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A Systematic Method of Product Design for Flexibility for Future Evolution

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Abstract: The design of a product determines the flexibility of that product to future evolutions, which may arise from a variety of change modes such as new market needs or technological change. Previous work has produced a set of guidelines for product flexibility for future evolution which have been shown to improve the ability of a design to be adapted when new needs arise. In this paper, the method by which the guidelines are used during the design process is improved by creating a systematic method for product improvement. 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.

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 to future evolution. There is a relationship between a product's flexibility and its architecture [1-4]. 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 [4]. Without a clear understanding of the interconnections between elements in the system, an ad hoc redesign process may require significant iteration to achieve an acceptable design. In this paper, we present a systematic method for product improvement in which the product to be redesigned is transformed into a High-Definition Design Structure Matrix (HD-DSM) model representation. The HD-DSM captures information about the way in which components within the product interact based on a standard interaction basis. The different interactions between elements of the system are filtered and related to characteristics for flexibility for future evolution so that potential design improvements can be highlighted for consideration.

Characteristics of a design that make it more flexible for future evolution have been recorded in previous research and presented as a list of guidelines [5]. The recognition and application of these guidelines in case studies and design exercises has been done using rubric tables and qualitative tools. This paper lays the groundwork for a more systematic method to identify where guidelines can be, or have been, used in a product's design. The method of guideline application will be shown in this and future work to be systematic by meeting the following criteria:

- Logical – It should use an intuitive representation.
- Relevant – It should produce useful results for its intended purpose.
- Repeatable – It should produce consistent results.
- Reproducible – Different examiners should produce similar conclusions.
- Universal – It should be useful for all products in the complex system domain.

A systematic method for the application of guidelines requires both a model of the product and an interpretation of the guidelines that can be applied to that model. For this reason, this paper builds upon research in both product modeling and product flexibility. The first two criteria listed above are addressed in this paper. Therefore, it is the purpose of this paper to present a product model that is shown to be a logical representation of the product for the intention of being able to apply guidelines. Secondly, examples will be introduced to show that the application of guidelines to this model will produce relevant results that can aid the creation of an improved, evolvable design.

In Section 2, a review of related research is presented with an emphasis on explaining how the objectives of this paper fit into the existing research field. In Section 3, the standard for a High-Definition Design Structrure Matrix is presented as a logical representation for systematic product improvement. A product example is used to show the process of creating an HD-DSM in Section 4. In Section 5, the usefulness of the HD-DSM is shown by applying selected guidelines and using it as a tool for innovative design.

2. Related Work: Product platforms are a successful strategy for creating a product family to meet a range of market segments [6]. 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" [7]. 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 [8]. 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 [5].

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 N2 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.

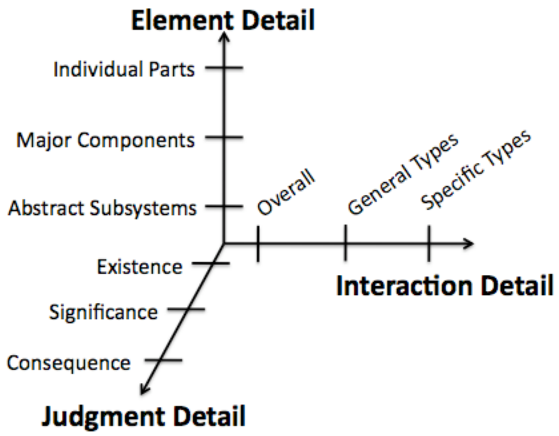


Figure 1: Information Content Space of DSM

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 recording the existence of an interaction. The significance of an interaction requires a range of positive integers or ratios

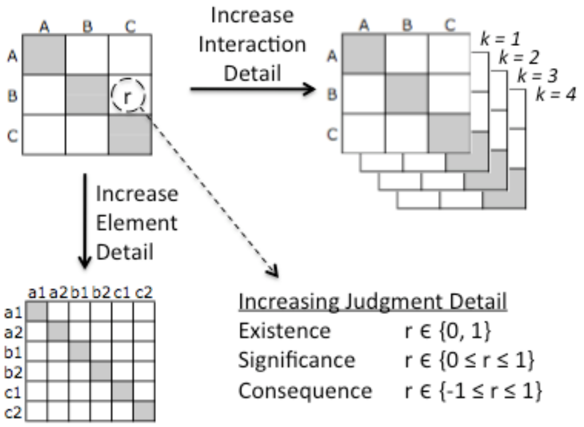


Figure 2: Element, Interaction, and Judgement Detail

and the consequence of an interaction requires both positive and negative numbers.

