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ANALYSIS OF PRODUCT FLEXIBILITY FOR FUTURE EVOLUTION BASED ON DESIGN GUIDELINES AND A HIGH-DEFINITION DESIGN STRUCTURE MATRIX

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ABSTRACT

The design of a product determines the flexibility of that product for future evolutions, which may arise from a variety of change modes such as new market needs or technological change. The energy, material, and information exchanged between components of a product along with the spatial relationships and movement between those components all influence the ability of that product's design to be evolved to meet the new requirements of a future generation. Previous work has produced a set of guidelines for product flexibility for future evolution that have been shown to improve the ability of a design to be adapted when new needs arise. Although these guidelines are conceptually easy to understand, it is difficult to assess the extent to which a product follows the guidelines. This paper presents a systematic method to analyze the flexibility for future evolution of products based on selected guidelines. The High-Definition Design Structure Matrix is presented as a product representation model which captures sufficient interaction information to highlight potential design improvements based on the aforementioned guidelines. An interaction basis is used to facilitate the consistency and comparison of HD-DSM models created by different examiners and/or for different systems. The selected guidelines are interpreted in terms of the HD-DSM by creating analysis processes that relate to the characteristics described by the guideline. Two similar power screwdrivers are compared for flexibility for future evolution based on a quantitative analysis of their respective HD-DSMs.

1. INTRODUCTION

When market needs require a new product, the first response of a company may be to leverage its existing resources by *evolving* the design of a previous product to meet the new needs. This process will be facilitated if the current product has characteristics that make it flexible for future evolution. Flexibility is different from other types of product variety for which required product variations are known and can be planned. For example in product family design, product variants are selected to meet a range of market segments [1]. While product families address a variety of market needs with distinct product options, other strategies focus on meeting variable requirements with a single product or system. Changeable systems are defined as "those systems whose configurations can be changed, altered, or modified with or without external influence after the system has been deployed" [2]. The focus of flexibility for future evolution is different; it is intended to reduce the redesign effort required for addressing evolutionary changes that may not be anticipated or precisely defined during the design of the original product [3].

Through empirical studies of products and patents, a list of guidelines has been created that are intended to increase a product's flexibility for future evolution (Appendix A) [4]. The design of a product that implements these guidelines should be more easily reused, updated, or evolved to meet a set of unforeseen future needs. These guidelines have been found to be useful for evaluating and designing industrial products [3].

Qualitative tools have been presented to analyze the flexibility of a product for future evolutions. In a Change Modes and Effects Analysis (CMEA) table, a set of predicted change modes are used to evaluate a product's flexibility for future evolution [3, 4]. The design flexibility, likelihood of occurrence, and manufacturing readiness are rated individually and then combined to obtain the change potential number for each change mode. This information can be used to draw attention to problematic change modes or to assess the overall evolvability of a design. However, these tools are influenced by the examiner's redesign capabilities and familiarity with the guidelines. This paper lays the groundwork for a more systematic method to identify the extent to which are embodied in a product design.

There is a relationship between a product's flexibility and its architecture [5-8]. The architecture of a product is determined by the mapping of necessary functions to the physical components within the product and the interactions between those components [8]. Therefore, to assess the flexibility of a design, it is necessary to understand the interactions of the parts that make up the system. For example, some of the guidelines for flexibility for future evolution, such as Guidelines 6 and 18 in Appendix A, require the distinction between different types of energy, material, or signals.

In this paper, product flexibility for future evolution is analyzed by relating the guidelines in Appendix A to a product architecture representation called the High-Definition Design Structure Matrix (HD-DSM). Section 2 reviews related work on the Design Structure Matrix (DSM), which is commonly used for product architecture representation. The High-Definition Design Structure Matrix (HD-DSM) is defined in Section 3 as a standard model for the analysis of product flexibility for future evolution. Section 4 addresses the process of creating an HD-DSM by assigning parts to subsystems during product disassembly and then merging the subsystem models. Two different power screwdrivers are compared in Section 5 by analyzing their HD-DSMs based on five selected guidelines.

2. RELATED WORK

The Design Structure Matrix (DSM) is a product representation tool that is widely used for a variety of purposes. Browning et al. provide a review of DSM methods and applications in various fields of research [9]. The component-based DSM is one particular type in which the components of a system are listed across both the rows and columns of a square matrix. A mark in the cell of the matrix indicates that there is an interaction between the components. Generally, a mark can be interpreted such that the component in the row of the matrix in some way depends on the component in the particular column. For this reason, some researchers also refer to a DSM as a Dependency Structure Matrix. Other terms used in literature are an N^2 diagram, adjacency matrix, "dependency source matrix, dependency map, interaction matrix, incidence matrix, precedence matrix, and others [9]."

The information content of a DSM is tailored to the intended objective. We recognize this information content as the combined level of detail along three independent axes as shown in Figure 1. The "Element Detail" of a DSM ranges from an abstract representation of major subsystems within the product to an exhaustive list of every individual part within the system. The "Interaction Detail" of a DSM can range from a single overall interaction to a DSM containing multiple layers, each of which captures a specific type of interaction. The "Judgment Detail" of a DSM falls into three categories. At the simplest level, a binary DSM is created in which the people creating the DSM must make only a *judgment of existence*. At the next level, a *judgment of significance* is made in an attempt to prevent unimportant interactions from confusing the analysis. At the most detailed level, a *judgment of consequence* is made in which not only the significance of an interaction is recorded, but also the desirability of an interaction.

