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Sorting automated concept generator results based on manufacture and assembly concerns

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SORTING AUTOMATED CONCEPT GENERATOR RESULTS BASED ON MANUFACTURE AND ASSEMBLY CONCERNS

by

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Approved by

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ABSTRACT

Early in the design process, it is desirable to produce a large number of potential solutions. Completely exploring a problem's solution space is an unreasonable expectation for an unaided designer or design team. Computational tools have emerged to help designers more fully explore possible solutions. These automated concept generators use knowledge from existing designs and the desired functionality of the new product to suggest solutions. Existing automated concept generation methods produce many candidate solutions, but produce unmanageably large sets of solutions. Techniques are needed to organize the set of concepts into smaller groups, more easily parsed by the human designer. This work proceeds from the hypothesis that the utility of automated concept generators can be enhanced if their output is sorted based on design for manufacture and assembly heuristics. Data to sort concepts is collected and a sorting method is proposed. Finally a case study is presented to demonstrate the method.

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1. INTRODUCTION

1.1. INTRODUCTION

Early in the design process, it is desirable to produce a large number of potential solutions. However, fully exploring a problem's solution space is an unreasonable expectation for the designer or design team. The ability to generate solutions will be limited by the designer's knowledge, creativity, and available time. Recently computational tools have emerged to help designers more fully explore possible solutions. These automated concept generators use knowledge from existing designs and the desired functionality of the new product to suggest solutions.

Existing automated concept generation methods solve the problem of producing many design variants. However, for all but the simplest products, these methods produce an unmanageably large set of solutions for the designer to evaluate. Techniques are needed to organize the set of concepts into smaller groups, more easily parsed by the human designer.

1.2. MOTIVATION AND HYPOTHESIS

1.2.1.1 Motivation. The intensely competitive nature of the consumer products demands that costs are kept low and good design decisions are made early. The cost of engineering changes rises rapidly as the design process proceeds [1]. Automated concept generators provide valuable aid to the designer by producing many possible solutions. However their solutions sets are often too large to be effectively analyzed by the designer. This suggests the following hypothesis.

1.2.1.2 Hypothesis. The utility of automated concept generators can be enhanced if their output is sorted based, ability to use standard parts, cost of thin walled parts, avoidance parts requiring machining, and part count.

1.3. ORGANIZATION

The work proceeds with a presentation of some background information on the design process, functional modeling, and design for manufacture and assembly. Tools that will be used in the proposed method are discussed, and two prevailing methods of automatic concept generation are presented. A method is then proposed for sorting concept generator output. The method begins with a discussion of the product domain in question, presents the of the state of manufacturing information in the design repository, collects data for four concept ranking metrics, and proposes a ranking method. The work concludes with a brief case study of the method and suggests some future work

2. BACKGROUND AND PRIOR WORK

2.1. A DESIGN PROCESS

Engineering design is a systematic, problem oriented, search for optimal solutions. Though it relies heavily on the talent, creativity, and knowledge of the individual practitioner, it is a process that can be learned.[2] Significant effort has been devoted to studying and algorithmically describing this process, but there is still debate on its individual steps and boundaries. Despite these disagreements, design can be broadly divided into three phases: understanding the problem; developing potential solutions; and implementing a final concept.[3] The diagram below shows an overview of this process with some of the potential tasks for each phase of the process. This work will focus on the development of potential solutions; it presupposes a thorough understanding of the problem by the designer, and asserts there are already many sufficient tools to aid the engineer in the detailed design and embodiment of the final concept once it has been identified.

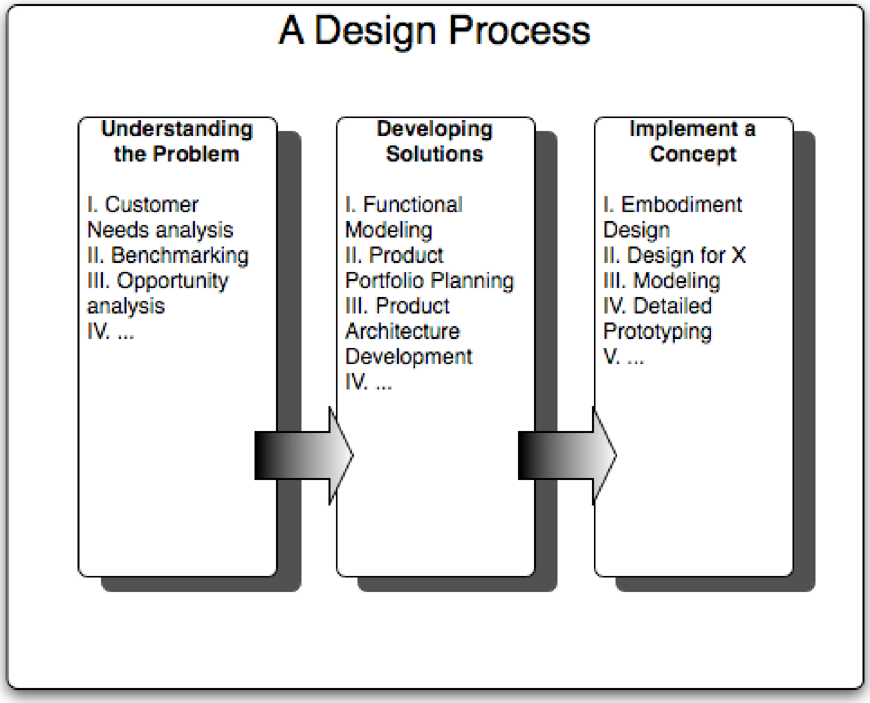


Figure 2.1. Overview of Proposed Design Process

2.2. FUNCTIONAL MODELING

A functional model, or function structure, is an abstraction that allows for an understanding and description of the design problem that is independent of specific possible solutions.[2] This work will use a device centric, operation on flows approach to modeling. In short, flows are introduced to the product and the sub functions of the product are operations on these flows. Functional models can also be purposive, environment centric models. In this case the operational environment is central to the model and operates on or with the device to specified results. Conversion between the two types of models is possible though it may take significant effort on the part of the designer.[4] Functional modeling begins with the premise that all products have an overall function, a specified relationship between systems inputs and outputs.[5] Products exist in the physical world so inputs will be flows of either matter or energy and the applicable laws of conservation will apply. For convenience a third flow, signal, is also considered. Practically, a signal must be a flow of matter or energy, but often within the context of a model the designer is more interested in the information carried by the flow than the flow itself. [3]

A product can be thought of as a series of sub functions selected and arranged to transform the available input flows into the desired output flows as specified by the overall function.[5] The selection of these sub functions is at the discretion of the designer and it is reasonable to assume that functional models of the same problem created by different designers will have some variation. Modelers may differ in their interpretation of the appropriate level of detail for the model, and in their individual assumptions about the problem. This is not undesirable, and is common trait of many types of abstract models.

2.3. DESIGN FOR MANUFACTURE AND ASSEMBLY

Design for Manufacture and Assembly (DFMA) is a catchall term for a set of heuristics and best practices, empirically derived, which if followed reduces assembly time and manufacturing cost. Adoption of these techniques has resulted in considerable cost savings for U.S. industry. The rules have been derived for a large variety of process and materials. Automated tools exist for DFMA and are increasingly be made available as part of CAD packages. The DFMA techniques cannot however be directly applied until the detailed phase of design when specifying components and configurations are known.[6] Much has been said and written about DFMA since it emerged in 1970's, but Boothroyd and Dewhurst's text remains the most influential in the field. The heuristics derived later in this work are all based on their prescriptions.

2.4. PREREQUISITE TOOLS

The methods for concept generation discussed, and the method proposed for ranking those concepts assume the designer has access to three tools: a standardized language for functional modeling, a common language to describe components, and a store of knowledge from previous designs.

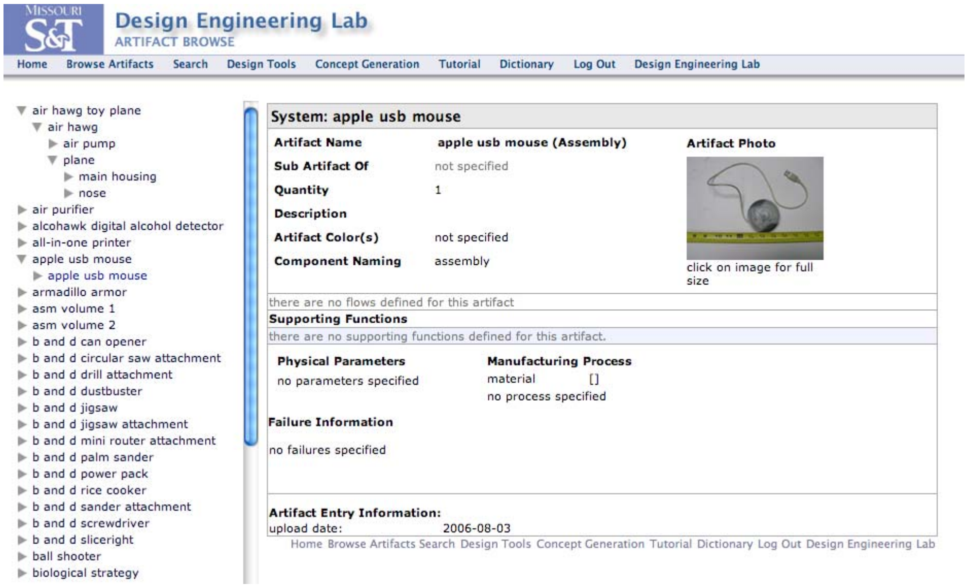
2.4.1.1 Functional Basis. A standardized approach to model development and description is necessary both to facilitate communication between designers and to accommodate computational techniques either to aid the designer or to store design knowledge. The Functional Basis [5, 7] was selected for this work. This basis, presented in Appendix A, is intended to adequately describe the full range of electromechanical products in a consistent, standardized, hierarchical language. Though the Functional Basis is used, the methodology explored is not dependant on it and should be compatible with any similar formalized language for the functional description of a product. Conversion between functional modeling languages is possible, though mappings may not be direct. [4]

2.4.1.2 Component Taxonomy. Components are the parts that compose individual concepts. Two concepts represent distinct solutions when they are comprised of different components, or a different arrangement of components. To avoid confusion among designers, and to facilitate the assistance of the computer in concept development, a common language to describe components is needed. The concept generation methods discussed later rely on a common taxonomy of components that is arranged based on component functionality [8]. The details of this taxonomy are also presented in Appendix A. This taxonomy was chosen primarily for its compatibility with existing concept generators, as with the Functional Basis, the methodology presented simply requires a standardized language and is not dependent on a particular taxonomy or lexicon.