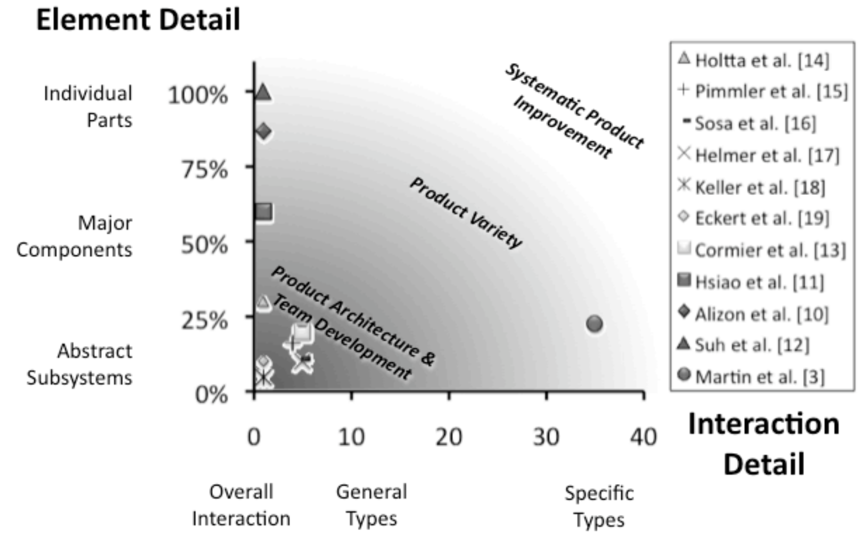


Figure 3: Information Content of DSMs in related work

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 information content of component DSMs from related work are plotted on the Element Detail-Interaction Detail plane. 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 [3]. 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].

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 jet engine [16]. Helmer et al. propose improved clustering procedures based on these five types of interaction [17].

The creation of product variety is aided by using a DSM to recognize which components 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 [3]. By reducing the overall coupling index, they show the design can be more easily varied to meet the customer objectives for product family 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 products to recognize common modules across the product family [10]. 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]. Keller et al. describe tools for visualizing change propagation data such as the network diagram [18]. Eckert et al. discuss the roles elements have as change multipliers, carriers, or absorbers in terms of change propagation [19].

For systematic product improvement 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 High Definition DSM:

The High-Definition Design Structure Matrix (HD-DSM) is a three-dimensional array that captures the different types of interactions between elements within the system. This information can then be used to evaluate or improve the design of the system. In this section, the distinction of a HD-DSM is defined by discussing the Element Detail and Interaction Detail that should be captured. In Section 4, the process of creating a HD-DSM is explained with the use of a product example.

3.1 Increased Element Detail

The Element Detail of a DSM is a relative measure of the number of elements used to represent the total parts in the system. It can be determined by dividing the elements used in the DSM by the total quantity of parts in the system's bill of materials (Equation 1). This total includes multiple quantities that might be listed as a single part on the bill of materials. Standard components and assemblies can be counted as a single part if the part is not eligible for redesign. For example, there are 32 unique components in the Black & Decker screwdriver but a total quantity of 42 parts. The DC motor in this screwdriver is likely a standard component that the screwdriver design team is not able to entirely redesign. Therefore, although a different DC motor may be selected, from the designer's point of view it is still a single component. However, if a product contains two DC motors, each should be counted separately.

$$\text{Element Detail} = N_{\text{elements}} / N_{\text{total parts}} \qquad (1)$$

