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THE REPEATABILITY OF HIGH DEFINITION DESIGN STRUCTURE MATRIX (HDDSM) MODELS FOR REPRESENTING PRODUCT ARCHITECTURE

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ABSTRACT

Product architecture has implications for product success that go beyond meeting basic customer needs or performance requirements. The mapping of functions to components and the interactions between them impacts the potential for using all or part of the product to build a family of products, the ease with which the product can be redesigned to meet previously unanticipated customer needs, and the way in which engineering design changes propagate during the design process. For practical applications of design theory, it would be beneficial to have a comprehensive and robust model that captures product architecture and can be used for multiple purposes. Some fields of design research have used variations of a Design Structure Matrix (DSM) to record the interactions between elements of a system. The High Definition Design Structure Matrix (HDDSM) has been proposed as a model that limits the subjectivity required from designers by capturing the existence of very specific types of interactions between product components. This work evaluates the repeatability of HDDSM models created by different examiners for a set of electromechanical products. The inter-rater agreement between HDDSM models created by pairs of examiners is determined by calculating the kappa agreement index for each type of component interaction. The results of this initial study demonstrate very encouraging levels of repeatability across examiners for different types of products. Based on these results, recommendations are provided for creating objective models of product architecture and using such models for a number of exploratory research tasks, such as automated analysis of design guidelines.

1. INTRODUCTION

Many aspects of engineering design research involve the architectural design of products. Research on product family design recognizes the value of creating a product platform that can be used to support a variety of products [1]. Research on flexibility for future evolution considers how the specific design of a product determines the ease with which it can be evolved into a future product offering [2]. Change propagation research studies the impact of engineering changes during or after the design process as a function of architectural features [3]. Research on design for adaptability has studied the cost and benefit associated with designing a system that can be upgraded and changed during its lifetime [4]. In all these areas of research, a product representation is created for the purposes of better understanding or analyzing the design.

For practical application of these various design methodologies, an individual designer, or team of designers, would benefit immensely from having a multi-purpose model of the product that:

- allows analysis and measurement of the design for various purposes without amendment to the model,
- is transferrable between persons and groups without additional explanation,
- can be created by the combination of different models, which may have been created at different times by different people.

In short, design methodology research would benefit from an architectural model of a product that is based on physical, observable traits of the design rather than on expert interpretation. The High Definition Design Structure Matrix (HDDSM) proposed in previous work, was specifically designed to have these benefits [5]. The HDDSM is standardized on an Interaction Basis so that it can be used for a wide variety of products (Appendix A). Specific interactions are recorded at a level of existence to reduce the subjectivity recorded in the model. The requirement of an 'External' element allows for models to be created in groups and then assembled to reduce the effort in creating a high resolution model [6].

In this paper, we evaluate the repeatability of HDDSM modeling by having groups of examiners model a set of products. The study leads to many insights, from which the strengths and weaknesses of the HDDSM are discussed. In Section 2, an introduction to DSM methods is given along with examples of DSM use in design research. The HDDSM is also presented and explained. The research method is discussed in detail in Section 3. Results of a multiple product HDDSM repeatability study are presented in Section 4. The results of a second study, which focuses on the interaction modeling of a single product, are discussed in Section 5. In Section 6 the results of the two studies are discussed. In Section 7, conclusions are drawn from both studies and the implications are considered.

2. BACKGROUND

In this section, we will provide an overview of the Design Structure Matrix (DSM) and the distinction of the HDDSM, followed by a review of how DSM-style product representations are used in design methodology research.

A component Design Structure Matrix is used to capture and represent the interactions between elements of a system [7]. An ‘element’ may represent a single component, an assembly of components, or an abstract area of the system. The only requirement is that elements of the system are defined by non-overlapping boundaries. The elements of the system are used to label the rows and columns of a square matrix. A mark is placed in the matrix cell whenever two elements interact. We will introduce the concept of the component DSM, its relationship to graphs, and the HDDSM using the cordless drill pictured in Figure 1. The HDDSM format includes an ‘External’ element to capture any interactions that cross out of the system’s boundary. The system boundary for the cordless drill is drawn on Figure 1. An abstract representation of the drill could be created as shown in Figure 2. Here the drill is represented by three elements: a handle, a power source, and a drill bit. The handle is held by something outside of the system boundary, the power source is connected to the handle, the drill bit is connected to the power source, and the drill bit is working on something outside of the system boundary. This simple set of relationships can be recorded in a DSM as shown. The same information could also be shown using a graph.

