-0.0015	0.0005
-0.0001	-0.0002	-0.0001	-0.0001	0.0083	-0.0001	-0.0001	-0.0004	-0.0001	-0.0006	-0.0005	0.0059

Table 7. Partial PC1 for housing component



PC1	Functions	Summation
0.0073	actuate electrical	1
0.0242	change mechanical	3
0.0067	convert electrical to control	1
-0.0156	convert human energy to control	1
-0.0417	convert human energy to mechanical	4
0.0067	convert mechanical to electrical	1
0.0068	couple solid	1
0.0209	distribute mechanical	5
0.0072	distribute electromagnetic	1
-0.0663	export gas	8
0.0611	export human energy	7
-0.5641	export human material	37
0.0220	export mechanical	3
0.0147	export mixture	2
0.0073	export mixture to solid	1
0.0686	export solid	7
0.0068	guide electrical	1
-0.0151	guide gas	5
0.0611	guide human energy	7
-0.5557	guide human material	36
0.0075	guide liquid	1
0.0138	guide mechanical	2
0.0513	guide solid	11
0.0071	guide mixture	1
0.0142	import control	2
0.0168	import electrical	2
0.0216	import electromagnetic	3
-0.0042	import gas	3
-0.0165	import human energy to chemical	1
0.0269	import human energy	13
-0.5672	import human material	42

housing, and hence, they are not included in the template. This issue is not of concern because the templates can be modified as necessary to fit the needs of the moment when building any unique system's functional model.

A quick glance at the prescribed function structures from PC1 hints at the essential flows that are required for the housing template. The function-flow structure can easily be broken down to find the human material flow that is evident in all three of these functions. Determining the proper order is based on an engineering analysis of the particular component and the flows that have been identified. In this case, the three functions happen to fall in the exact opposite order in which they are organized in the template. This is not always the case and should not be assumed to be the correct configuration for other templates. From the definitions of the functional basis terms and the limitations of the prescribed functions, the temporal order for this template is quite easy to establish. By an elementary deduction, it can be assumed that the input function occurs before the export function and also that any other functions related to that flow must also occur before it exits the system boundary, but only after it has been imported into the system. The function order has been combined with the proper flow to form the component functional template for the housing component shown in Fig. 6.

It is easy to see that the majority of products with housings found in the repository would fit the description of "handheld consumer products" based on the PCA results and the consequential template. For such products, the template in Fig. 8 is an adequate match for some or all of the main functions of the component. Doing a walk-through based on the general descriptive image of

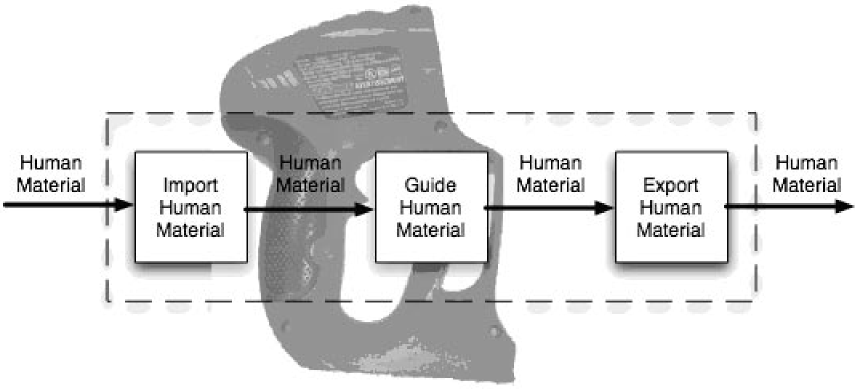


Fig. 6. Housing component functional template.

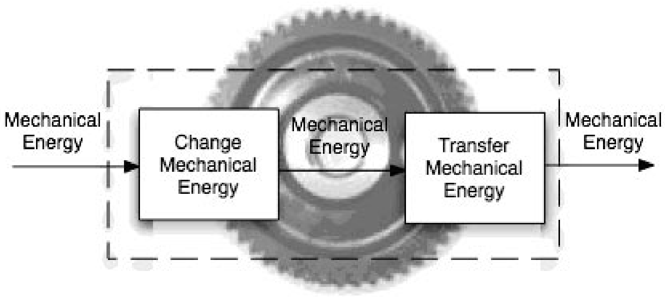


Fig. 7. Gear component functional template.