2.4.1.3 Repository. The concept generators and sorting methodology proposed later both rely on access to an existing store of design knowledge. Beginning in the late 1990's significant effort has been expended to develop design repositories that facilitate knowledge capture and reuse.[9, 10] A design repository is distinct from more traditional design databases in that it records not only what has been designed, but also enough information to reason why and how the how artifact was created.[10]

This work will utilize the design repository developed by the Design Engineering Lab at the Missouri University of Science and Technology (http://repository.designengineeringlab.org). This repository was the result of a collaborative effort between Missouri S&T and University of Texas at Austin, and later, Bucknell University, Virginia Polytechnic Institute and State University, and Pennsylvania State University. The repository is an artifact centric relational database populated with information from the disassembly and reverse engineering of existing products. The artifacts stored in the repository range from complete products to the smallest non disassemble components for a product. The repository stores a variety of information; data is input using a stand-alone entry application available from the repository webpage and is retrievable via either an online interface or via a direct query of the database. The data of most interest to this work are artifact function, component taxonomy name, dimensions, material, and manufacturing process.[9]

As with the other necessary components of this work, the method should be applicable as long as a design repository populated with similar information is available. In fact a suitable ontology could replace all three of these tools.[11] However, despite significant research interest such an ontology does not yet exist.



System: apple usb mouse

Artifact Name	apple usb mouse (Assembly)
Sub Artifact Of	not specified
Quantity	1
Description	
Artifact Color(s)	not specified
Component Naming	assembly

Artifact Photo

click on image for full size

there are no flows defined for this artifact

Supporting Functions

there are no supporting functions defined for this artifact.

Physical Parameters

no parameters specified

Manufacturing Process

material []

no process specified

Failure Information

no failures specified

Artifact Entry Information:

upload date: 2006-08-03

Figure 2.2. Screenshot of Design Repository Web Interface

2.5. CONCEPT GENERATORS

Until recently little effort has been devoted to providing computational assistance to the designer early in the design process even though the importance of generating many alternative solutions early in design is widely accepted.[12] However, a number of tools and techniques already exist to aide during embodiment design. Today major CAD packages either ship with or allow as third party add-ons, expert knowledge based systems to automate detailed design tasks. For a nearly a decade, the closest functioning software tools, to assist in early design were the design compilers of Ward and Seering.[13] The design complier took as inputs system schematics, specifications, and utility functions and supplied as outputs a list of detailed components.[14] This was effectively an automated catalogue design system. Unfortunately this approach still required detailed knowledge of the form of the final design. Tools were still needed for the fuzzy front end of design, what Hyman calls “the design swamp”. [15]

To meet this need, two automated concept generators have been developed: one matrix based and the other based on a graph grammar approach. The two systems share a common set of inputs, but arrive at their results via different concept generation algorithms. A third approach by Tiwari et al is similar to the matrix-based approach, and bridges some of the gap between these efforts and earlier design compliers.[16] However this method requires far more detailed information about the final configuration, and is therefore excluded from this work.

The matrix method begins with a functional model of the design problem. The design repository is then queried to produce a Function Component Matrix (FCM). The FCM captures every component that has solved the function in the past, and is essentially a morphological chart where a non-zero entry indicates that the component is capable of fulfilling the function. If the functional model is represented as a vector of functions, a series of matrix manipulations can be employed to create a component-to-component matrix representing all possible solutions to the functional model. Another query to the repository can produce a Design Structure Matrix (DSM). The DSM is a component-to-component matrix where nonzero entries indicate that the two components have been connected before in an existing product. With the aid of the DSM, disregarding any solution that contains a component pair that has historically never been connected can eliminate some infeasible concepts. The approach results in a very large combinatorial problem, and produces a large set of possible solutions for modestly sized functional models. This approach outputs the solutions as chains of components.[8]

The graph grammar based approach also begins with a functional model. However in this approach the functional model is treated as a graph where each sub function is a node. Then grammars are applied to replace the functional elements of the graph with components. Grammars are derived by studying existing products and noting the components historically used to solve functions; the process is manual and subjective, though data mining could in the future automate the grammar creation process. Grammars are applied until all functions have been replaced with a component. Each concept is the result of a distinct recipe, the application of different grammar rules or a different order of application. The graph grammar method generally produces fewer concepts than the matrix-based approach, but still results in an unmanageably large set of solutions. [17]

The creators of the two concept generators acknowledge the large sets of solutions produced by these concept generators are a significant hurdle for the designer.[17, 18]

To alleviate some of the strain Bryant allows the user to select one concept at a time and indicates the historical popularity of components [8], but this approach may diminish some of the advantage of the automated concept generator as it indulges the novice designers desire to select only a few conceptual solutions. Solutions from graph-based approach have been sorted either using a penalty function based search to select an apparently optimal set of components [19], or using historical designer preferences for specific components[17]. The penalty function based approach draws obvious parallels with other catalogue design approaches, however it requires precise information that may not be present so early in the design. It may eliminate some feasible designs because no member of a class of components in its catalogue possesses the required attributes. The designer preference method suffers from the fact that designers’ preferences may change from problem to problem. It also assumes that the designer whose preferences are being sampled is making good choices. This may not always be a reasonable assumption. The remainder of this work presents an alternative sorting scheme that attempts to address some of these concerns.

3. METHOD

3.1. A FEW WORDS ABOUT DOMAIN AND MATERIALS

The following procedure and results are restricted to a domain that is loosely defined as consumer products. This is a set of products that, in general, are produced in relatively high volume, aimed at a retail market, not subject to particularly hostile environments, and are of such a scale that they can be operated or transported by a single person. Thus, a home appliance would be within this domain, a satellite would not. Obviously this is a somewhat arbitrary distinction with ill-defined boundaries. The automobile, for example, contains aspects that are within the domain and aspects that are not. This is, however, roughly the domain of products currently found in the Missouri University of Science and Technology's design repository. Since later results will be based on data in the repository, the scope of this work will be constrained to the consumer products domain

Materials and materials selection are intentionally ignored within this method. Within this domain material selection is driven by many factors other than functionally. Ignoring material for the time being allows the confounding factors including cost and aesthetics to also be ignored[20]. Given this limitation, the approach of a designer using this method would be first to select generalized components, then to follow the method of Ashby [20] to select an optimal material. Proponents of concurrent engineering will likely disapprove of such an approach, and are encouraged to refer to Messer et al for a method that attempts to integrate material information earlier in the design process [21].

3.2. STATE OF THE REPOSITORY

The design repository will be used heavily in the methodology presented later; it is worthwhile to begin with a examination of the current state of affairs within the repository. Currently the repository contains 5167 individual artifacts. According to the data they are produced using one of nine manufacturing processes, from one of nineteen materials. Table 3.1 shows a breakdown of artifacts by manufacturing process.

Process	# of Artifacts	% of Artifacts
Casting	228	4.41%
Extrusion	262	5.07%
Forging	13	0.25%
Forming	144	2.79%
Injection Molding	895	17.32%
Machining	268	5.19%
OEM	187	3.62%
Rolling	364	7.04%
Stamping	234	4.53%
Not Specified	2572	49.78%
Total # of Artifacts	5167	

Table 3.1. Repository Artifacts by Manufacturing Process

There are some areas of immediate concern. First, nearly half of artifacts have no manufacturing process associated with them. This may be partially explained by artifacts that are assemblies of other artifacts and thus are not clearly associated with a single process. However this is not solely the case and many non-decomposable artifacts are not properly tagged with a manufacturing process. This will limit the set of artifacts that can be used to draw inferences. Second, this set of processes is used to provide suggestions to the user inputting data in the entry application. It is clearly not an exhaustive list. Ashby identifies 20 shaping processes, four joining processes, and four finishing processes.[20] The user should be presented with more choices, and perhaps more guidance. On a more positive note, injection molding and stamping are two of the most prevalent process that would be expected for this product domain, and they are represented by a large number of artifacts.[20] However, machining, a process that due to cost would not likely be a popular choice, is the second most prevalent process. This is likely due to the fact that machining is an easily recognized process. It is more likely to be recognized and entered by the user even though it is more often used in this domain as a finishing process rather as a primary forming process. Table 3.2 shows the breakdown of materials associated with artifacts in the repository.