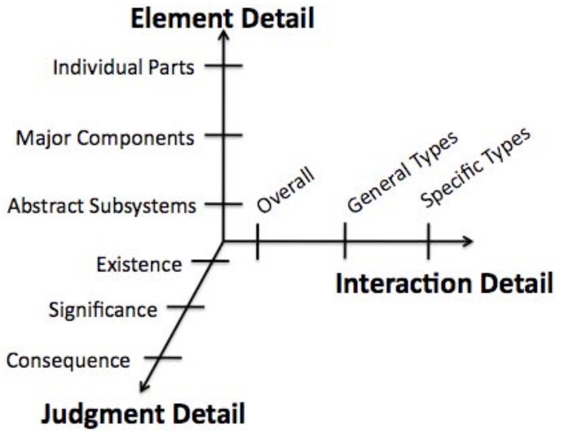


Figure 1: Information Content Space of DSM

The magnitude of information contained in a DSM is represented by its distance to the origin in the information content space in Figure 1. This directly correlates to the data structure required to record the DSM. The level of Element Detail determines the dimensions of the square matrix as shown in Figure 2. This can be quantified as the percentage of elements used to represent the total quantity of parts in the system. The level of Interaction Detail determines the length of the vector contained in each cell of the DSM. This can also be thought of as creating layers of matrices (Figure 2), each containing one specific type of interaction. The level of Judgment Detail determines the type of variable contained in each individual cell. A Boolean variable is sufficient for

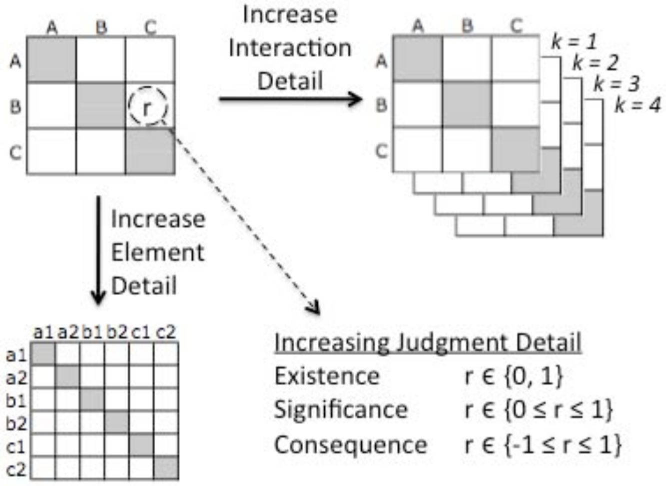


Figure 2: Element, Interaction, and Judgment Detail

recording the existence of an interaction. The significance of an interaction requires a range of positive integers or ratios and the consequence of an interaction requires both positive and negative numbers.

An important and necessary inference to draw from Figure 1 is that the information content of a DSM can always be decreased by projecting it to a lower level of detail along one or multiple axes. In Figure 3, the approximate information content of component DSMs from related works are plotted on the Element Detail-Interaction Detail plane. The plot is based on the level of detail in published examples. The majority of research involving DSMs rests in the lower left corner with abstract system components and just a few general types of interactions. These papers are focused on understanding the product architecture and its relationship to the product development process. Each author shows that the information content they use is appropriate for addressing their stated objectives. There are a handful of examples that are not in the lower left corner. Interestingly, the key objectives of these papers are more focused on creating variety within a product family. In all of these examples, an abstract DSM does not contain enough information to manage the product variety objectives of the authors. Suh, Alizon, and Hsiao and their respective coauthors increase the information content of the DSM by increasing the Element Detail [10-12]. Martin and Ishii use abstract elements in their coupling matrix, but increase the Interaction Detail of the DSM by recording all the different types of specifications in the product [7]. Cormier et al. are an exception to this trend in that they study the flows between abstract subsystems for the purpose of quantifying the system's flexibility for mass customization [13].

Research on product architecture uses clustering algorithms to arrange the components in a DSM in such a way that distinct modules exist such that the internal interactions within components of a module are greater than the interactions of that module with other components and modules in the system. This information can then be used to define subsystems in the actual product and to organize product development teams. Visually, a clustered DSM will contain blocks of interactions along the diagonal. Holtta et al. study the tradeoff between modularity and performance by comparing DSMs of products with opposing requirements [14].

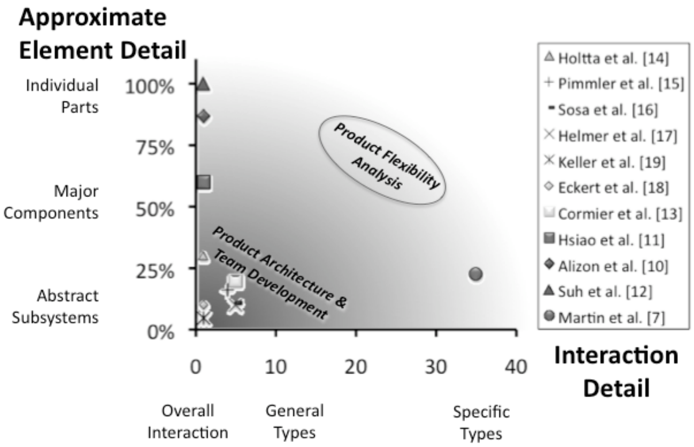


Figure 3: Information Content used in related work

Pimmler and Eppinger use a component-based DSM to decompose and analyze an automatic climate control system [15]. They consider four generic types of interactions between different components as being energy, material, information, and spatial interactions. By clustering the elements based on the material interactions, they improve the system's design and improve the management of the design task. Sosa, Eppinger, and Rowles extend the four generic interaction types to include "structural" as a fifth type of interaction in their study of a design interface matrix and team interaction matrix for a jet engine [16]. Helmer et al. propose an approach to aggregate these five types of interactions in order to efficiently identify clusters and solve the heterogeneity of the interactions [17]. The research presented in this paper is different because we are not trying to recognize the "optimal" clusters for a single product's design.

The creation of product variety is aided by using a DSM to recognize common product platforms and components that can be easily varied to create distinct product options. Martin and Ishii use a DSM-style "coupling matrix" to study the specifications between the components in a water cooler product to manage variety in subsequent product offerings [7]. By reducing the overall coupling index, they show the design can be more easily varied to meet the customer objectives for product variants. Hsiao and Liu study the interactions between the parts in a drip coffee maker to manage the variety between different products in a product family [11]. Alizon et al. stack the DSMs of variants in a product family to recognize common interactions and modules for the purpose of better managing their variety [10].

Research in change propagation studies the interconnection of elements in a DSM. Eckert et al. discuss the roles elements have as change multipliers, carriers, or absorbers in terms of change propagation [18]. Keller et al. describe tools for visualizing change propagation data such as the network diagram [19]. Suh, de Weck, and Chang use a DSM-style "change propagation matrix" to create a flexible platform for an automotive structural frame that can be used in different market segments [12].

For objective product analysis based on the evaluation and application of guidelines, the information content of a DSM product representation needs to be increased along both the Element Detail and Interaction Detail axes, creating a High-Definition Design Structure Matrix (HD-DSM). As can be seen in Figure 3, this region of the information content space and its benefits have not yet been explored. A deterrent to capturing this high definition of component and interaction information may be the effort involved in gathering the required information. However, in the following sections, a standard basis for component interactions is developed that allows comparison across systems and subsystems. By considering a standard set of interactions, the model creation task can be distributed among different examiners for very large systems.