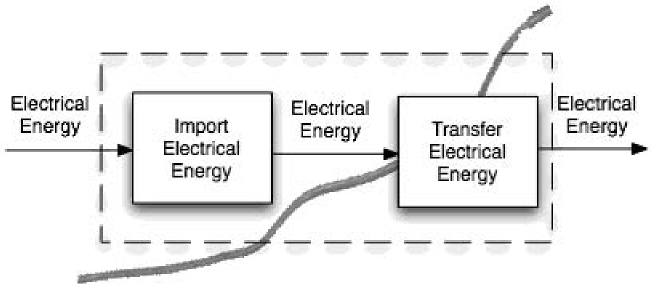


Fig. 8. Wire component functional template.

a drill housing shown in the template, as the human material (most likely a hand) comes into contact with the component it must be imported into the system boundary for which the first function accounts. As a byproduct of the handle design of this component, the second function accounts for guiding the hand into the correct position and placement to operate the drill. At this point, the user operates the tool under specification of the design. Following the same logic as the input of the human material flow, since the hand will, at some point, release the housing, it also exports the hand. This is accounted for by the last function in the template. Generally speaking, the housing template is an acceptable representation of the main functional requirements of housing components. Using an exact replication of this process, the other templates in the first group are generated and can be seen in Fig. 7 for the gear and Fig. 8 for the electric wire. The templates in these figures will be used by designers who are limiting their creativity by thinking of components in the design process. The templates allow them to translate their premature component solutions into functional form to promote creativity during the design concept generation.

6.2 Partially subjective templates

The difference between the first and second groupings of templates is found in the size of the populations of their CFMs. All of the templates in the first group were easily discernable based on their scree plots, but many of the components in the second group were not so obvious while templates from other groups suffered from dimension issues. The second category is a combination of some well-defined templates and some ill-defined templates. There is a general trend of higher populations producing more accurate results while lower populations produce results that do not necessarily represent the design information correctly. This trend is quite prevalent in the second group simply because the lower limit cut-off point is set to populations with magnitudes between 10^2 and 10^1. For a number of the lower populated components, templates can still be generated based on the PCA but the process must also include some subjective analysis in determining the included functions. The same can be said of some templates in the third grouping but they are not included in the second group because of their population magnitudes.

The belt is a good example of a low population component in the second group. With only ten artifacts in the repository to extract information from and a crippling maximum number of only four functions, the belt's CFM is shown in Table 8 and the resulting first principal component values in Table 9.

A general description of a belt may not be as accurate as components in the first group and more difficult to distinguish due to the lack of the traditional "elbow" in the Scree plot as shown in Fig. 9. Without the elbow, it can be noted that the highest function will be included but the cutoff for the remaining functions is not easily defined. Furthermore, due to the lower artifact population for this template, a comparison to the function summations across the artifacts shows that the

Table 8. Belt component CFM

	change mechanical	convert mechanical	guide mechanical	transfer mechanical
printer belt in all-in-one printer	0	1	0	0
scanner belt in all-in-one printer	0	1	1	0
drive belt in brother sewing machine	1	0	0	1
left right belt in cassette player	1	0	0	1
open close belt in cassette player	0	0	0	1
belt in datsun truck	1	0	0	0
belt in digger dog	0	0	0	1
belt in eyeglass cleaner	0	0	0	1
drive belt in irobot roomba	0	0	0	1
belt 1 in versapak sander	0	0	0	1

other three functions are improperly represented in the PCA and scree plot.

Accepting the first function as applicable, a hybrid subjective approach must now be applied to this template. From a subjective engineering judgment based on experience and a comparison with the function summations, it is decided that the other functions are not nearly as representative of the belt component as the transfer mechanical energy function and therefore are disregarded for the purposes of historical representations. The resulting template is shown in Fig. 10.