Material	# of Artifacts	% of Artifacts
ABS	40	0.77%
Aluminum	65	1.26%
Brass	6	0.12%
Cardboard	2	0.04%
Composite	368	7.12%
Concrete	0	0.00%
Copper	37	0.72%
Foam	20	0.39%
Glass	19	0.37%
Iron	17	0.33%
Metal	842	16.30%
Metal Alloy	2	0.04%
Nylon	77	1.49%
Paper	4	0.08%
Plastic	1108	21.44%
Rubber	143	2.77%
Steel	720	13.93%
Wood	2	0.04%
Not Specified	1695	32.80%
Total # of artifacts	5167	

Table 3.2. Repository Artifacts by Material

Again many artifacts have no material specified for the reasons suggested above. Clearly this list is also not exhaustive, but an exhaustive list of materials is probably unreasonable. However the inconsistent level of specificity in the list is a cause for concern. When presented with a plastic artifact, the user might record it as plastic, ABS, or nylon depending on their level of confidence in identifying the material used. Users would benefit from more organization of the list of possible materials. A sensible suggestion for a top-level list would be to adopt Ashby’s list of Metals, Ceramics, Composites, Natural Materials, and Polymers and Elastomers.[20] Appropriate sub categories could be added as necessary.

There is room for improvement in the data that is collected in the repository, and the method of collection. Extra support needs to be given to the user of the repository entry app in these areas. Many data enterers will have limited expertise in materials and process. Nonetheless, the data set is large, and errors are relatively few. The repository is still a reasonable source of data, and will become even better as it is populated with more data.

3.3. OVERVIEW OF PROPOSED METHOD

Both concept generators give a list of components as their output. A sensible approach to sorting the concepts must be based at the component level. The general approach to sorting concepts will begin with selecting certain desirable or undesirable characteristics, determining the propensity for a particular component to have that characteristic, and then sorting concepts into groups based on the properties of their constituent components. The following diagram summarizes the proposed method.

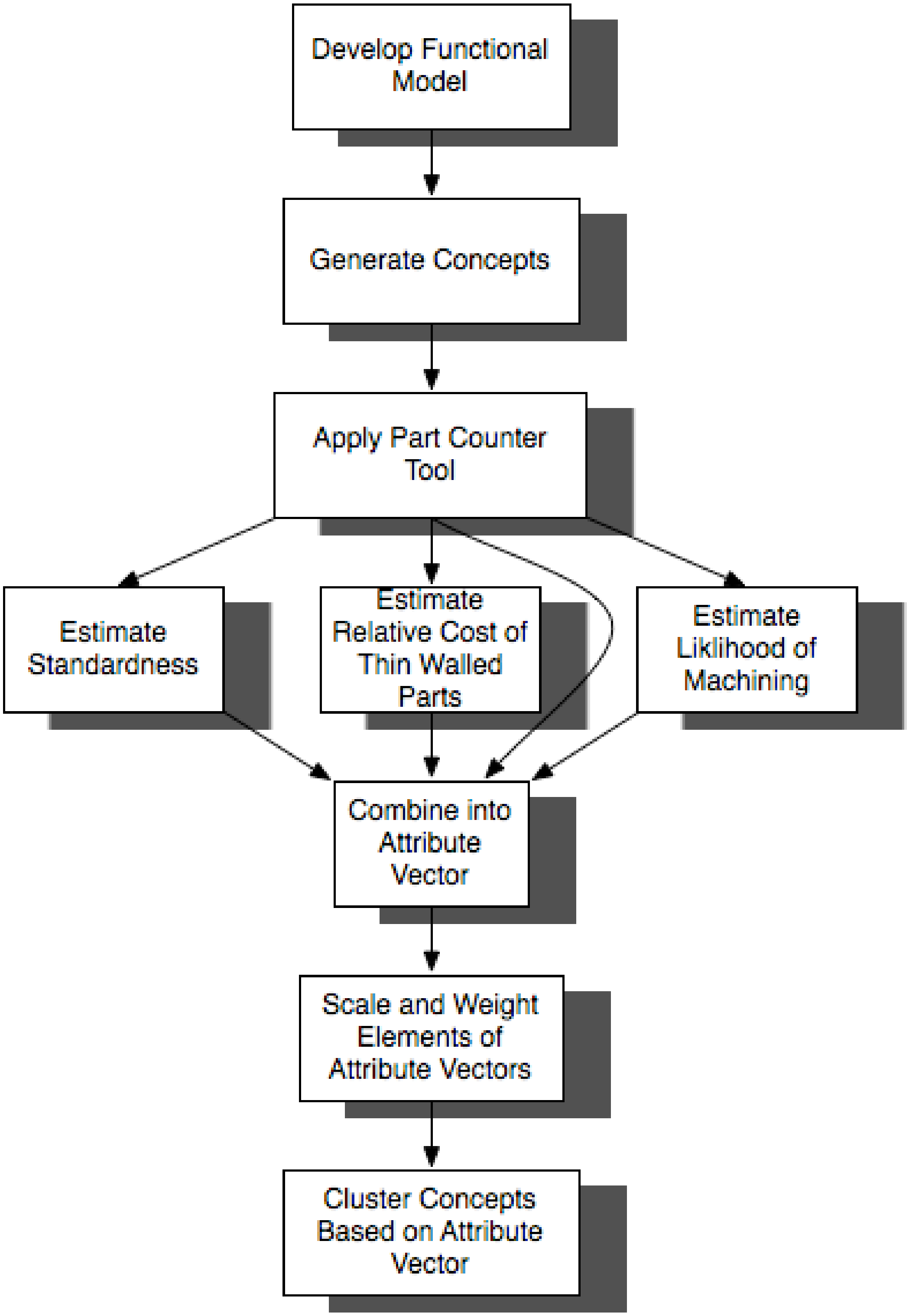


Figure 3.1. Overview of Sorting Method

Following the approach of Boothroyd and Dewhurst four characteristics are identified based on DFMA suggestions. First, it is desirable to use standard parts whenever possible. Standard parts are common, standardized components that can be sourced from a variety of suppliers. OEM, or original equipment manufacturer, is a common substitute for the term standard parts in some industries. The basic assumption is that market forces will drive the price of these standard parts below the cost of the manufacturer to make a custom part. The caution is that slavish devotion to standard parts can stifle innovation and drive up costs.[6] This is reasonable, but the purpose of our ranking will be to suggest concepts that could be made with mostly standard parts, not to insist that the designer do so.

Second, it is desirable to use thin walled parts produced using stamping or injection molding. These processes are common and relatively low cost for the high volume parts produced for consumer products. These processes are likely to be selected, so concepts that include components which can be produced at a low cost with these methods are preferred.[6]

Third, machining is a wasteful and costly process that should be avoided if possible. Concepts built from components that are unlikely to require machining are preferred.

Finally, a proxy for assembly cost is needed. The form of the individual solutions and the way they are joined together embodies much of the assembly cost. Prashar has developed a part counting tool that interfaces with the design repository and the matrix based concept generators to produce an estimate of the number of parts necessary to complete the concept. The counter is based on the average number of instances of a component found when that component is used to solve a specified function. [22] The count produced by Prashar's tool will be the fourth metric used to sort components.

Once the characteristics of each concept have been found, they will be combined into an attribute vector that suggests the manufacturability of the concepts. Concepts will be sorted into groups based on their similarity to one another. The intent is to find a group of relatively lower cost concepts for further exploration, and a set of relatively more expensive concepts that the designer might disregard. The sorting method used in this work is K-means clustering. K-means is a classical hard clustering technique that sorts data into a specified number of clusters by reducing the mean square distance between each element in the cluster and the cluster center. [23]

3.4. ESTIMATING STANDARDNESS OF A CONCEPT

To estimate the degree to which a concept can be built using standard parts, it is first necessary to associate some measure so standardness with each term in the component taxonomy. All artifacts tagged with a component taxonomy name were extracted from the repository. Using artifact photos and other data the artifact was tagged as either standard or not standard. For the purpose of this exercise an artifact was a standard part if it could reasonably be assumed to be procured on the open market from a parts supplier. The binary nature of the data implied a Bernoulli distribution for each artifact, from which could be estimated a mean, variance, and confidence intervals for the mean. The findings mimic what would be expected. Electric motors, which are almost universally standard parts, have a high average, while housings, which tend to be custom parts to accommodate product architecture as well as branding and aesthetic concerns, have a very low average value. Some components have particularly low sample sizes, but this problem should resolve itself as the database grows.

Once the expected standardness for each component is known, a measure of standardness for the concept as a whole can be generated. There are two approaches to estimate component standardness. The first would be to multiply together the standardness of each component in the concept to produce an estimate of the likelihood that the entire concept could be made from standard parts. This would be preferred because in reality all components should have some non-zero standardness, and the aggregate of these would be a reasonable representation of our ability to build the concept from standard parts. Unfortunately given the small sample sizes of some components in the repository many of the current estimates of mean standardness are zero. This would strongly penalize a strong concept due to one non-standard component. To mitigate this effect, for now, standardness of the concept is estimated by simply averaging the standardness of the components.

3.5. ESTIMATING RELATIVE COST OF THIN WALLED PARTS

It is desirable, within this product domain, to use thin walled parts produced using stamping or injection molding. These processes are common and relatively low cost for high production volumes. These processes are likely to be selected, so concepts that include components with lower relative costs for these processes are preferred. To estimate the relative cost of these processes for each component taxonomy term, the database is queried to find all artifacts produced using one of these processes. Any artifact without a component basis name was excluded from the list. Then any artifact without a picture and other data needed to produce an estimate was discarded. As a result of this paring down of the data set, all stamped parts were excluded. For now, a discussion of costs for stamping will be omitted and the estimate will be based solely on injection molding.