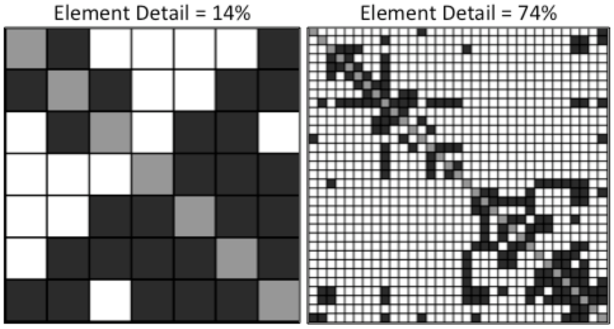


Figure 4: Different levels of element detail

Figure 4 shows two DSMs at different levels of Element Detail for the Black & Decker screwdriver. A darkened cell indicates the existence of an interaction from the element in the column to the element in the row. The element labels are not included in Figure 4 to focus the reader's attention just on the difference in resolution.

Equation 1 provides a relative metric for the comparison of systems as a percentage of representation detail. However, it should not be assumed that the upper limit of this metric is 100%. If necessary, the individual features of a molding or a weldment can be represented by different elements in the DSM so long as the interconnections between the features are recorded. By using the modeling steps outlined in Section 4, the HD-DSM can be expanded to any level of element detail necessary. For the case study in this paper it was found that the element detail should be high enough to capture each line-item of the bill of materials.

3.2 Increased Interaction Detail

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 and the flow set of the reconciled functional basis. 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 dependences, and this leads to an extremely coupled design matrix" [20]. 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

[2]-Used in related DSM research

Many of the interaction types listed in Table 1 have been used and defined in previous literature. Interactions which are familiar to the reconciled functional basis [21] or other DSM research, such as that of Pimmler and Eppinger [15], are indicated in Table 1.

4. Creating a HD-DSM 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 5) 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. 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 relevant for complex systems of any scale.

Figure 5: Black & Decker Alkaline Power Screwdriver

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.

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

During product teardown, a Bill of Materials was created which indicated a total quantity of 42 parts as discussed previously. Therefore, this system-level HD-

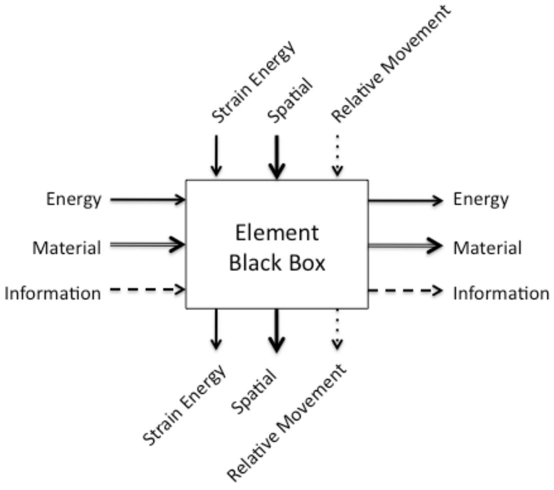


Figure 6: Generic Element Black Box

DSM is at 14% relative element detail. 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

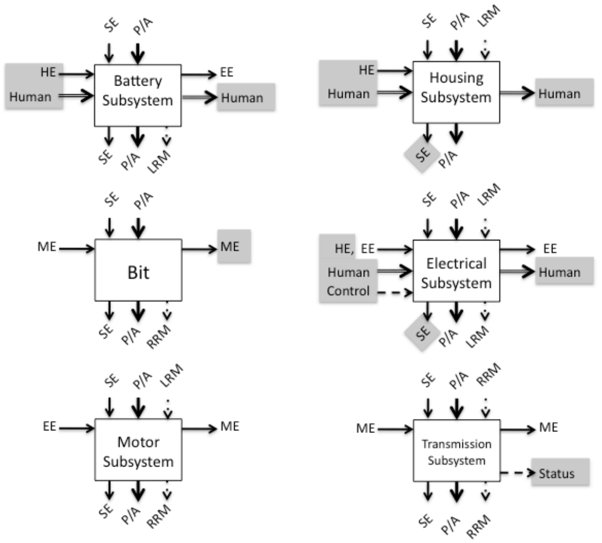


Figure 7: Element Black Box for each subsystem

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 6. The additional interactions discussed in Section 3 are added to the black box model on the top and bottom of the box. Figure 7 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.