Other low population components must undergo the same analysis because of unique formulations of the CFM. This includes when all of the functions in a CFM have only one instance of each function in the entire CFM. A PCA on a CFM such as this returns higher values for some functions and lower values for others, which does not correctly represent the original data. Additionally, it should be stated that a PCA would only be performed on CFMs where there are a large number of artifacts and functions to sort through so that components such as this traditionally wouldn't even be evaluated using this method. Also, some PCAs are skewed when used in applications such as this, where every artifact in the group contains the same function. Such an occurrence yields a value of zero in the PCA because when the mean of that function column is calculated, it is returned as the same value. The mean vector is then subtracted from each artifact vector in the original CFM and the function whose mean was equal to every value in the vector retains an empty set when the covariance matrix is computed.

Table 9. First principal component for belt

PC1	Defining functions from PC1	Summation
0.2472	change mechanical	3
-0.6202	convert mechanical	2
-0.3574	guide mechanical	1
0.6531	transfer mechanical	7

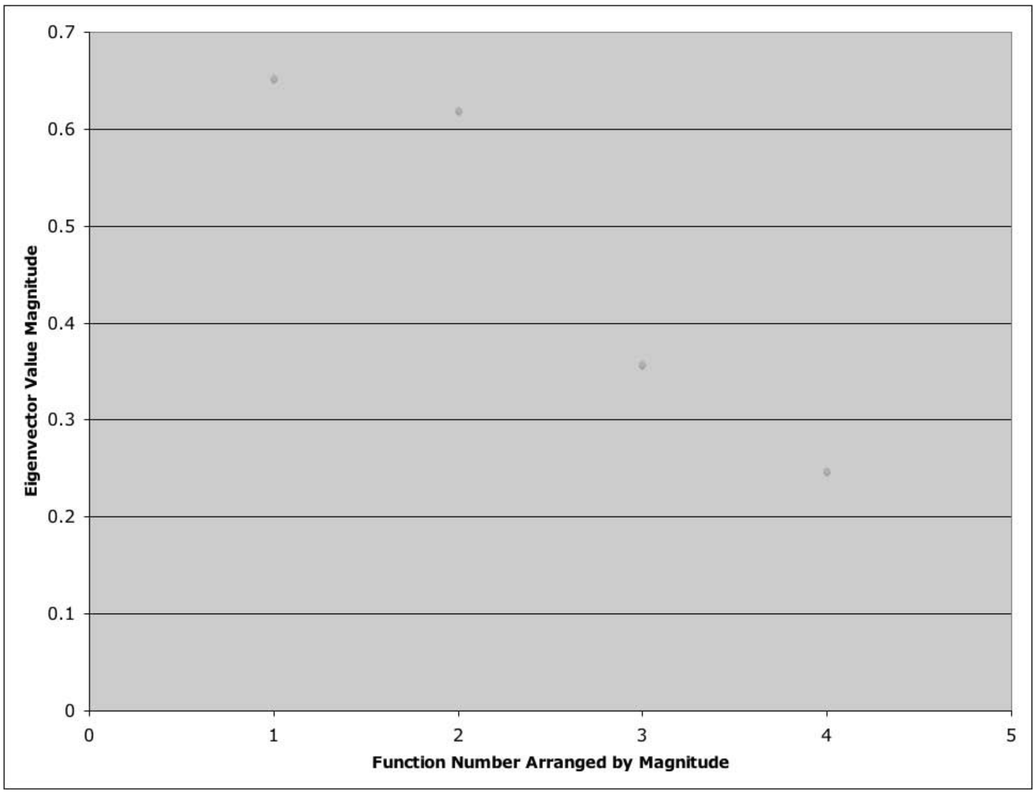


Fig. 9. Example scree plot of first principal component—category 2.

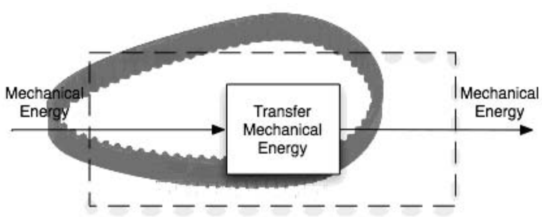


Fig. 10. Belt component functional template.

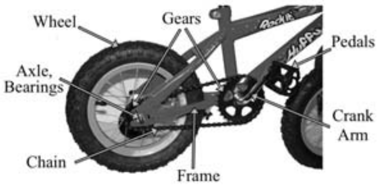


Fig. 11. Bicycle drive train components.