For each artifact a cost estimate is then calculated. Boothroyd and Dewhurst suggest a method for cost estimates that relate the cost of the part to the cost of a standard unit washer. The cost becomes a product of several factors based on the parts features, parts, and materials. Excluding factors related primarily to material or fit and finish, leaves basic and subsidiary part complexity to base an relative cost upon. Using the group technology heuristics these factors are calculated for each artifact, and multiplied together for a total relative cost. These costs are then averaged for each component within the taxonmy. This data is presented in Appendix B. A thin walled part cost factor for each component is calculated by averaging the relative costs of its thin walled parts.

3.6. AVOIDING COMPONENTS THAT REQUIRE MACHINING

Machining is a costly and undesirable process for components within the specified product domain. The likelihood that a particular component taxonomy term will have to be machined can be estimated by querying the database for all artifacts of a particular component basis type that are machined and dividing by the total instances of that component basis type that have any manufacturing process associated with them. Dividing only by instances that have a specified manufacturing process prevents incompletely recorded artifacts from heavily swaying the results. This data is also presented in Appendix B. The results conform to basic expectations about this domain; the likelihood that a part will be machined is low for all component taxonomy terms.

3.7. CLUSTERING CONCEPTS

The four calculated product attributes are assembled into a vector representing the relative manufacturability of the concept. The designer wishes to minimize three attributes: thin walled part cost, likelihood of machining, and part count. The number of standard parts, on the other hand, should be maximized. For convenience the standard part likelihood is transformed into a not standard part likelihood by subtracting it from one. Now all dimensions should be minimized. A sample calculation of an attribute vector for a concept including a electric wire, an electric switch, and a battery is shown in figure 3.2. To avoid undue weighting of a particular attribute all are normalized on a scale from 0 to 1. The normalized product vectors are clustered using a k-means algorithm. The appropriate number of clusters is at the discretion of the designer, and may take some iteration to determine. The appropriate number of clusters will result in mean distances from the cluster centers to members of the cluster that are less than the distance between cluster centers. The intent is to find concepts with small attribute vectors, so the cluster whose center has the smallest Euclidian distance from the origin contains the concepts that should be explored further.

Sample Concept				***Attribute Vector***
Components	*battery*	*electric switch*	*electric wire*	
Standardness	0.6750	0.3874	0.8839	**0.6488**
Machining Liklihood	0.0000	0.0078	0.0051	**0.0043**
Thin Wall Relative Cost	na	2.0772	na	**2.0772**
Part Count				**7.3559**

Figure 3.2. Sample Concept Attribute Vector

4. A CASE STUDY

4.1. PROBLEM

To demonstrate the DFMA based concept variant sorting method, concepts for a child's toy will be developed. It is desired that the toy translate across a surface using stored electrical energy. It might be a toy car, or something more novel. A functional model for the toy generated using FunctionCAD, a functional modeling program, is shown below in Figure 4.1.

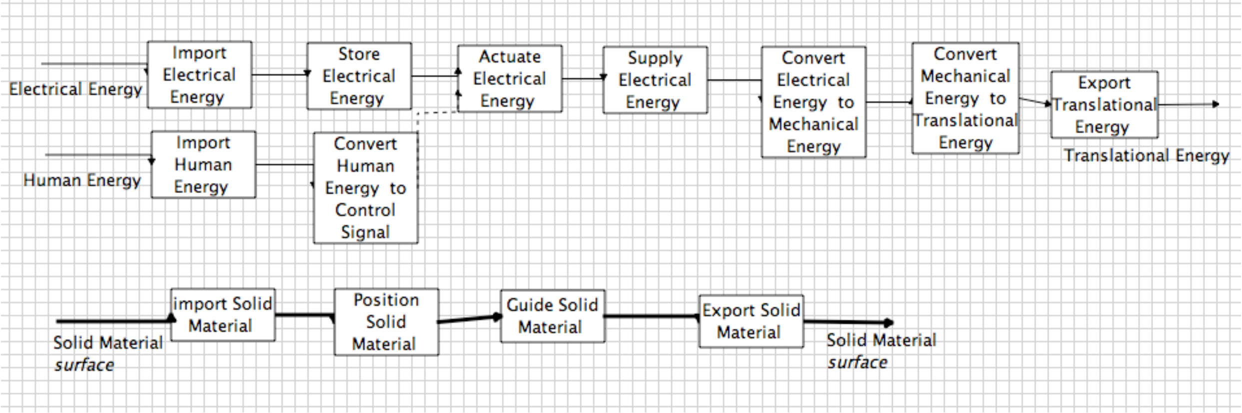
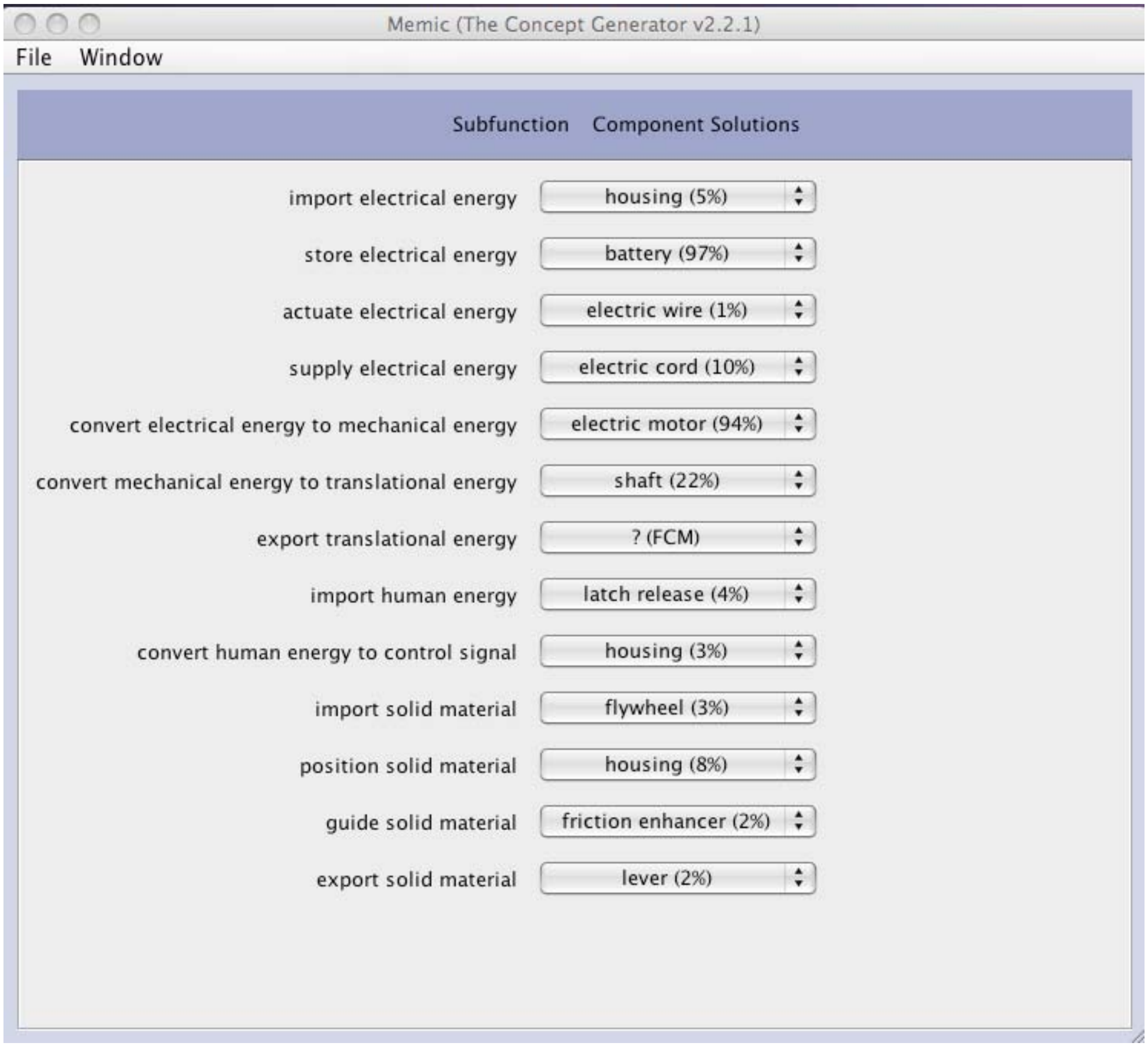


Figure 4.1. Toy Functional Model

4.2. CONCEPT GENERATION

The functional model is input into the matrix based concept generator along with a FCM and DSM Matrix from the design repository. A sample of the results is shown below in Figure 4.2. Many concepts are produced, but in the interest of producing an understandable set, twenty-five are selected at random for further review. No effort is made to eliminate infeasible concepts and some may reflect errors present in the repository. The concepts produced are stored in Appendix C.



Subfunction	Component Solutions
import electrical energy	housing (5%)
store electrical energy	battery (97%)
actuate electrical energy	electric wire (1%)
supply electrical energy	electric cord (10%)
convert electrical energy to mechanical energy	electric motor (94%)
convert mechanical energy to translational energy	shaft (22%)
export translational energy	? (FCM)
import human energy	latch release (4%)
convert human energy to control signal	housing (3%)
import solid material	flywheel (3%)
position solid material	housing (8%)
guide solid material	friction enhancer (2%)
export solid material	lever (2%)

Figure 4.2.Sample Matrix Based Concept Generator Output

4.3. SORTING RESULTS

Applying the algorithm discussed in the previous section the attribute vectors are calculated for each component. With only twenty-five concepts, it is possible with effort to identify preferred concepts. If the set were larger the computer’s assistance would be needed. The vectors are supplied to the k-means algorithm, which is used to suggest four clusters. The following table shows the attribute vector and cluster membership of each concept.