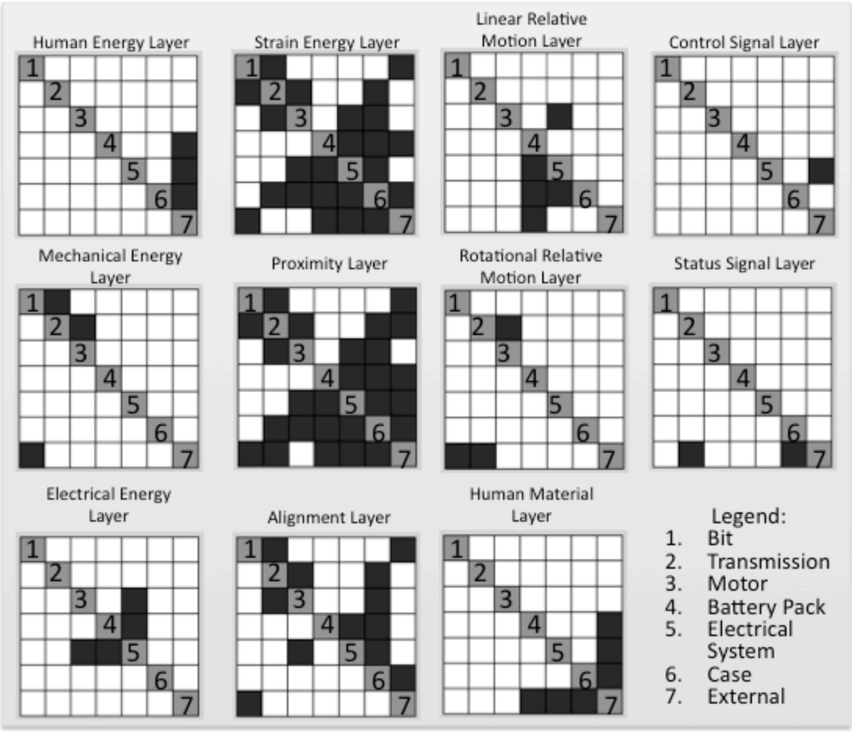


Figure 8: Eleven populated layers for B&D Screwdriver HD-DSM

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 8. The remaining fourteen layers of interaction are empty.

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 a single layer of interaction of 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 9a.

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 9b.

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 9c. 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 9a, 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 9b, 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 9a).

Step 6: Review system interactions
The system level examiner 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 9d 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 9d. By inferring which interactions are possible, the manual examination of an additional 80 element pairs is avoided.