3. THE HD-DSM AND THE INTERACTION BASIS

The HD-DSM is a three dimensional array that is a detailed representation of how elements in a complex system interact. It is essentially a layered collection of DSMs that are each based on a specific type of interaction. A standard interaction basis is required in order to develop methods and tools that allow for the creation of a HD-DSM and analysis of design guidelines.

The interaction layers of the HD-DSM are defined by the interaction basis presented in Table 1. This list of specific interactions is an extension of the general interactions presented in other DSM related research [15, 17] and the flow set of the reconciled functional basis [20]. In the simplest form of a DSM, overall interaction is captured by a binary assessment of whether any interaction exists between a pair of components. In task-based DSMs it has been noted that "the binary matrix is often crowded with weak dependencies, and this leads to an extremely coupled design matrix" [21]. By creating a standard interaction basis, the distinction between different types of element dependencies can be seen while still only requiring a judgment of existence to be made by the examiner.

Table 1: Interaction Basis for HD-DSM

General	Specific	Abbr.
Information[1,2]	Status[1]	SI
	Control[1]	CI
Material[1,2]	Human[1]	HM
	Gas[1]	GM
	Liquid[1]	LM
	Solid[1]	SM
	Plasma[1]	PM
	Mixture[1]	MM
Energy[1,2]	Human[1]	HE
	Acoustic[1]	AE
	Biological[1]	BE
	Chemical[1]	CE
	Electrical[1]	EE
	Electromagnetic[1]	EME
	Hydraulic[1]	HYE
	Mechanical[1]	ME
	Magnetic[1]	MAG
	Pneumatic[1]	PE
	Radioactive[1]	NE
	Thermal[1]	TE
	Strain Energy	SE
Spatial[2]	Proximity	P
	Alignment	A
Movement	Translational	LRM
	Rotational	RRM

[1]-Used in flow set of functional basis [20]
[2]-Used in related DSM research (such as [15, 17])

Many of the interaction types listed in Table 1 have been used and defined in previous literature. The reconciled functional basis is a common language for functional modeling. It represents a standard vocabulary of functional modeling related terms that is intended to reduce ambiguity in functional models, facilitate comparison across functional models for different products, and increase uniformity of information across models created by different researchers [20]. The primary and secondary classes of the reconciled flow set define specific interactions between elements in a functional model. At the primary level, the flows in functional modeling are signal, material, and energy. The secondary class of the flow set provides a more detailed list of these types of flows as shown. Hirtz et al. offer a complete description of the terms indicated in Table 1 [20].

The flow set from the functional basis is not sufficient to describe the interactions between physical products because functional models are intentionally created independently of product form. Pimmler and Eppinger define a spatial-type interaction as "needs for adjacency or orientation between two elements" [15]. Similarly, in Table 1, the specific interactions of the spatial type are extended to proximity and alignment. Proximity simply identifies that the two elements are physically close to each other. A criterion for proximity is that if any dimension of the component is increased by a reasonable fraction it will contact the corresponding component. An interaction of alignment means that an element determines the location or path of the corresponding element.

Proximity is a necessary but not sufficient condition of two components that are in contact. Strain energy is introduced to represent the potential of two components that are in contact with each other to remain in contact. This concept can be illustrated by a well-designed bolted connection of two plates. In this simple type of connection, the shear load is carried not by the bolt, but by the surface of the plates, which are pressed together by the bolt tension. The plates will remain in contact as long as the external loads do not exceed the preload. It is common to think of the bolt as a spring pulling the plates together, but less intuitive to understand that the plates are also in elastic deformation and have an equal amount of potential strain energy. This same type of energy is present with any two components that are pressed together. Therefore, proximity along with strain energy is sufficient to capture the structural connections of elements.

Movement between components is the fifth type of general interaction. The specific types of movement may be translational relative movement or rotational relative movement. Although movement has not been included as a type of interaction in related research, it is found to be important in this research for better understanding the complete interactions between components. For example, the gears in a transmission are 'connected' in a sense, but that connection is much different from the connection of two beams because the gears are in motion.

4. CREATING A HD-DSM MODEL FOR A PRODUCT

The process of creating a High-Definition Design Structure Matrix (HD-DSM) is presented using a consumer product as an example. The Black & Decker Alkaline Power Screwdriver (Figure 4) is a simple consumer power tool that allows users to select a forward or reverse direction to drive screws. The device is powered by replaceable AA batteries. A bill of materials is included in Appendix B. Although this complex system is of a relatively small scale, it is of reasonable size for explaining the modeling procedure and showing the use of the HD-DSM. The methods and benefits of the HD-DSM are expected to be relevant for complex systems of any scale.

4.1 System element HD-DSM

The model is first created at the system level using subsystems as elements. The subsystems are then modeled separately and inserted into the system model. In this process, the subsystems are assumed to be recognized during the disassembly of the product (Figure 4) and are assigned on the BOM (Appendix B). The final, complete HD-DSM, which lists each part as an element of the model, will be the same regardless of the assigned subsystems.

Figure 4: Black & Decker Alkaline Power Screwdriver

Step 1: Define the HD-DSM model's scope

When creating a model, it is necessary to explicitly define the state of operation that the model covers. If necessary, creating an activity diagram for the product will illuminate different states that may be of interest. Two primary activities for the power screwdriver are 1) use tool to drive screws and 2) remove battery holder to replace AA batteries. These two activities will happen many times during the tool's lifetime. Both of these activities put parts of the product in relative motion. This HD-DSM will consider both activities in a quasi-static state.

Step 2: Select Elements to be used in HD-DSM

The Black & Decker screwdriver will be modeled first at the system level. The six subsystems selected are listed below along with an 'External' element. The 'External' element is used to capture all of the system's interactions with its surroundings.

1. Bit
2. Transmission
3. Motor
4. Electrical System
5. Battery Holder
6. Case
7. External

The Bill of Materials created during disassembly indicated a total quantity of 42 parts. Since this system-level HD-DSM uses 6 elements to represent all 42 parts it is at 14% relative element detail (6/42 = 0.14). As the subsystems are modeled and expanded, the percent of relative element detail will be increased to 100%.