Concept	Std Pts	Machining	Thin Wall	Pt. Count	Cluster
Concept01	0.82401548	0.976809557	0.808852859	0.641287954	4
Concept02	0.801169616	0.959732375	0.525030656	0.572511626	3
Concept03	0.658704858	0.990963266	0.862110802	0.740528305	4
Concept04	0.933676401	0.993497508	0.638541241	0.774303361	1
Concept05	0.825347734	1	0.603684528	0.558270407	3
Concept06	0.73091307	0.976166423	0.623011702	1	2
Concept07	0.743033417	0.945185473	0.640033478	0.699554584	3
Concept08	0.891164296	0.950362769	0.608336415	0.753712008	1
Concept09	0.64489291	0.979355792	0.806314109	0.761376483	4
Concept10	0.808605488	0.992122689	0.835698205	0.817807567	4
Concept11	0.969088516	0.986224373	0.625825596	0.61665286	1
Concept12	0.779456923	0.97598038	0.852106974	0.736124505	4
Concept13	0.597567537	0.949219688	1	0.811711741	4
Concept14	0.912340803	0.968996871	0.629237467	0.709661419	1
Concept15	0.679201086	0.946179679	0.738865802	0.727838109	4
Concept16	0.973932667	0.985837172	0.825267684	0.878025567	1
Concept17	1	0.982853289	0.785781575	0.756408675	1
Concept18	0.720974795	0.997201947	0.816444696	0.580578965	4
Concept19	0.844268925	0.995282914	0.704968501	0.619203489	3
Concept20	0.712299567	0.951171355	0.679263094	0.39922751	3
Concept21	0.760215756	0.963718778	0.681848963	0.592617026	3
Concept22	0.665106602	0.995483614	0.899384939	0.637626933	4
Concept23	0.565272557	0.966778156	0.861542697	0.700561743	4
Concept24	0.785649712	0.964526991	0.6029795	0.579355268	3
Concept25	0.650181146	0.983515056	0.849090222	0.839406079	4

Table 4.1.Case Study Results Table

An examination shows that cluster three’s center is closest to the origin. Its members have relatively low combinations of costly attributes. Concepts 2, 5, 7, 19, 20, 21, and 24 likely merit further study based on DFMA concerns.

A further examination of these concepts suggests that they fall into two general categories. Given the very general approach used to model the problem some interpretation is required. Concepts 2, 5, 7, and 21 imply a walking toy, like a toy robot. Concepts 19, 20, and 24 suggest something more like a toy car. Based on these results the designer would have a few concepts suggesting two different solution types to work with.

5. CONCLUSION

5.1. CONCLUSIONS

The results of the case study provide preliminary evidence to support the hypothesis that manufacturing attributes can be used to effectively sort the output of automated concept generators. Generalizations about the likelihood that a component will be a standard part, machined, or relatively more or less costly to injection mold have been suggested based on data in the repository.

This data can be used to estimate the compatibility of concepts produced by automated concept generators and design for manufacture and assembly guidelines. Using these estimates, groups of concepts that appear to be highly compliant with DFMA guidelines can be selected for further study, and groups of concepts that are highly incompatible can be discarded. This allows the designer to reduce the very large set of concepts produced by automated concept generators down to a more manageable set while also eliminating concepts that would likely be rejected later due to high manufacture and assembly cost.

The collection of data necessary to establish these estimates highlighted limitations in the current design repositories method of storing and representing manufacturing information. A more complete and more logically arranged set of terms for material and manufacturing process should be implemented to assist novice data collectors and to reduce errors.

The discussed limitations in the repository data lead to the inevitable conclusion that some of these relationships found are unreliable. This does not diminish the potential of the proposed sorting method, it simply suggests the need for more data in the repository, and a closer review of the data already collected. The method deserves further exploration, and experimentation with actual designers and design problems.

5.2. FUTURE WORK

Significant additional testing of the proposed method is needed with a variety of different users and problems. This testing would permit a more thorough vetting and validation of the method. Beyond this particular method, the general approach can and should be extended to other Design for X concerns beyond manufacturing. Finally, the difficulties posed by automated concept generators are not solely problems of the size of the results, but also with their representation. There is significant work still to be done to address the best methods to present concepts to the designer. The impact of presenting the data in graphics or text format needs to be assessed, as does the appropriate size set of solutions to return. Finally, a comparison between the matrix and graph based approach to generating concepts should be undertaken.

APPENDIX A.

COMPONENT TAXONOMY AND FUNCTIONAL BASIS

COMPONENT TAXONOMY AND HIERARCHY

Primary	***Secondary***	***Tertiary***	
brancher	separator	divider	
		abrasive	
		blade	
		vibrator	
		centrifuge	
		material filter	permeable membrane
			rake
			screen
	distributor	brush	
		diverger	
		nozzle	
		electric distributor	
channeler	importer-exporter	housing	
		electric cord	
	transferor	carousel	
		conveyer	
		electric conductor	electric wire
			electric plate
		electric socket	
		electric plug	
		projectile	
		belt	
		clutch	
		extension	
		rotational coupler	
		shaft	
		heat exchanger	
		thermal conductor	thermal wire
			thermal plate
		em transmitter	
	guiders	hinge	
		tube	
		diode	
		bearing	

		link	
		sled	
connector	coupler	clamp	
		fastener	glue
			key
			nut-bolt
			retaining clip
			rivet
			screw
			solder
	mixer	agitator	
magnitude controller	actuator	door	
		electric switch	
		latch release	
	regulator	valve	
		potentiometer	
		thermostat	
		transistor	
	changer	mold	
		punch	
		stuffing	
		choke	
		electric resistor	
		mechanical transformer	gear
			pulley
			sprocket
		inclined plane	
		lever	
		needle	
		lens	
		capacitor	
		inductor	
		signal filter	
	stopper	cap	
		cover	
		seal	
		acoustic insulator	
		electric insulator	
		fuse	

		cushion	
		friction enhancer	
		stop	
		thermal insulator	
converter	output gas material	catalytic converter	
		evaporator	
	output liquid material	condenser	
	output acoustic energy	speaker	
	output electrical energy	generator	
	output electromagnetic energy	light source	
	output hydraulic energy	hydraulic pump	
		screw propeller	
	output magnetic energy	electromagnet	
	output mechanical energy	ic motor	
		electric motor	
		hydraulic piston	
		armature	
		cam	
		crank	
		wheel	
		airfoil	
		pneumatic piston	
	output pneumatic energy	fan	
		pneumatic pump	
	output thermal energy	burner	
		heating element	
	output control signal	knob	
provisioner	material supplier	reservoir	
		container	
		bladder	
		pressure vessel	
	energy supplier	battery	
		magnet	
		flywheel	
		spring	
signaler	sensor	level gauge	
		voltmeter	
		ammeter	
		pressure gauge	

		displacement gauge	
		speed gauge	
		em sensor	
	indicator	visual indicator	analog display
			digital display
			flag
			indicator light
		auditory indicator	bell
			buzzer
			recording
	processor	circuit board	
supporter	stabilizer	insert	
		support	
	securer	bracket	
	positioner	washer	
		handle	

FUNCTIONAL BASIS FUNCTION TERMS

Class (Primary)	***Secondary***	***Tertiary***	***Correspondents***
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock
Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack
Control Magnitude	Actuate		Enable, initiate, start, turn-on
	Regulate		Control, equalize, limit, maintain
		Increase	*Allow*, open
		Decrease	Close, delay, interrupt
	Change		Adjust, modulate, *clear*, demodulate, invert, normalize, rectify, reset, scale, vary, modify
		Increment	Amplify, enhance, magnify, multiply
		Decrement	Attenuate, dampen, reduce
		Shape	Compact, compress, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop		End, halt, pause, interrupt, restrain
		Prevent	Disable, turn-off
		Inhibit	Shield, insulate, protect, resist
Convert	Convert		Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, *process*, solidify, transform
Provision	Store		Accumulate
		Contain	*Capture*, enclose
		Collect	Absorb, consume, fill, reserve
	Supply		Provide, replenish, retrieve
Signal	Sense		Feel, determine

		Detect	Discern, perceive, recognize
		Measure	Identify, *locate*
	Indicate		Announce, show, denote, record, register
		Track	Mark, time
		Display	*Emit*, expose, select
	Process		Compare, calculate, check
Support	Stabilize		Steady
	Secure		*Constrain*, hold, place, fix
	Position		Align, *locate*, orient
Overall increasing degree of specification →			

APPENDIX B.

COLLECTED DATA

COMPONENT TAXONOMY TERM STANDARDNESS DATA

The following table summarized the results of standard parts analysis on data within the design repository. The table tabulates the results of tagging each component as either standard or non-standard, thus the data conforms to a Bernoulli distribution. The name is the component taxonomy name, and count is the number artifacts tagged as that component. The mean is the expected standardness of the part. Variance indicates the spread of the data, and the two confidence intervals are 90% confidence intervals for the mean.