This, in turn gives way to a corresponding eigenvector with a zero for that function. When situations like this occur, manual manipulations of the template must take place. For the purposes of this paper, in such cases, summations of the individual functions are substituted in place of the PCA. The twenty-seven templates falling in this category are presented in the Appendix, ordered according to the rank of the CFM population. Components whose design information was scantly present or completely absent from the repository belong to the following categories.

6.3 Limited design information

The third group is comprised of components that had severely limited artifacts (e.g. less than ten), and while templates can be created for these components, they would be based on almost pure subjective decisions and are considered out of the scope of this paper. For some of these components, there was only a single artifact. A template built on a single artifact would inherently suffer from biases and application specific favoring from the original modeler lending even more reason that they are avoided here.

Similarly, a large list of components is found in the fourth category belonging to components that had no information stored about them in the design repository. Even if it were desired to create templates for these components, again it would be based strictly on a single instance or artifact of the component instead of a collection of previous applications of the components, and hence are out of the scope of this paper as well.

7. APPLICATION CASE STUDY AND DISCUSSION

To test the usefulness of the templates as they have been developed thus far, a case study is performed on a subsystem of a common children's bicycle. Knowing that the system being considered is a bicycle transmission, and the templates are already created, the user must first identify the components to find their component functional templates. Since the system has not yet been incorporated into an easy-to-use software program this will consist of searching through a hard copy collection of the templates and retrieving the ones desired. The chosen subsystem is the drive train where human energy enters the system from the user pedaling the bike to the physical translational motion of the bike and the rider. The individual components seen in Fig. 11 must be established and listed so that they can be combined to form the subsystem functional model. Component templates that are not included in the first two categories are generated similar to the hybrid subjective approach that was discussed for the belt component.

Using the definitions of the taxonomy terms and already knowing that the gear, wheel, and bearings are in the proper terminology, it is found that the pedal is a hinge, the chain is a belt, the axle is a shaft, the crank arm is a link, and the framework is a support. The correlating templates are then gathered and morphed together at the necessary analogous points to form the function chains, much like the pedal and crank arm function morph shown in Fig. 12. At this point it is important to note that the initial templates may change at the will of the user to accomplish the needs of the task at hand. This is meant to account for functions that have not been included in the original template that are necessary and may be added for a unique need, or functions that have been included and are not necessary may be removed.

Beginning with the human energy entering the system at the pedal, the flow can easily be followed through the different components of the bicycle as it encounters each one. After the pedal converts the human energy to mechanical energy, that energy is then transferred and guided to the front bearing, axle and gear using the crank arm or linkage. Then the gear changes the rotational energy to translational energy along the chain or belt. The chain then allows the energy at the front of the system to be transferred to the rear gear and other components. The wheel imports the ground as a solid and guides that solid along the length of the tire. This is where the conversion of rotational energy in the rear wheel is converted to the ultimate translational energy of the bicycle and its rider with respect to the ground.

In this case study, the templates proved to be a good starting point for building a detailed functional model of a simple bicycle's drive train. While some manual manipulation, as described in the morph example above, was still needed, the overall process was intuitive and straightforward which materialized into the detailed functional model shown in Fig. 13. The dashed lines are the bounds of the different templates as they merge