Step 3: Create an Element Black-Box model for each element

A black box model is used to understand the overall function of a product. The black box model shows how the "materials, energies, and signals are transformed by the design system into desired outputs" [22]. In the Element Black Box, the inputs and outputs of a particular element are defined in terms of the interaction basis presented in Table 1. Graphically, the element black box can be drawn as shown in Figure 5. The additional interactions discussed in Section 3 are added to the black box model on the top and bottom of the box. Figure 6 shows the element black boxes for the screwdriver's subsystems. Inputs and outputs that cross the system boundary are highlighted in gray. These represent interactions with the 'External' element in the HD-DSM.

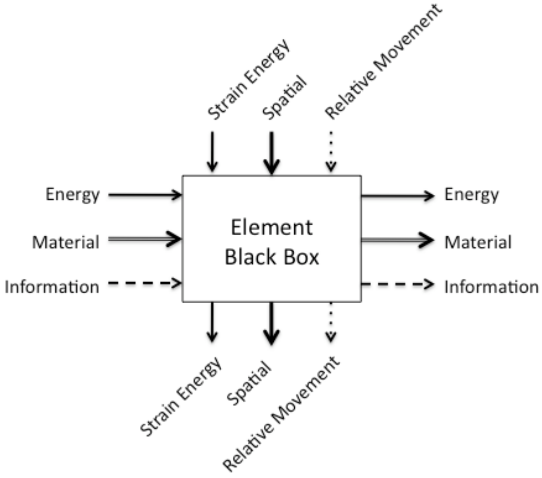


Figure 5: Generic Element Black Box

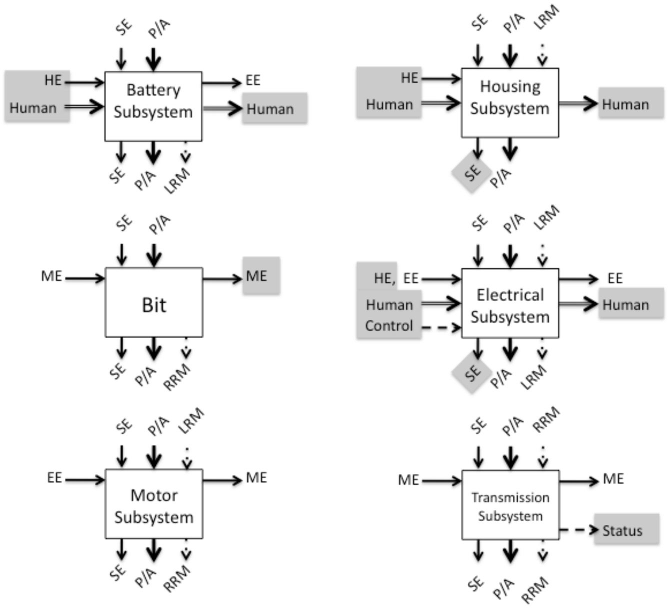


Figure 6: Element black boxes for screwdriver subsystems

Step 4: Fill in HD-DSM

The HD-DSM can be filled in by comparing the element black boxes for all the elements in the HD-DSM. In the Black & Decker screwdriver, eleven of the 25 basis interactions are identified between the subsystems. For each of these interactions, a DSM matrix is created which constitutes one 'layer' of the HD-DSM as shown in Figure 7. The remaining fourteen layers of interaction are empty for this product. Even at this abstract level of part representation, the additional interactions captured by the HD-DSM offer information that can be related to the guidelines for flexibility for future evolution. Examples include identification of the subsystems that are near the exterior of the device or the subsystems that perform functions on the same energy domain.

4.2 Expand HD-DSM by merging subsystems

Each of the elements in the current system HD-DSM represents a subsystem of the Black & Decker power screwdriver. In the physical product, each of these subsystems contains a number of actual parts. The steps for expanding an abstract HD-DSM are illustrated by focusing on the single layer of proximity interaction for the 'transmission' subsystem.

Step 1: Create subsystem HD-DSM

The HD-DSM for each subsystem is created by following the steps in Section 4.1. The elements of each subsystem are the parts assigned to that subsystem in the bill of materials along with an 'External' element. The 'External' element is used to indicate interactions between parts of this subsystem and other subsystems or things outside the system.

Step 2: Identify the system-level placeholder

Each subsystem is represented by an abstract 'placeholder' in the system HD-DSM. The 'Transmission' placeholder is highlighted in Figure 8a.

Step 3: Identify intra-subsystem interactions

The interactions between elements within the subsystem remain unchanged when considering them as part of the whole system. The intra-subsystem interactions of the transmission subsystem are highlighted in Figure 8b.