Name	**Count**	**Mean**	**Variance**	**90%CI_1**	**90%CI_2**
brancher	67	0.2687	0.1995	0.1776	0.3597
magnitude controller	763	0.2647	0.2107	0.2374	0.2921
signaler	82	0.2561	0.1929	0.1754	0.3368
supporter	378	0.2143	0.1688	0.1794	0.2491
separator	55	0.2909	0.2101	0.1875	0.3943
distributor	12	0.1667	0.1515	0	0.3685
guiders	388	0.2474	0.4813	0.1894	0.3055
actuator	164	0.3171	0.2915	0.2473	0.3868
regulator	20	0.25	0.1974	0.0782	0.4218
changer	273	0.348	0.2277	0.3003	0.3957
stopper	305	0.1639	0.1375	0.1289	0.199
output pneumatic energy	24	0.25	0.1957	0.0953	0.4047
material filter	19	0.2105	0.1754	0.0439	0.3772
clamp	25	0.2	0.1667	0.0603	0.3397
door	4	0.25	0.25	0	0.8383
latch release	46	0.1739	0.1469	0.079	0.2688
cushion	13	0.1538	0.141	0	0.3395
pneumatic piston	3	0.3333	0.3333	0	1.3067
fan	23	0.2174	0.1779	0.0664	0.3684
magnet	3	0.3333	0.3333	0	1.3067
flywheel	6	0.3333	0.2667	0	0.7581
washer	14	0.2857	0.2198	0.0638	0.5076
key	5	0.2	0.2	0	0.6264
transferor	540	0.687	0.4158	0.6413	0.7328
output mechanical energy	113	0.6903	0.2157	0.6178	0.7627
energy supplier	191	0.6963	0.2126	0.6412	0.7515
indicator	24	0.625	0.2446	0.452	0.798
positioner	77	0.5714	0.2481	0.4769	0.666
belt	18	0.7222	0.2124	0.5332	0.9112
electric resistor	6	0.6667	0.2667	0.2419	1.0915
seal	40	0.7	0.2154	0.5764	0.8236
hydraulic pump	3	0.6667	0.3333	0	1.64
battery	40	0.675	0.225	0.5486	0.8014
spring	141	0.7234	0.2015	0.6608	0.786

visual indicator	21	0.7143	0.2143	0.5401	0.8885
retaining clip	3	0.6667	0.3333	0	1.64
channeler	1371	0.3581	0.3279	0.3327	0.3836
converter	242	0.4628	0.2496	0.4098	0.5158
provisioner	253	0.5534	0.2481	0.5017	0.6051
mixer	4	0.5	0.3333	0	1.1794
output liquid material	2	0.5	0.5	0	3.6569
sensor	12	0.4167	0.2652	0.1497	0.6836
blade	30	0.4	0.2483	0.2454	0.5546
electric socket	8	0.5	0.2857	0.142	0.858
heat exchanger	6	0.5	0.3	0.0494	0.9506
hinge	26	0.3846	0.2462	0.2184	0.5508
tube	55	0.4	0.2444	0.2884	0.5116
electric switch	111	0.3874	0.3486	0.2944	0.4803
mechanical transformer	182	0.4341	0.247	0.3732	0.495
needle	4	0.5	0.3333	0	1.1794
capacitor	2	0.5	0.5	0	3.6569
stop	34	0.3529	0.2353	0.2122	0.4937
condenser	2	0.5	0.5	0	3.6569
wheel	19	0.4211	0.2573	0.2193	0.6229
displacement gauge	2	0.5	0.5	0	3.6569
em sensor	2	0.5	0.5	0	3.6569
insert	10	0.4	0.2667	0.1007	0.6993
gear	170	0.4118	0.2436	0.3492	0.4744
sprocket	4	0.5	0.3333	0	1.1794
importer-exporter	403	0.0794	0.0733	0.0572	0.1016
output hydraulic energy	50	0.1	0.0918	0.0281	0.1719
output thermal energy	19	0.0526	0.0526	0	0.1439
output control signal	13	0.0769	0.0769	0	0.214
material supplier	62	0.1129	0.1018	0.0452	0.1806
processor	44	0.0227	0.0227	0	0.0609
stabilizer	246	0.1341	0.1166	0.0982	0.1701
securer	55	0.0727	0.0687	0.0136	0.1319
divider	5	0	0	0	0
abrasive	1	0	0	0	0
nozzle	11	0.0909	0.0909	0	0.2557
housing	371	0.0054	0.0054	0	0.0117
carousel	3	0	0	0	0
extension	3	0	0	0	0
rotational coupler	2	0	0	0	0
shaft	109	0.1009	0.0916	0.0528	0.149
thermal conductor	1	0	0	0	0
link	76	0.0658	0.0623	0.0181	0.1135
sled	22	0	0	0	0
agitator	2	0	0	0	0
valve	10	0	0	0	0
transistor	3	0	0	0	0
stuffing	1	0	0	0	0
lever	69	0.087	0.0806	0.03	0.1439

lens	6	0	0	0	0
cap	38	0.1316	0.1174	0.0378	0.2253
cover	158	0	0	0	0
friction enhancer	16	0.125	0.1167	0	0.2747
thermal insulator	4	0	0	0	0
hydraulic piston	7	0.1429	0.1429	0	0.4205
cam	8	0.125	0.125	0	0.3618
crank	1	0	0	1	1
airfoil	5	0	0	0	0
heating element	17	0.0588	0.0588	0	0.1615
knob	13	0.0769	0.0769	0	0.214
reservoir	28	0.0714	0.0688	0	0.1558
container	32	0.125	0.1129	0.0243	0.2257
pressure vessel	1	0	0	0	0
pressure gauge	1	0	0	0	0
auditory indicator	1	0	0	0	0
circuit board	44	0.0227	0.0227	0	0.0609
support	235	0.1234	0.1086	0.0879	0.1589
bracket	47	0.0426	0.0416	0	0.0925
handle	47	0.0638	0.0611	0.0033	0.1243
rake	2	0	0	0	0
screen	2	0	0	0	0
electric plate	3	0	0	0	0
analog display	1	0	0	0	0
buzzer	1	0	0	0	0
connector	622	0.9148	0.0781	0.8963	0.9332
coupler	618	0.9175	0.0758	0.8992	0.9357
output acoustic energy	8	1	0	1	1
output electrical energy	2	1	0	1	1
output electromagnetic energy	10	0.9	0.1	0.7167	1.0833
electric cord	32	0.9375	0.0605	0.8638	1.0112
electric conductor	386	0.8756	0.3897	0.8233	0.928
clutch	2	1	0	1	1
diode	2	1	0	1	1
bearing	10	1.6	1.6	0.8668	2.3332
fastener	584	0.9538	0.0442	0.9394	0.9681
thermostat	4	1	0	1	1
inductor	2	1	0	1	1
signal filter	1	1	0	1	1
acoustic insulator	1	1	0	1	1
speaker	7	1	0	1	1
generator	1	1	0	1	1
light source	10	0.9	0.1	0.7167	1.0833
ic motor	2	1	0	1	1
electric motor	67	0.9552	0.0434	0.9128	0.9977
pneumatic pump	1	1	0	1	1
electric wire	379	0.8839	0.3886	0.8311	0.9367
nut-bolt	54	0.8333	0.1415	0.7476	0.919
rivet	8	1	0	1	1

screw	489	0.9816	0.0181	0.9716	0.9916
solder	16	0.875	0.1167	0.7253	1.0247
pulley	7	1	0	1	1
digital display	1	1	0	1	1
indicator light	16	0.875	0.1167	0.7253	1.0247

RELATIVE COST OF THIN-WALL COMPONENT TAXONOMY TERMS

Average product of basic and subsidiary injection molding costs per component taxonomy term.

Component	Count	Average
actuator	7	2.1962
belt	1	1.2500
bracket	5	3.2295
Brancher	1	2.0500
cap	10	2.4312
carousel	1	4.4280
changer	26	2.4038
Channeler	52	4.9910
clamp	2	2.0000
Connector	3	1.8000
Converter	7	2.9925
coupler	3	1.8000
Distributor	1	2.0500
electric switch	5	2.0772
fastener	1	1.6000
gear	15	2.2459
guiders	5	2.0710
handle	8	4.3973
housing	39	5.8385
importer-exporter	39	5.8385
indicator	2	2.3560
knob	5	3.3145
latch release	2	2.4938
lens	3	1.2600
lever	8	3.1290
link	3	1.8683
Magnitude Controller	61	2.2361
mechanical transformer	15	2.2459
Nozzle	1	2.0500
nut-bolt	1	1.6000
output control signal	5	3.3145
output mechanical energy	2	2.1875
positioner	9	4.1364
regulator	1	3.9875
seal	12	1.5506
securer	5	3.2295
shaft	6	2.6331
Signaler	2	2.3560
stabilizer	12	2.2374
stop	4	2.2060
stopper	27	2.0201
support	12	2.2374

Supporter	26	3.0855
thermal insulator	1	2.8000
transferor	8	2.6846
tube	2	2.3750
valve	1	3.9875
visual indicator	2	2.3560
washer	1	2.0500
wheel	2	2.1875