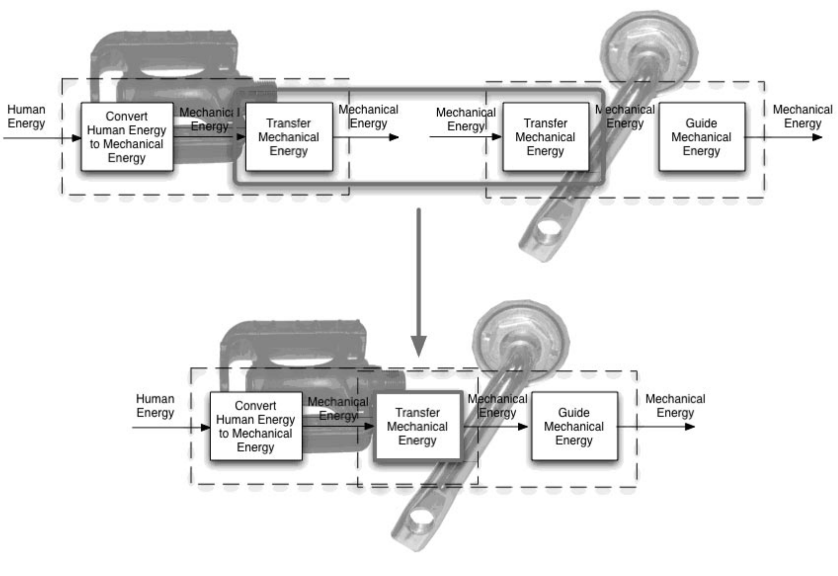


Fig. 12. Bicycle drive train function model construction example.

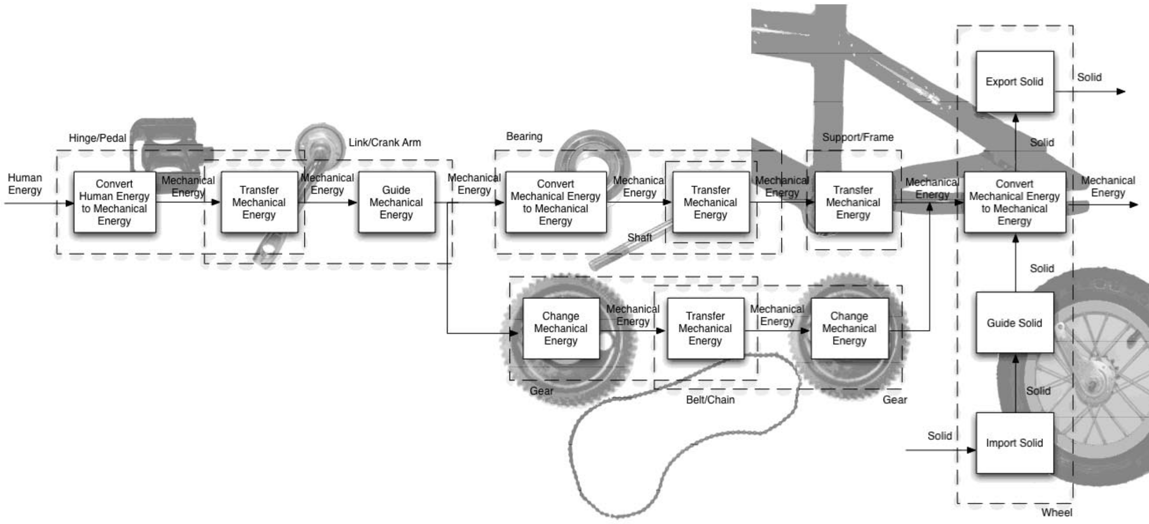


Fig. 13. Bicycle drive train functional model.>

together at their shared functions. Though the bicycle transmission functional model example may seem trivial, functional embodiments of these basic physical components will be similar to those of larger more complicated systems, thus providing valuable insight to the method and how it can be applied to many different areas of design.

For example, the function template of a spring that is used in the construction of a toy car to provide needed suspension will follow much the same format and structure as the function template of a spring used in the suspension of highly sensitive electronics components on a remotely controlled robot used in exploratory space missions. The sub-system that is used here to illustrate the use of the templates is irrelevant because the approach to build the functional model will be the same. This single example does not limit the scope of useful design applications but rather provides some insight on the usefulness of the templates in formulating functional models.

8. CONCLUSIONS AND FUTURE WORK

This paper has described the development of component functional templates as a functional modeling aid. As representations of the functions that are found within individual physical components based on historical data, the component functional templates establish a new approach to aid the functional modeling process of those new to the concept. Effectively, this approach allows for a conceptual designer to make the connection between difficult-to-grasp abstract ideas and well-understood concrete objects. Though this seems contrary to the abstract nature of functional modeling and its purpose in the conceptual design process, the resulting model can be used in their abstract form to generate numerous component solutions for a design problem. Given the surveyed results of novice functional modelers (both at UMR and NASA) this type of seemingly simple aid is needed.