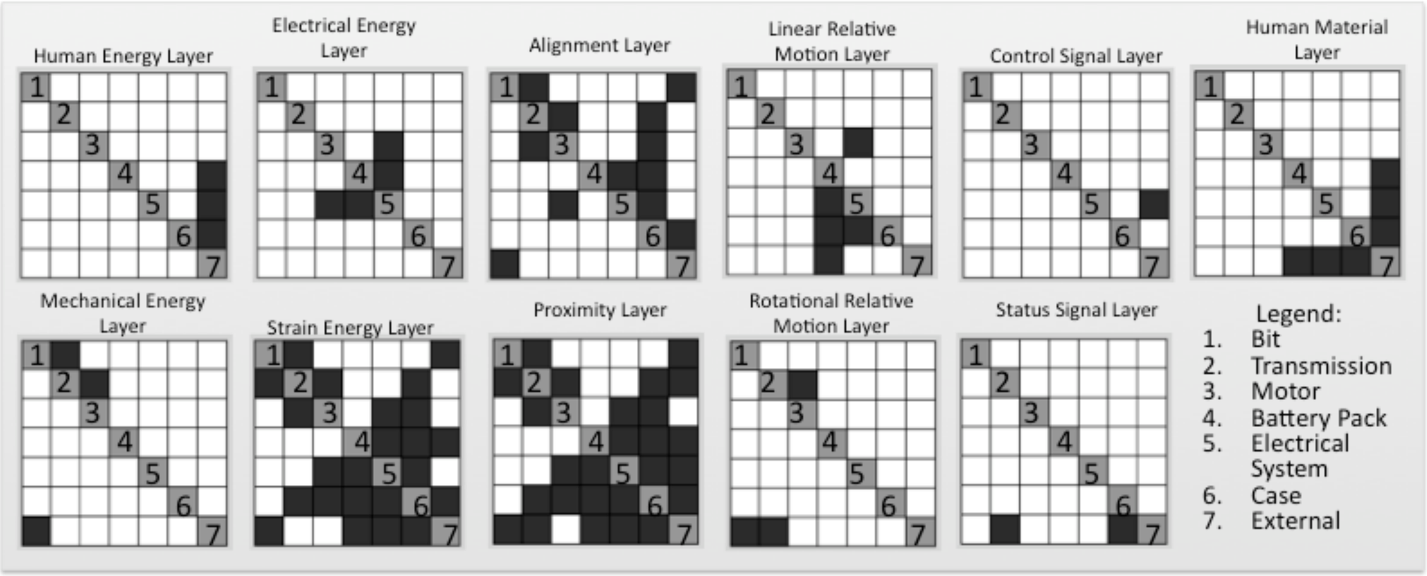


Figure 7: The data recorded in the HD-DSM of the B&D Screwdriver at the abstract, system level

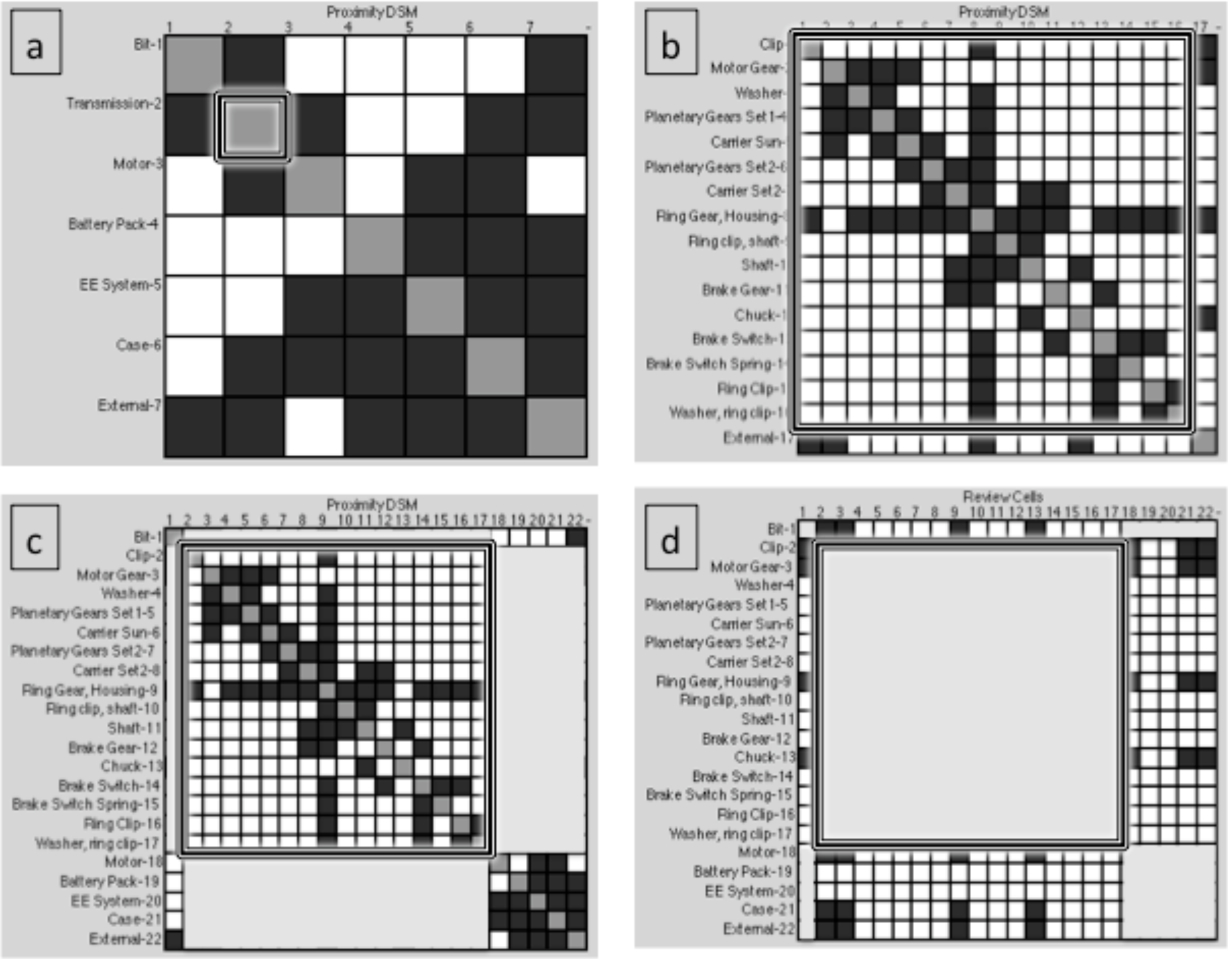


Figure 8: Transmission subsystem insertion for proximity interactions

Step 4: Insert subsystem into placeholder's diagonal cell

The diagonal cell of the placeholder element in the system HD-DSM is replaced by the intra-subsystem interactions as shown in Figure 8c. The blank space to each side of the inserted subsystem must now be filled in with the interactions of the subsystem elements with other system elements.

Step 5: Identify possible system interactions with new elements

The possible new system interactions can be partially automated using the interactions of the original system placeholder element and the external interactions of the subsystem HD-DSM. For example, in Figure 8a, the 'Transmission' placeholder element in row 2 and column 2 is shown to be in proximity with the 'Case' element in row 6 and column 6. In the subsystem HD-DSM in Figure 8b, the 'Clip' element in row 1 and column 1 is shown to be in proximity with things external to the subsystem. Therefore, it can be inferred that the 'Clip' element of the transmission subsystem may be in proximity to the 'Case' element of the system. Similarly, the 'Clip' may also be in proximity to the 'Motor' and 'Bit' since these system elements are marked as being in proximity with the 'Transmission' placeholder element (Figure 8a) but it definitely will not be in proximity to the 'Battery Pack.'

Step 6: Review system interactions

The person examining the system can review the possible new system interactions created in the previous step to determine which interactions truly exist in the product. Continuing with the previous example, examination of the product would confirm that the 'Clip' element of the transmission is indeed proximal to the 'Case' element. It is also indicated in Figure 8d that the 'Clip' could be proximal to the 'Motor' element. However, examination of the product shows this not to be true.