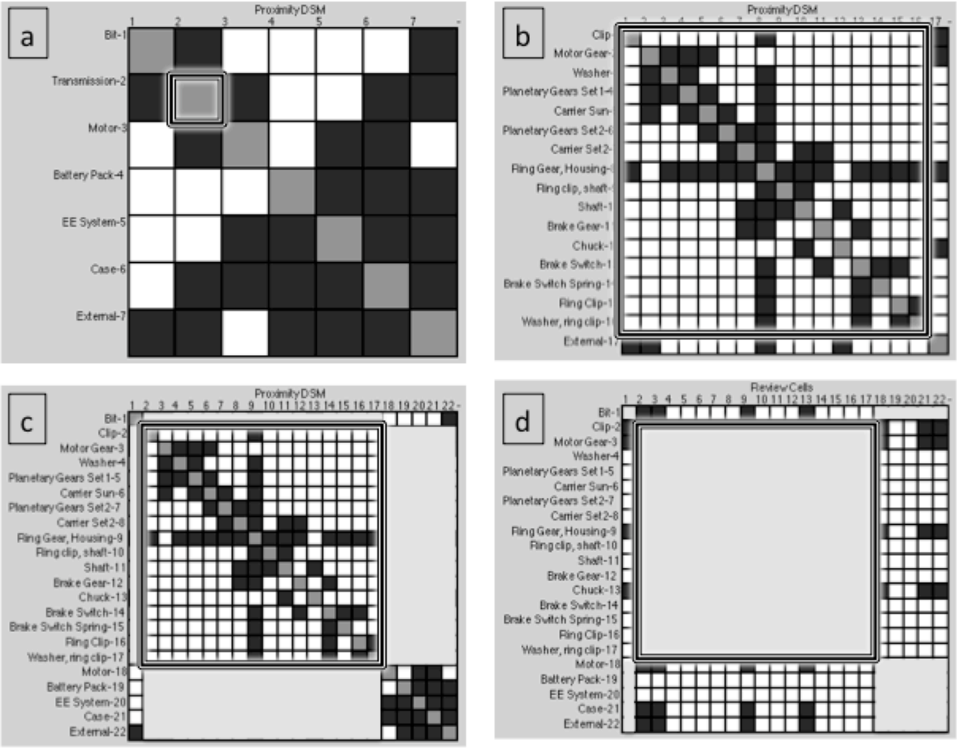


Figure 9: Transmission subsystem insertion for proximity interaction layer

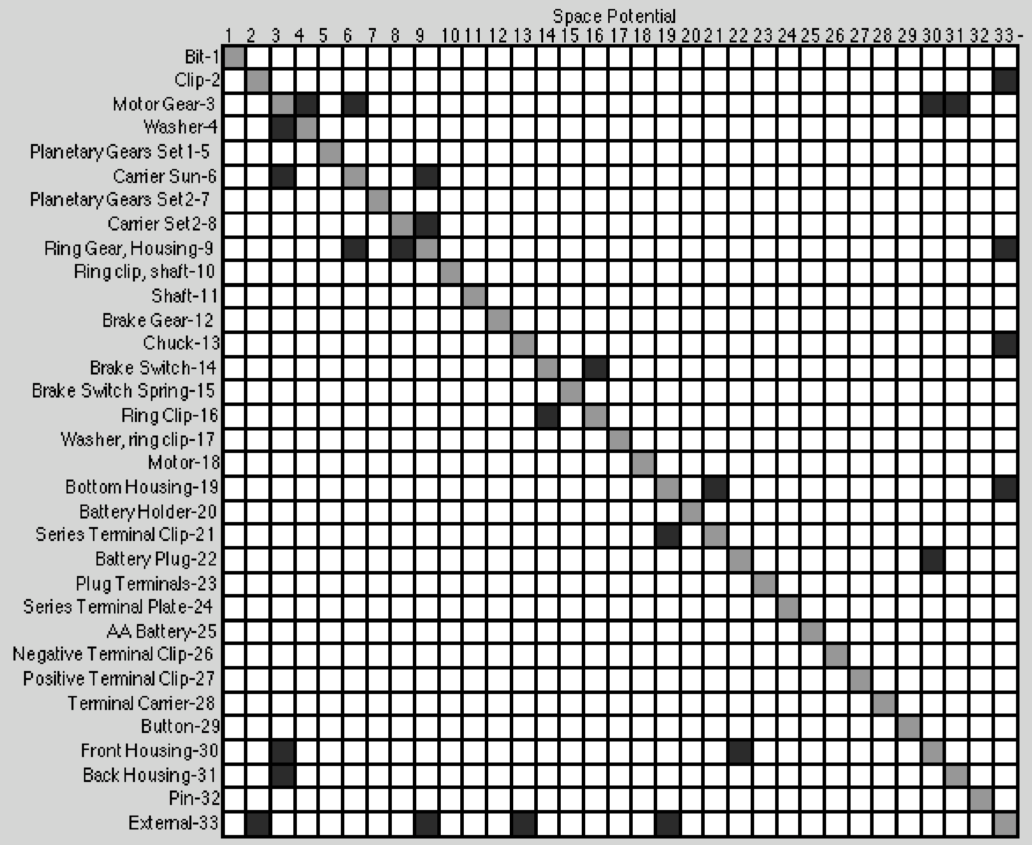
Steps 1-5 described above can be easily automated simultaneously across all interaction layers of the HD-DSM. The author created a HD-DSM for the Black & Decker Alkaline Power Screwdriver at 74% element detail, meaning that each of the 32 parts on the bill of materials has a corresponding element in the final HD-DSM. (Total quantity of parts is 42.) Using appropriate software functions, 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. Case Study: The HD-DSM is shown to be a logical representation of the product because, in the simplest sense, it captures the inputs and outputs of each element in the system using a standard interaction basis. In this section, the relevance of the HD-DSM model is motivated by showing that the model is sufficient to capture selected flexibility for future evolution guidelines.