Average likelihood that a component basis element is machined

Basis Name	Machined	Total	Chance Machined
abrasive	0	8	0
acoustic insulator	0	1	0
actuator	0	2	0
agitator	0	2	0
airfoil	0	14	0
analog display	0	1	0
auditory indicator	0	0	0
battery	0	42	0
bearing	2	18	0.111111111
belt	0	26	0
blade	4	34	0.117647059
bracket	0	51	0
brancher	0	0	0
buzzer	0	3	0
cam	1	9	0.111111111
cap	0	43	0
capacitor	0	7	0
carousel	0	3	0
changer	0	0	0
channeler	0	41	0
circuit board	0	52	0
clamp	5	41	0.12195122
clutch	0	4	0
condenser	0	2	0
connector	0	7	0
container	3	37	0.081081081
converter	0	16	0
coupler	0	14	0
cover	4	179	0.022346369
crank	0	1	0
cushion	0	15	0
digital display	0	1	0
diode	0	6	0
displacement gauge	0	2	0
distributor	1	2	0.5
divider	0	8	0
door	0	4	0
electric conductor	0	11	0
electric cord	0	33	0
electric motor	0	77	0
electric plate	0	3	0
electric resistor	0	12	0
electric socket	1	13	0.076923077
electric switch	1	128	0.0078125
electric wire	2	393	0.005089059

em sensor	0	2	0
energy supplier	0	2	0
extension	0	3	0
fan	0	24	0
fastener	1	29	0.034482759
flywheel	0	7	0
friction enhancer	0	18	0
gear	30	176	0.170454545
generator	0	1	0
guiders	21	206	0.101941748
handle	1	50	0.02
heat exchanger	1	12	0.083333333
heating element	0	26	0
hinge	7	32	0.21875
housing	7	403	0.017369727
hydraulic piston	2	11	0.181818182
hydraulic pump	3	10	0.3
ic motor	0	2	0
importer-exporter	0	0	0
indicator	0	4	0
indicator light	0	20	0
inductor	0	6	0
insert	2	16	0.125
key	1	24	0.041666667
knob	0	22	0
latch release	1	48	0.020833333
lens	0	9	0
lever	0	73	0
light source	0	12	0
link	20	83	0.240963855
magnet	0	4	0
magnitude controller	0	2	0
material filter	0	21	0
material supplier	0	0	0
mechanical transformer	0	4	0
mixer	0	2	0
needle	1	5	0.2
nozzle	0	13	0
nut-bolt	17	61	0.278688525
output acoustic energy	0	1	0
output control signal	0	0	0
output electrical energy	0	1	0
output electromagnetic energy	0	0	0
output hydraulic energy	0	0	0
output liquid material	0	0	0
output mechanical energy	0	1	0
output pneumatic energy	0	0	0
output thermal energy	0	2	0
pneumatic piston	0	3	0

pneumatic pump	0	1	0
positioner	6	63	0.095238095
pressure gauge	0	1	0
pressure vessel	0	3	0
processor	0	0	0
provisioner	0	0	0
pulley	1	9	0.111111111
rake	0	2	0
regulator	0	6	0
reservoir	1	40	0.025
retaining clip	0	12	0
rivet	0	9	0
rotational coupler	0	18	0
screen	0	3	0
screw	44	524	0.083969466
seal	0	66	0
securer	0	8	0
sensor	0	32	0
separator	0	0	0
shaft	29	117	0.247863248
signal filter	0	1	0
signaler	0	3	0
sled	3	23	0.130434783
solder	0	26	0
speaker	0	8	0
spring	1	150	0.006666667
sprocket	1	8	0.125
stabilizer	0	2	0
stop	3	34	0.088235294
stopper	0	2	0
stuffing	0	1	0
support	19	248	0.076612903
supporter	0	8	0
thermal conductor	1	1	1
thermal insulator	0	6	0
thermostat	0	4	0
transferor	0	2	0
transistor	0	15	0
tube	6	81	0.074074074
valve	1	14	0.071428571
visual indicator	0	7	0
washer	6	42	0.142857143
wheel	3	32	0.09375

APPENDIX C.

CONCEPTS FOR CASE STUDY

The following table presents the concepts analyzed and data produced for the case study.

Concept1	electric cord	electric switch	battery	electric wire	electric motor	link	wheel	electric switch	housing	reservoir	housing	blade				Total
std pts	0.9375	0.3874	0.6750	0.8839	0.9552	0.0658	0.4211	0.3874	0.0054	0.0714	0.0054	0.4000				0.4330
machining	0.0000	0.0078	0.0000	0.0051	0.0000	0.2410	0.0938	0.0078	0.0174	0.0250	0.0174	0.1176				0.0444
thin wall						1.8683	2.1875	2.0772	5.8384		5.8385					3.5620
count																25.4692
Concept 2	electric switch	electric resistor	electric wire	electric motor	link	circuit board	cap	coupler	shaft	gear	lever					Total
std pts	0.3874	0.6667	0.8839	0.9552	0.0658	0.0227	0.1316	0.9175	0.1009	0.4118	0.0870					0.4210
machining	0.0078	0.0000	0.0051	0.0000	0.2410	0.0000	0.0000	0.0000	0.2479	0.1705	0.0000					0.0611
thin wall	2.0772				1.8683		2.4312	1.8000	2.6331	2.2459	3.1290					2.3121
count																22.7377
Concept 3	battery	electric wire	electric cord	electric motor	link	handle	housing	lever	magnet	lever	housing	tube	cover			Total
std pts	0.6750	0.8839	0.9375	0.9552	0.0658	0.0638	0.0054	0.0870	0.3333	0.0870	0.0054	0.4000	0.0000			0.3461
machining	0.0000	0.0051	0.0000	0.0000	0.2410	0.0200	0.0174	0.0000	0.0000	0.0000	0.0174	0.0741	0.0223			0.0306
thin wall					1.8683	4.3973	5.8385	3.1290		3.1290	5.8385	2.3750				3.7965
count																29.4106
Concept 4	electric cord	electric wire	electric resistor	electric wire	electric motor	belt	hydraulic piston	housing	lever	housing	electric switch	sled	seal			Total
std pts	0.9375	0.8839	0.6667	0.8839	0.9552	0.7222	0.1429	0.0054	0.0870	0.0054	0.3874	0.0000	0.7000			0.4906
machining	0.0000	0.0051	0.0000	0.0051	0.0000	0.0000	0.1818	0.0174	0.0000	0.0174	0.0078	0.1304	0.0000			0.0281
thin wall						1.2500		5.8385	3.1290	5.8385	2.0772	0.0000	1.5506			2.8120
count																30.7520
Concept 5	housing	battery	electric switch	electric cord	electric motor	belt	clamp	support	electric switch	lever	spring	cover				Total
std pts	0.0054	0.6750	0.3874	0.9375	0.9552	0.7222	0.2000	0.1234	0.3874	0.0870	0.7234	0.0000				0.4337
machining	0.0174	0.0000	0.0078	0.0000	0.0000	0.0000	0.1220	0.0766	0.0078	0.0000	0.0067	0.0223				0.0217
thin wall	5.8385		2.0772			1.2500	2.0000	2.2374	2.0772	3.1290						2.6585
count																22.1721
Concept 6	electric cord	electric wire	electric resistor	electric wire	electric motor	link	sled	electric switch	housing	assembly	rotational coupler	shaft	seal	assembly	latch release	Total
std pts	0.9375	0.8839	0.6667	0.8839	0.9552	0.0658	0.0000	0.3874	0.0054	0.0000	0.0000	0.1009	0.7000	0.0000	0.1739	0.3840
machining	0.0000	0.0051	0.0000	0.0051	0.0000	0.2410	0.1304	0.0078	0.0174	0.0000	0.0000	0.2479	0.0000	0.0000	0.0208	0.0000
thin wall						1.8683		2.0772	5.8385			2.6331	1.5506		2.4938	2.7436

count																39.7157
Concept 7	battery	housing	electric motor	electric wire	shaft	electric switch	lever	spring	shaft	link	sled	seal				Total
std pts	0.6750	0.0054	0.9552	0.8839	0.1009	0.3874	0.0870	0.7234	0.1009	0.0658	0.0000	0.7000				0.3904
machining	0.0000	0.0174	0.0000	0.0051	0.2479	0.0078	0.0000	0.0067	0.2479	0.2410	0.1304	0.0000				0.0753
thin wall		5.8385			2.6331	2.0772	3.1290		2.6331	1.8683		1.5506				2.8185
count																27.7833
Concept 8	electric cord	electric wire	electric resistor	heating element	electric cord	electric motor	link	lever	housing	guiders	flywheel	clamp	nut-bolt	blade	gear	Total
std pts	0.9375	0.8839	0.6667	0.0588	0.9375	0.9552	0.0658	0.0870	0.0054	0.2474	0.3333	0.2000	0.8333	0.4000	0.4118	0.4682
machining	0.0000	0.0051	0.0000	0.0000	0.0000	0.0000	0.2410	0.0000	0.0174	0.1019	0.0000	0.1220	0.2787	0.1176	0.1705	0.0000
thin wall							1.8683	3.1290	5.8385	2.0710		2.0000	1.6000		2.2459	2.6790
count																29.9342
Concept 9	electric switch	battery	electric wire	electric cord	electric motor	shaft	clamp	housing	reservoir	material filter	guiders	handle	housing	cover		Total
std pts	0.3874	0.6750	0.8839	0.9375	0.9552	0.1009	0.2000	0.0054	0.0714	0.2105	0.2474	0.0638	0.0054	0.0000		0.3388
machining	0.0078	0.0000	0.0051	0.0000	0.0000	0.2479	0.1220	0.0174	0.0250	0.0000	0.1019	0.0200	0.0174	0.0223		0.0419
thin wall	2.0772					2.6331	2.0000	5.8385			2.0710	4.3973	5.8385			3.5508
count																30.2386
Concept 10	housing	battery	electric wire	electric motor	belt	gear	housing	tube	friction enhancer	spring	housing	tube	material filter			Total
std pts	0.0054	0.6750	0.8839	0.9552	0.7222	0.4118	0.0054	0.4000	0.1250	0.7234	0.0054	0.4000	0.2105			0.4249
machining	0.0174	0.0000	0.0051	0.0000	0.0000	0.1705	0.0174	0.0741	0.0000	0.0067	0.0174	0.0741	0.0000			0.0294
thin wall	5.8385				1.2500	2.2459	5.8385	2.3750			5.8385	2.3750				3.6802
count																32.4798
Concept 11	housing	battery	electric switch	electric cord	electric motor	belt	latch release	gear	positioner	coupler	cover	stop				Total
std pts	0.0054	0.6750	0.3874	0.9375	0.9552	0.7222	0.1739	0.4118	0.5714	0.9175	0.0000	0.3529				0.5092
machining	0.0174	0.0000	0.0078	0.0000	0.0000	0.0000	0.0208	0.1705	0.0952	0.0000	0.0223	0.0882				0.0352
thin wall	5.8385		2.0772			1.2500	2.4938	2.2459	4.1364	1.8000		2.2060				2.7560
count																24.4908
Concept 12	electric wire	battery	housing	electric cord	electric motor	shaft	sled	electric switch	housing	container	spring	friction enhancer	tube			Total
std pts	0.8839	0.6750	0.0054	0.9375	0.9552	0.1009	0.0000	0.3874	0.0054	0.1250	0.7234	0.1250	0.4000			0.4095
machining	0.0051	0.0000	0.0174	0.0000	0.0000	0.2479	0.1304	0.0078	0.0174	0.0811	0.0067	0.0000	0.0741			0.0452
thin wall			5.8385			2.6331		2.0772	5.8385				2.3750			3.7525
count																29.2357
Concept 13	housing	battery	electric	electric	shaft	hydraulic	housing	container	spring	housing	stop	housing	shaft			Total