This basic example is a binary record of one type of interaction. The information content of the DSM, however, can be increased in three different ways. The number of components modeled can be increased, different types of interactions can be defined, and the significance of each interaction can be numerically rated. Depending on the type of interaction, it may also be valuable to indicate the direction of the interaction. We use the standard that the element in the column is providing the interaction to the element in the row.

Figure 1: Cordless drill shown with system boundary

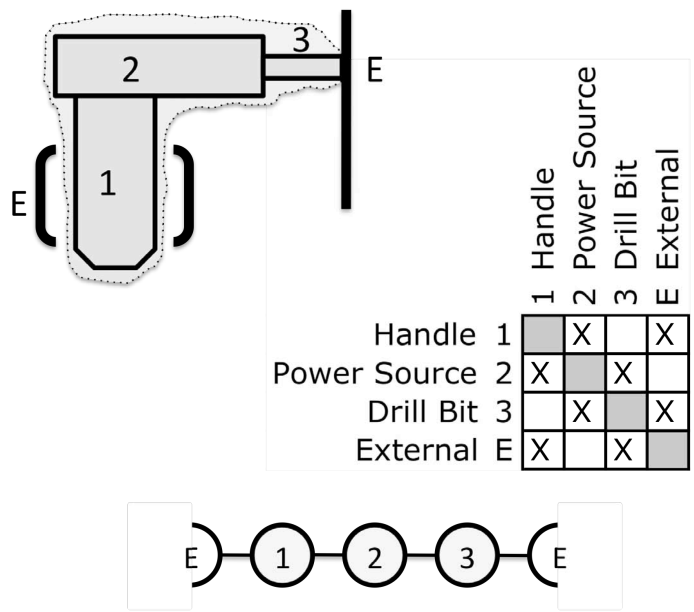
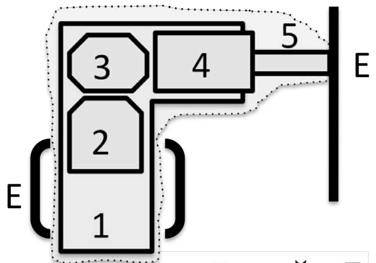


Figure 2: Diagram, DSM, and graph of drill

Continuing with the drill example, we decide to increase the resolution by using more elements to represent the product. In addition, we also decide to capture the flow of energy in addition to the physical connections. The information can be shown using multiple DSMs or a graph as shown in Figure 3. The DSM can continue to be grown in this way to include a higher resolution of elements and more specific types of interactions.



Connection	1 Housing	2 Battery	3 Motor	4 Gearbox	5 Drill Bit	E External
Housing 1		X	X	X		X
Battery 2	X		X			
Motor 3	X	X		X		
Gearbox 4	X		X		X	
Drill Bit 5				X		X
External E	X				X	

Energy	1 Housing	2 Battery	3 Motor	4 Gearbox	5 Drill Bit	E External
Housing 1						
Battery 2						
Motor 3		X				
Gearbox 4			X			
Drill Bit 5				X		
External E					X	

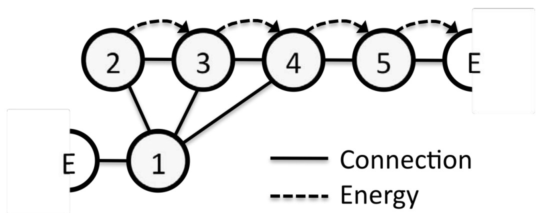


Figure 3: Increased information content by higher component resolution and multiple interactions

The High Definition Design Structure Matrix (HDDSM) uses the complete set of components listed in a product's bill of materials and captures interactions specified by a standard basis. The Interaction Basis, as listed in Appendix A, contains 25 types of functional and physical interactions extended from research on a Functional Basis and DSMs [8-10]. Each type of interaction is recorded in a separate layer of the HDDSM using a binary mark. Rarely would every type of interaction be used to model a given product, but using an interaction basis allows for the development of standard software tools and analysis functions for a wide variety of products. The specific interactions are necessary to avoid ambiguity. For example, if electrical energy and mechanical energy are both being used within a product, it could be confusing to model them both as energy and doing so could abstract away from details of the product architecture that are important for subsequent analysis.

A HDDSM of the cordless drill is shown in Appendix B. The elements of the HDDSM are based on the components within the actual drill. Only interactions that were found in the drill are shown. Due to the high level of detail, it quickly becomes impractical to look at a HDDSM in the way shown in Appendix B. However, the information recorded in a HDDSM can be visualized in any number of ways. Each layer can be viewed individually as a matrix or specific combinations of layers can be viewed. As shown in the examples above, the information in the HDDSM can also be used to draw a directed graph.