It must be emphasized that without a high quality abstract functional model, like the ones even novices can generate using the templates presented, high quality concrete design solutions will not be feasible. By using this tool as an initial guide to build system models, designers who are new to the functional modeling design method can begin to think functionally instead of the thinking of the physical components that make up the system and eventually wean themselves from using the templates at all. The templates will be akin to training wheels for a bicycle. As the designers are first learning how to use the method, they can rely more on the templates and be less concerned about the rest of the details. Eventually, when applied practice has provided significant functional modeling experience, use of the templates can be tapered off or stopped completely.

A necessary next step in this research effort will be to perform a summative assessment to validate that the tool improves student mastery of learning outcomes 3–6. This will include an evaluation of student performance on the instructional objectives by comparing pre and post-tests on experimental module sets.

As a follow up to the template development, all of the templates should be reevaluated after vast amounts of design information have been added to the repository because as the population of the design repository grows, the less populated categories that were not analyzed in this project can have historically based templates associated with them as well. Combinations of multiple principal components will be analyzed and reported on. Also, a computer program will be implemented so that digital forms of the templates can be manipulated in real time via a graphical user interface. This will promote active learning activities in the classroom as well as professional software for the industrial user.

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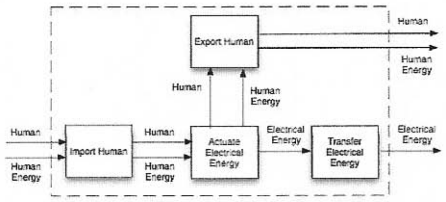
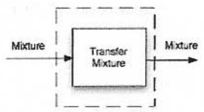
APPENDIX