			wire	motor		piston										
std pts	0.0054	0.6750	0.8839	0.9552	0.1009	0.1429	0.0054	0.1250	0.7234	0.0054	0.3529	0.0054	0.1009			0.3140
machining	0.0174	0.0000	0.0051	0.0000	0.2479	0.1818	0.0174	0.0811	0.0067	0.0174	0.0882	0.0174	0.2479			0.0714
thin wall	5.8385				2.6331		5.8385			5.8385	2.2060	5.8385	2.6331			4.4037
count																32.2377
Concept 14	electric wire	electric resistor	electric wire	electric motor	link	housing	electric switch	guiders	flywheel	clamp	spring	blade				Total
std pts	0.8839	0.6667	0.8839	0.9552	0.0658	0.0054	0.3874	0.2474	0.3333	0.2000	0.7234	0.4000				0.4794
machining	0.0051	0.0000	0.0051	0.0000	0.2410	0.0174	0.0078	0.1019	0.0000	0.1220	0.0067	0.1176				0.0520
thin wall					1.8683	5.8385	2.0772	2.0710		2.0000						2.7710
count																28.1847
Concept 15	electric switch	battery	housing	electric motor	electric wire	shaft	cover	electric switch	shaft	support	positioner	hinge	handle			Total
std pts	0.3874	0.6750	0.0054	0.9552	0.8839	0.1009	0.0000	0.3874	0.1009	0.1234	0.5714	0.3846	0.0638			0.3569
machining	0.0078	0.0000	0.0174	0.0000	0.0051	0.2479	0.0223	0.0078	0.2479	0.0766	0.0952	0.2188	0.0200			0.0744
thin wall	2.0772		5.8385			2.6331		2.0772	2.6331	2.2374	4.1364		4.3973			3.2538
count																28.9066
Concept 16	electric cord	electric wire	electric resistor	electric wire	electric motor	shaft	handle	housing	tube	housing	coupler	wheel	coupler	housing		Total
std pts	0.9375	0.8839	0.6667	0.8839	0.9552	0.1009	0.0638	0.0054	0.4000	0.0054	0.9175	0.4211	0.9175	0.0054		0.5117
machining	0.0000	0.0051	0.0000	0.0051	0.0000	0.2479	0.0200	0.0174	0.0741	0.0174	0.0000	0.0938	0.0000	0.0174		0.0356
thin wall						2.6331	4.3973	5.8385	2.3750	5.8385	1.8000	2.1875	1.8000	5.8385		3.6343
count																34.8714
Concept 17	electric wire	electric resistor	electric wire	electric cord	electric motor	link	housing	stop	housing	spring	container	seal				Total
std pts	0.8839	0.6667	0.8839	0.9375	0.9552	0.0658	0.0054	0.3529	0.0054	0.7234	0.1250	0.7000				0.5254
machining	0.0051	0.0000	0.0051	0.0000	0.0000	0.2410	0.0174	0.0882	0.0174	0.0067	0.0811	0.0000				0.0385
thin wall						1.8683	5.8385	2.2060	5.8385			1.5506				3.4604
count																30.0413
Concept 18	battery	housing	electric cord	electric motor	belt	lever	latch release	housing	tube	clamp	housing					Total
std pts	0.6750	0.0054	0.9375	0.9552	0.7222	0.0870	0.1739	0.0054	0.4000	0.2000	0.0054					0.3788
machining	0.0000	0.0174	0.0000	0.0000	0.0000	0.0000	0.0208	0.0174	0.0741	0.1220	0.0174					0.0245
thin wall		5.8385			1.2500	3.1290	2.4938	5.8385	2.3750	2.0000	5.8385					3.5954
count																23.0581
Concept 19	battery	electric switch	electric cord	electric motor	belt	cover	electric switch	housing	container	spring	housing	hydraulic piston	seal			Total
std pts	0.6750	0.3874	0.9375	0.9552	0.7222	0.0000	0.3874	0.0054	0.1250	0.7234	0.0054	0.1429	0.7000			0.4436
machining	0.0000	0.0078	0.0000	0.0000	0.0000	0.0223	0.0078	0.0174	0.0811	0.0067	0.0174	0.1818	0.0000			0.0263

thin wall		2.0772			1.2500		2.0722	5.8385			5.8385		1.5506			3.1045
count																24.5921
Concept 20	battery	electric switch	electric cord	electric motor	shaft	gear	latch release	carousel	shaft	carousel						Total
std pts	0.6750	0.3874	0.9375	0.9552	0.1009	0.4118	0.1739	0.0000	0.1009	0.0000						0.3743
machining	0.0000	0.0078	0.0000	0.0000	0.2479	0.1705	0.0208	0.0000	0.2479	0.0000						0.0695
thin wall		2.0772			2.6331	2.2459	2.4938	4.4280	2.6331	4.4280						2.9913
count																15.8556
Concept 21	electric switch	battery	housing	electric cord	electric motor	link	lever	latch release	gear	positioner	support					Total
std pts	0.3874	0.6750	0.0054	0.9375	0.9552	0.0658	0.0870	0.1739	0.4118	0.5714	0.1234					0.3994
machining	0.0078	0.0000	0.0174	0.0000	0.0000	0.2410	0.0000	0.0208	0.1705	0.0952	0.0766					0.0572
thin wall	2.0722		5.8385			1.8683	3.1290	2.4938	2.2459	4.1364	2.2374					3.0027
count																23.5362
Concept 22	housing	battery	electric wire	electric motor	link	circuit board	housing	lever	spring	lever	magnet					Total
std pts	0.0054	0.6750	0.8839	0.9552	0.0658	0.0227	0.0054	0.0870	0.7234	0.0870	0.3333					0.3495
machining	0.0174	0.0000	0.0051	0.0000	0.2410	0.0000	0.0174	0.0000	0.0067	0.0000	0.0000					0.0261
thin wall	5.8385				1.8683		5.8385	3.1290		3.1290						3.9607
count																25.3238
Concept 23	housing	battery	electric switch	electric wire	electric motor	link	hydraulic piston	housing	clamp	housing	latch release	handle				Total
std pts	0.0054	0.6750	0.3874	0.8839	0.9552	0.0658	0.1429	0.0054	0.2000	0.0054	0.1739	0.0638				0.2970
machining	0.0174	0.0000	0.0078	0.0051	0.0000	0.2410	0.1818	0.0174	0.1220	0.0174	0.0208	0.0200				0.0542
thin wall	5.8385		2.0772			1.8683		5.8385	2.0000	5.8385	2.4938	4.3973				3.7940
count																27.8233
Concept 24	battery	electric switch	electric wire	electric motor	link	electric switch	guiders	flywheel	clamp	housing	blade					Total
std pts	0.6750	0.3874	0.8839	0.9552	0.0658	0.3874	0.2474	0.3333	0.2000	0.0054	0.4000					0.4128
machining	0.0000	0.0078	0.0051	0.0000	0.2410	0.0078	0.1019	0.0000	0.1220	0.0174	0.1176					0.0564
thin wall		2.0772			1.8683	2.0772	2.0710		2.0000	5.8385						2.6554
count																23.0095
Concept 25	housing	battery	electric wire	electric cord	electric motor	shaft	latch release	housing	guiders	flywheel	guiders	housing	lever	friction enhancer		Total
std pts	0.0054	0.6750	0.8839	0.9375	0.9552	0.1009	0.1739	0.0054	0.2474	0.3333	0.2474	0.0054	0.0870	0.1250		0.3416
machining	0.0174	0.0000	0.0051	0.0000	0.0000	0.2479	0.0208	0.0174	0.1019	0.0000	0.1019	0.0174	0.0000	0.0000		0.0378
thin wall	5.8385					2.6331	2.4938	5.8385	2.0710		2.0710	5.8385	3.1290			3.7392
count																33.3376

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