In this example, there are 16 element pairs that need to be reviewed as shown by the filled-in cells in Figure 8d. By inferring which interactions are possible, the manual examination of an additional 80 element pairs is avoided.

Steps 1-5 described above can be easily automated simultaneously across all interaction layers of the HD-DSM. The author created a HD-DSM for the Black & Decker Alkaline Power Screwdriver at 74% element detail, meaning that each of the 32 parts on the bill of materials has a corresponding element in the final HD-DSM. (Total quantity of parts is 42 when duplicate parts are counted.) Using appropriate software functions created in Matlab, this task was performed in less than a day. The process of inferring and reviewing possible interactions through merging subsystems reduced the overall number of element pairs to be manually evaluated by 52%. A further advantage of this method is the possibility of distributed modeling in which each subsystem of a complex system could be modeled, in detail, by persons familiar with the subsystem.

5. ANALYSIS AND COMPARISON OF PRODUCT FLEXIBILITY FOR FUTURE EVOLUTION

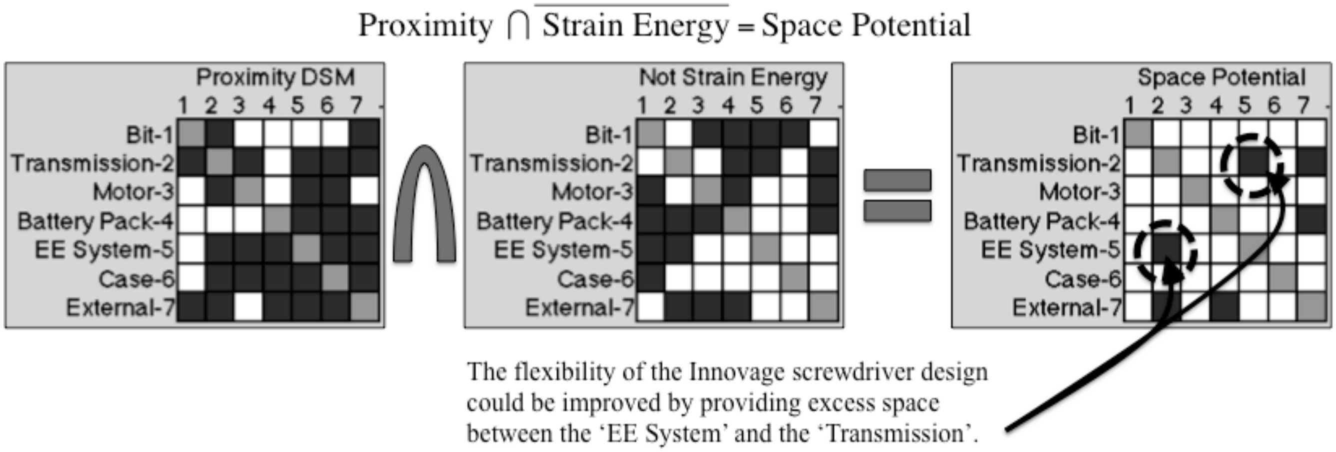
By relating the information in the HD-DSM to the design guidelines for flexibility for future evolution, a tool is created to compare the flexibility for future evolution of different products. The Black and Decker Power Screwdriver discussed earlier is compared to an Innovage Power Screwdriver to determine which design is more flexible for future evolution. Both products use four replaceable AA batteries and have a feature that allows them to be used as manual screwdrivers. The bill of materials (BOM) for each product is included in Appendix B. A HD-DSM, which includes each part on the BOM as an element, was created for each screwdriver as discussed in Section 4. This section discusses the specific analysis done based on each selected guideline along with the results for each product. The actual analysis was performed by an automated function which was applied equally to each product's HD-DSM.

Table 2 lists five selected guidelines that are used to compare the flexibility for future evolution of the two products. The number in the table corresponds to the numbered list of guidelines in Appendix A. The guidelines are explained and justified in detail in previous work [4].

Table 2: Selected Guidelines for Flexibility Analysis

Number	Guideline
9	Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans.
16	Reduce the number of contact points between modules.
20	Use a framework for mounting multiple modules.
12	Locating those parts which are anticipated to change near the exterior of the device.
6	Collect parts which perform functions associated with the same energy domain into separate modules.

Characteristics of the first two guidelines listed in Table 2 are quantified by filtering the HD-DSM and then counting the effected pairs of elements. The filtering process can be visualized by overlaying layers of the HD-DSM so that the resulting DSM highlights only cells that have marks in all of the included layers. The characteristic of Guideline 9 is found by looking for pairs of elements that are in proximity but not actually in contact. This can be seen by overlaying the inverse of the strain energy layer onto the proximity layer as shown in Figure 9 for a system-level HD-DSM of the Innovage screwdriver. The system-level HD-DSM is shown for illustrative purposes but it does not reveal where the potential for improvement is specifically located. By looking at the full, 32-element HD-DSM, which contains all of the parts listed in the BOM, it is seen that the button base and the motor plate, which closes the back of the transmission, are in proximity to each other. If this proximity could be removed, unneeded change propagation may be avoided. The results in Table 3 show that the Black and Decker screwdriver has fewer elements with space potential between them. This result indicates that the design is more refined and has fewer potentially unnecessary interactions.



The flexibility of the Innovage screwdriver design could be improved by providing excess space between the 'EE System' and the 'Transmission'.

Figure 9: Information in the HD-DSM can be filtered by selectively combining layers related to particular guidelines

Table 3: Results of analysis of flexibility for future evolution for selected guidelines

		Guideline:	9	16	20	12	6	6
Product	Elements	Possible Pairs	Space Potential	Exclusive Contact Points	Framework Recognized	Reachability to External	Closeness Ratio of Electrical Energy Cluster	Closeness Ratio of Mechanical Energy Cluster
Black and Decker	32	496	9	27	Yes	0.7879	0.4286	0.6391
Innovage	32	496	13	32	Yes	1.2273	0.5460	0.6939
		Percent improvement of B&D:	31%	16%	Same	36%	22%	8%

Similarly, the characteristic of Guideline 16 is found by looking for pairs of elements with Exclusive Contact Points (ECP) meaning that the elements contact one another but do not interact in any other way. ECP's can be filtered out of the HD-DSM by overlaying the Proximity and Strain Energy layers with the inverse of all other layers in the HD-DSM. Again, the Black and Decker screwdriver has fewer elements that are exclusively in contact (Table 3).