Category 2 Templates

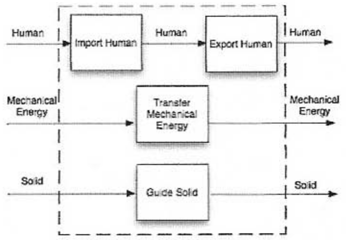
Electric Switch



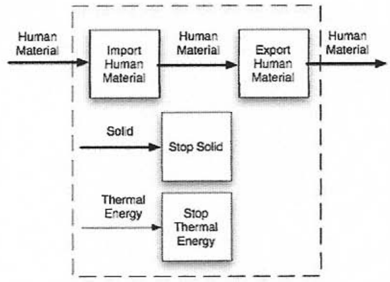
Tube



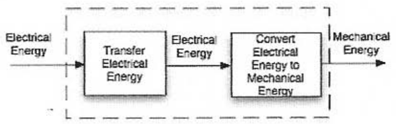
Guiders



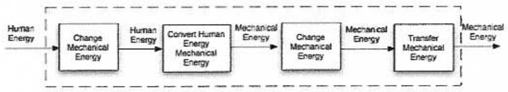
Cover



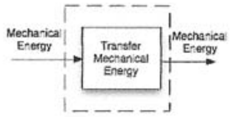
Electric Motor



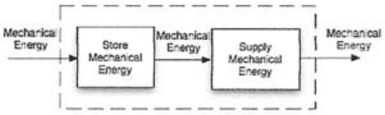
Lever



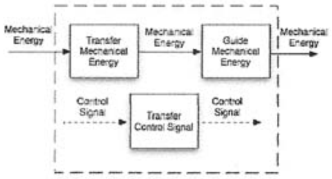
Shaft



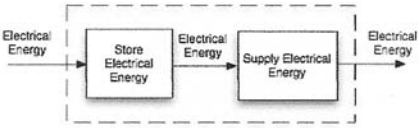
Spring



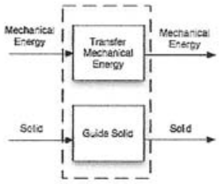
Link



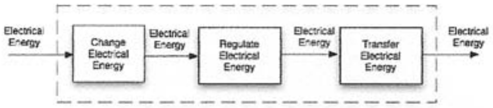
Battery



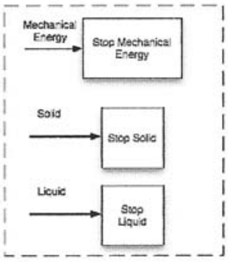
Support



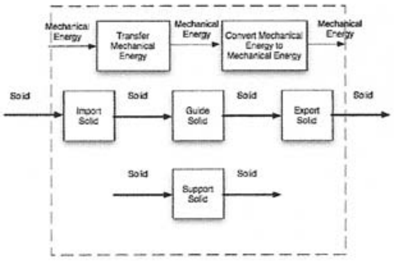
Circuit Board



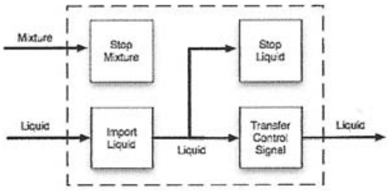
Stop



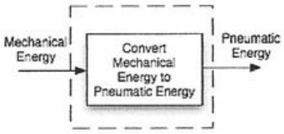
Wheel



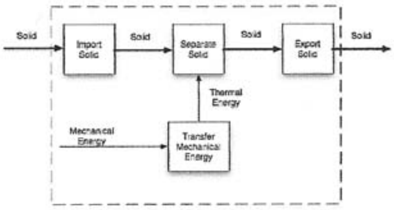
Seal



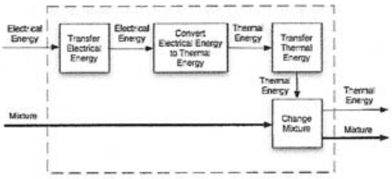
Fan

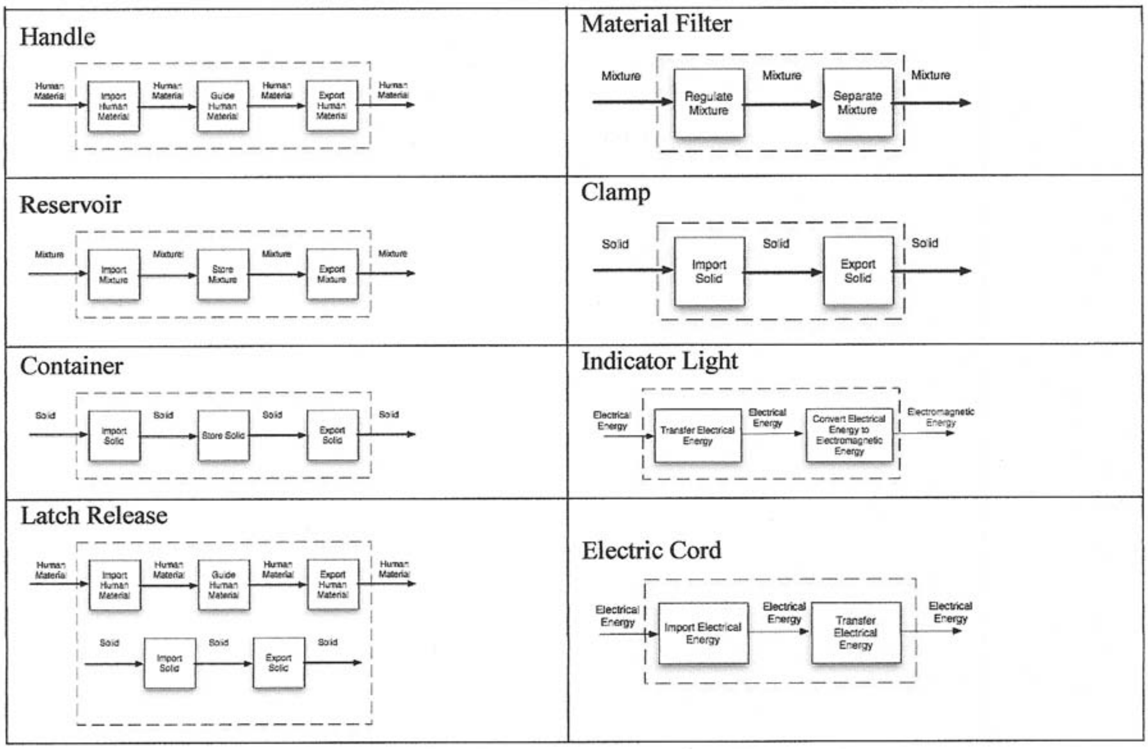


Blade



Heating Element





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