Selected Guideline:
Create room on the exterior surfaces of the device, around interior modules, and around those parts that are designed to interface with humans.

This guideline is simply suggesting that excess space should be provided between components. If future evolutions require the design to be changed, the excess space will reduce the propagation of that change through the system. Figure 10 shows those components which are only in close proximity to each other. Each of these pairs of components should be evaluated to determine if they can be moved out of proximity of each other. For example, the motor gear (Element #3) is in proximity to the front and back housings (Elements #30 and #31). If a change was required to the design that increased the size of the motor gear, it's likely that the front and back housings would also need to be changed. Otherwise, the matrix is sparse, indicating that in terms of this guideline, the design is good because elements are located next to each other only when needed or necessary.

The Black & Decker Screwdriver may be a small system compared to other complex systems that designers and engineers may encounter. Jet engines, vehicles, robots, or automated testing systems may contain orders-of-magnitude higher quantities of parts. However, the tools and methods exhibited by the simple examples of these guidelines using the HD-DSM can be applied to the HD-DSM of a much larger system. The information captured by the HD-DSM can be automatically filtered to highlight certain opportunities for designers, who then investigate



Space Potential

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33-
Bit-1	▨																																
Clip-2		▨																															■
Motor Gear-3			▨	■		■																								■	■		
Washer-4			■	▨																													
Planetary Gears Set 1-5					▨																												
Carrier Sun-6			■			▨			■																								
Planetary Gears Set 2-7							▨																										
Carrier Set 2-8								▨	■																								
Ring Gear, Housing-9						■		■	▨																								■
Ring clip, shaft-10										▨																							
Shaft-11											▨																						
Brake Gear-12												▨																					
Chuck-13													▨																				■
Brake Switch-14														▨		■																	
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Ring Clip-16														■		▨																	
Washer, ring clip-17																	▨																
Motor-18																		▨															
Bottom Housing-19																			▨		■												■
Battery Holder-20																				▨													
Series Terminal Clip-21																			■		▨												
Battery Plug-22																						▨								■			
Plug Terminals-23																							▨										
Series Terminal Plate-24																								▨									
AA Battery-25																									▨								
Negative Terminal Clip-26																										▨							
Positive Terminal Clip-27																											▨						
Terminal Carrier-28																												▨					
Button-29																													▨				
Front Housing-30			■																			■								▨			
Back Housing-31			■																												▨		
Pin-32																																▨	
External-33		■							■				■						■														▨

Figure 10: Black marks indicate component pairs which are only in proximity

this small set of opportunities and decide which ones are worthwhile to pursue. The utility of this method is in highlighting these opportunities from a very complex set of interactions.

6. Conclusions and Future Work: When engineers and designers use guidelines, they are mentally evaluating how the guideline applies to the given product and what impact its application would have. For products of large complexity and scale, thoughtful application of guidelines consistently throughout the product is not reasonable. This paper has presented a logical and relevant method for systematically improving products based on the knowledge and experience that are contained in the flexibility for future evolution guidelines. The High-Definition Design Structure Matrix is introduced as an intuitive 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. Ultimately, the HD-DSM is an information management tool that is helpful for consistently applying design rules throughout the entire design.

An example of how the guidelines can be applied to a design represented as an HD-DSM was presented for the Black & Decker screwdriver. More examples and a redesign scenario are presented in [23]. In future work, the remaining guidelines from the flexibility for future evolution research will be interpreted for application to the HD-DSM. The appropriateness of the HD-DSM for applying other Design for X guidelines will also be considered.

To complete the criteria defined in Section 1 for a systematic method, the HD-DSM still needs to be shown as repeatable, reproducible, and universal. Repeatability and reproducibility will be addressed through experiments in which the models created by different examiners are compared. A variety of complex systems in both scale and function will be evaluated to show the universal application of the method.

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