The interpretation of the remaining guidelines in Table 2 is slightly more involved since simple filtering is not sufficient to provide useful information. The process is supplemented by creating a reachability matrix based on filtered information to determine the degree of closeness of elements for the specified interaction or combination of interactions. The method of creating a reachability matrix is clearly explained and demonstrated by Hsaio et al. [11] (pgs 15-16) who credit the method to Warfield [23]. In the power screwdrivers being studied, a reachability matrix based on the mechanical energy layer is able to show that the motor is connected to the bit through each of the elements in the transmission, and it counts the number of intermediate elements.

Guideline 12 states that it is beneficial to have elements near the exterior of the device if they are anticipated to change. Although it is impossible to objectively know which elements will require change in the future, it is possible to determine how near elements of the product are to the exterior of the device. By performing a reachability analysis, the number of iterations required for each element to "reach" the exterior of the device based on proximity to other elements can be determined. The results of the reachability matrix are normalized to determine an average reachability for all elements in the system compared to the external element. If the average reachability to the external element were zero, it would indicate that every element in the system is proximal to the exterior of the product. Therefore, in terms of Guideline 12, a lower average reachability to the external element is more desirable for flexibility for future evolution. As seen in Table 3, the Black and Decker screwdriver has a much lower value for average reachability to the external element. This is supported by observations made during product disassembly. For example, the transmission for the Innovage is mounted inside of the screwdriver housing, such that a change to the transmission will almost necessarily require a change to the housing. In contrast, the Black and Decker transmission is attached to the screwdriver handle but not mounted inside of it.

Similarly, a closeness index can be obtained based on the reachability of the structural connections filtered from the HD-DSM. This allows a common framework to be automatically recognized by identifying elements that have a significantly lower average closeness index. Having a low average closeness index indicates that a part is reachable to many parts through few links. A framework is suggested by Guideline 20 as a way to improve product flexibility for future evolution. Therefore, the recognition of a framework suggests that the design conforms to this guideline. Based on this analysis, frameworks are recognized in both products as being the two halves of the outer housing. In the Black and Decker screwdriver, the transmission housing was also recognized as a framework.

Guideline 6 suggests to collect parts which perform functions associated with the same energy domain into modules. This is assessed in the product by first identifying groups of elements that act on the same energy domain, and then comparing the proximity of these elements to each other compared to those in the rest of the product. To automatically find groups of elements that act on each type of energy domain, a reachability analysis is conducted based on each of the different energy layers of the HD-DSM. Without this detailed interaction information, this analysis could not be automated.

In both screwdrivers, groups of components were found based on the mechanical energy layer and the electrical energy layer of the HD-DSM. Again the Black and Decker appears to perform better based on this guideline for flexibility for future evolution. In the Black and Decker screwdriver, the parts which interact with electrical energy are tightly connected behind the motor and in front of the battery pack. However in the Innovage screwdriver, the electrical parts are spread throughout the product and are connected by wires which travel over and around other components.

Based on the quantitative results of this analysis, the design of the Black and Decker screwdriver has characteristics that will make it easier to adapt the design in the future to meet new market needs. The Innovage screwdriver will be more difficult to evolve in the future due to the higher number of elements in proximity and contact (Guidelines 9 and 16), the higher number of elements nested from the exterior of the device (Guideline 12), and the less defined energy domain clusters (Guideline 6). The analysis presented here produces quantified results with minimal opportunity for the examiner's preferences to bias the results.

6. CONCLUSIONS AND FUTURE WORK

In this paper, an analysis tool is presented for comparing the flexibility for future evolution of similar products. The analysis is founded on characteristics of design that have been suggested in design guidelines for flexibility for future evolution. The High-Definition Design Structure Matrix is introduced as a sufficient representation of the interactions between elements within a system. By using a standard interaction basis, the creation of a HD-DSM can be separated into subsystems and then combined. This method reduces the effort required to create the HD-DSM and also facilitates distributed modeling which will allow modeling to be the combined effort of many people.

The analysis presented in Section 5 quantitatively indicated that one product was more flexible for future evolution than a similar product. In this study, the Black and Decker design was better than the Innovage design for four of the five guidelines considered. However, future work will have to address the issue of different products performing better with respect to different guidelines. One possibility is to normalize the metrics for each guideline and then combine them into a single flexibility rating. Normalized metrics will also allow products, which are not considered similar in function or form, to be compared based on their flexibility for future evolution. This work will require creating HD-DSMs for a larger number of products. Also, only five of the 24 guidelines from Appendix A were selected for the analysis presented in this paper. The remaining guidelines will be reviewed and interpreted to further complete the analysis. The appropriateness of the HD-DSM for analyzing other Design for X guidelines will also be considered.

Overall, this research was motivated by the need for a less subjective, quantitative assessment of a product’s flexibility for future evolution. Previous methods, such as the Change Modes and Effects Analysis (CMEA) rely heavily on the examiner’s ability to predict potential change modes and design responses. This paper has introduced a form of analysis that is capable of producing more objective results based on thorough and consistent application of design guidelines using automated tools. More work is needed to investigate the repeatability of the HD-DSM versus previous methods such as the Change Modes and Effects Analysis.

In addition, the two consumer products considered in the previous section are relatively small-scale systems compared to other complex systems that engineers encounter in practice. The products analyzed in Section 5 both contained 32 unique parts. A single DSM of this size contains 992 cells of possible interactions. As the number of elements increases, the number of possible interactions increases exponentially. The inclusion of different types of interactions further multiplies the number of possible cells to be considered. Few authors acknowledge the inherent difficulty of initially creating an accurate DSM and focus primarily on its use after being created. The process described in Section 4 addresses the seemingly overwhelming task of creating a HD-DSM by breaking the system into subsystems that can be modeled separately and even by different examiners. This process allows for distributed modeling and for the creation of subsystem model databases that can be used to quickly build up a complete system model. Since the HD-DSM is based only on the existence of interactions, the expertise level of the examiner is not a critical requirement. Future work will investigate the application of the HD-DSM to more complex systems.

Finally, the focus of this paper has been on assessing the final design of products, but the analysis could be useful during the design process to guide and justify the selection of different proposed designs, providing objective metrics for product flexibility for future evolution. Although the HD-DSM analysis does not directly automate the improvement of a particular design, the designer could use it as the basis for any number of product improvement methods based on clustering algorithms and module identification [17, 24, 25].

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APPENDIX A

DESIGN GUIDELINES FOR FLEXIBILITY FOR FUTURE EVOLUTION

Modularity Approach

Increase the degree of modularity of a device by…

1 Using separate modules to carry out functions that are not closely related.
2 Confining functions to single modules
3 Confining functions to as few unique components as possible.
4 Dividing modules into multiple smaller, identical modules.
5 Collecting parts which are not anticipated to change in time into separate modules.
6 Collecting parts which perform functions associated with the same energy domain into separate modules.

Parts Reduction Approach

Reduce the number of parts requiring manufacturing changes by…

7 Sharing functions in a module or part if the functions are closely related.
8 Using duplicate parts as much as possible without raising part count.

Spatial Approach

Facilitate the addition of new functionality and rearrangement or scaling of parts by…

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans.
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces.
11 Extending the available area on the transmission components of the device.
12 Locating those parts which are anticipated to change near the exterior of the device.
13 Reducing nesting of parts and modules.

Interface Decoupling Approach

Reduce the communications between modules, and enable the device to function normally regardless of the orientation, location and arrangement of its individual modules, by…

14 Standardizing or reducing the number of different connectors used between modules.
15 Reducing the number of fasteners used, or eliminating them entirely.
16 Reducing the number of contact points between modules.
17 Simplifying the geometry of modular interfaces.
18 Routing flows of energy, information and materials so that they are able to bypass each module at need.
19 Creating detachable modules.
20 Using a framework for mounting multiple modules.
21 Using compliant materials.
22 Simplifying the geometry of each component.

Adjustability Approach

Enable the device to respond to minor changes by…

23 Controlling the tuning of design parameters.
24 Providing the capability for excess energy storage or importation.

APPENDIX B: BILL OF MATERIALS

Table B1: Black and Decker Alkaline Power Screwdriver

Part		Subsystem (assigned during disassembly)	Qty	Mfg. Process	Material
1	Battery holder	Battery	1	Injection molded	Plastic
2	AA Battery	Battery	4	Standard Part	Various
3	Series terminal clip	Battery	2	Stamped and Bent	Steel
4	Battery plug	Battery	1	Injection molded	Plastic
5	Plug terminals	Battery	2	Stamped and Bent	Steel
6	Series terminal plate	Battery	1	Stamped and Bent	Steel
7	Bottom Housing	Battery	1	Injection molded	Plastic
8	Bit	Bit	1	Standard Part	Metal
9	Negative Terminal Clip	Electrical	1	Stamped and Bent	Steel
10	Positive Terminal Clip	Electrical	1	Stamped and Bent	Steel
11	Terminal carrier	Electrical	1	Injection molded	Plastic
12	Button	Electrical	1	Injection molded	Plastic
13	Front housing	Housing	1	Injection molded	Plastic
14	Back housing	Housing	1	Injection molded	Plastic
15	Pin	Housing	2	Standard Part	Metal
16	Motor	Motor	1	Standard Part	Various
17	Clip	Transmission	1	Bent rod	Steel
18	Motor Gear	Transmission	1	Standard Part	Metal
19	Washer	Transmission	1	Standard Part	Steel
20	Planetary Gears, Set1	Transmission	3	Injection molded	Plastic
21	Carrier Sun	Transmission	1	Machined	Steel
22	Planetary Gears, Set2	Transmission	3	Injection molded	Plastic
23	Planetary Carrier	Transmission	1	Machined	Steel
24	Ring Gear, Housing	Transmission	1	Injection molded	Plastic
25	Ring clip, shaft	Transmission	1	standard	Metal
26	Shaft	Transmission	1	Machined	Steel
27	Brake Gear	Transmission	1	Injection molded	Plastic
28	Chuck	Transmission	1	Machined	Steel
29	Brake Switch	Transmission	1	Injection molded	Plastic
30	Brake Switch Spring	Transmission	1	Stamped and Bent	Steel
31	Ring clip	Transmission	1	Standard Part	Metal
32	Washer, ring clip	Transmission	1	Standard Part	Metal

TOTAL QUANTITY OF COMPONENTS: 42

Table B2: Innovage Power Screwdriver

Part		Subsystem (assigned during disassembly)	Qty	Mfg. Process	Material
1	Battery holder	Battery	1	Injection molded	Plastic
2	Series terminal clip	Battery	2	Stamped and Bent	Steel
3	Battery plug	Battery	1	Injection molded	Plastic
4	Plug terminals	Battery	2	Stamped and Bent	Steel
5	Series terminal plate	Battery	1	Stamped and Bent	Steel
6	AA Battery	Battery	4	Standard Part	Various
7	Bit	Bit	1	Machined	Steel
8	Wire, Switch to Motor	Electrical	2	Standard Part	Various
9	Button, Top of Switch	Electrical	1	Injection molded	Plastic
10	Button base, bottom of switch	Electrical	1	Injection molded	Plastic
11	Wire, Battery terminal to switch	Electrical	1	Standard Part	Various
12	Battery Clip	Electrical	1	Standard Part	Various
13	Bottom Housing	Housing	1	Injection molded	Plastic
14	Back Housing	Housing	1	Injection molded	Plastic
15	Front Housing	Housing	1	Injection molded	Plastic
16	Screws	Housing	2	Standard Part	Metal
17	Pin	Housing	2	Standard Part	Metal
18	Motor	Motor	1	Standard Part	Various
19	Screws, motor plate	Motor	1	Standard Part	Metal
20	Motor Plate	Transmission	1	Injection molded	Plastic
21	Planetary Gears, set1	Transmission	3	Molded	Plastic
22	Planetary Carrier and sun gear	Transmission	1	Molded	Plastic
23	Planetary Gears, set2	Transmission	3	Molded	Plastic
24	Brake Coupler	Transmission	1	Molded	Plastic
25	Ring Gear	Transmission	1	Molded	Plastic
26	Coupler	Transmission	1	Machined	Metal
27	Brake Drum	Transmission	1	Machined	Metal
28	Brake Roller	Transmission	2	Machined	Steel
29	Shaft	Transmission	1	Machined	Steel
30	Spring Clip	Transmission	1	Standard Part	Metal
31	Washer	Transmission	1	Standard Part	Steel
32	Chuck	Transmission	1	Machined	Metal

TOTAL QUANTITY OF COMPONENTS: 45