Similar models for product representation have been created for change propagation [11], a design knowledge repository [12, 13], and representations for automated design [14]. A key distinction of the HDDSM is the format and process through which it is created. The HDDSM allows the resolution of the model to be continually increased by merging subsystem HDDSM models into a system level model [5]. For example, a HDDSM could be separately made for the DC motor in the cordless drill and then merged into the drill HDDSM shown in Appendix B. This process has been shown to significantly reduce the amount of effort required by human examiners to create the model [6].

Different aspects of design research have found it useful to represent a product in a DSM format. The square matrix lends itself to basic mathematical manipulation and can be a useful way of visualizing characteristics about a product. Hsiao and Liu [15] thoroughly explain a useful algorithm for establishing the hierarchical component interaction structure which can assist in designing a common platform for a product family. Alizon et al. [16] stack DSMs of similar products made with generic components to visualize common modules and common interfaces across the product set. Suh et al. [17] use a DSM to minimize the magnitude of change propagation in the design of an automotive platform. The tradeoff between modularity and performance is considered by Holtta et al. [18] by comparing a modularity metric based on the DSM of different products to their overall performance. They confirm an early observation by Ulrich [19] that modularity may come at the cost of global parameters such as weight and volume. Yu et al. [20] use genetic algorithms to optimize the module architecture for a single product by maximizing the interactions within modules and minimizing the interactions across modules. Engel and Browning [4] propose using a DSM to estimate the adaptability of a system based on the option values of components, their adaptability factor, and the corresponding interface costs between components.

The researchers referenced above thoroughly document the potential use of a component DSM. However, the tradeoff between the time and cost of developing an accurate model and the payoff of using any particular method are not well known. A DSM model created for a specific purpose by a group of experts, especially in the case where ratings of interaction significance are used, may not be readily transferrable for different uses because the experts' biases may be embedded in the model. Therefore, in practical application, the HDDSM is presented as a standard model that can be used either wholly or as a seed for the methods discussed above and possibly others.

Advancing the structure and use of DSMs will also impact the specific field of research on product flexibility. Cormier et al. [21] have proposed a metric to quantify design flexibility for mass customization. Mass customization aims to minimize the cost of manufacturing products tailored for individual customers. Research on design flexibility for future evolution differs because the product is designed to evolve into future product offerings in response to potentially unanticipated factors. A goal of the present research is to develop a quantified measurement of design evolvability. Previous methods rely heavily on the expert knowledge of the person examining a product and specific future changes that are predicted [22, 23]. This reliance on subjective information makes it difficult to compare products that have been examined by different experts, and also makes it unreasonable to compare products that vary in complexity and functional purpose. New methods hope to avoid these problems by creating evolvability analysis processes that operate on the HDDSM model and do not require expert knowledge of market trends and other qualitative factors [5]. The first step in creating a more objective measure of design evolvability is having a product model that is more independent of the specific examiner creating it. Our specific objective is:

> We assume that the architecture of a product is an inherent trait of the product's design that is independent of human interpretation. We have developed a tool to represent and 'measure' the architecture of products. Here we test the ability of our tool to produce repeatable representation models when used by different people.

3. RESEARCH METHOD[1]

The research method described here was created to address the following research questions:

- Can different human examiners create similar HDDSM models of a product?
- What recommendations can be made to improve the HDDSM as an objective model of product architecture?

Two separate experiments were used to test the repeatability of the modeling process. The research method is illustrated in Figure 4. In the first study, a set of participants independently examined four electromechanical products. Each participant examined two products so that each product was examined by three different people. In a second study, nine participants independently examined a single product and then responded to a questionnaire about the modeling process. This section describes the organization of each study and the methods used to compare HDDSM models created by different participants.

For this experiment, graphical user interface tools were created in MATLAB based on the modeling process for the HDDSM. The software allows examiners to indicate the presence and direction of interactions between pairs of elements. The software also includes some limited methods of reviewing the information entered. The HDDSM model and method could be created on any medium and is not restricted to any special software. The model could be created on paper or in basic spreadsheet software. However, due to the large quantity of information, it is beneficial to create specialized functions and programs for representing and processing the data.

[1] This research study was approved by the University of Texas at Austin Institutional Review Board. Consent was obtained from each participant. Participants were compensated for their time.

3.1 HDDSM Multiple Product Repeatability Study

Six students from the undergraduate and graduate mechanical engineering program at the University of Texas at Austin participated in the first study. Participants were required to be familiar with function structures, activity diagrams, and product disassembly. One female participant took part in the study. Five of the six participants were senior-level undergraduate mechanical engineering students and one participant was a first-year graduate student. Each participant was given a serial number and randomly assigned two products. Participants were provided with the assigned products, a workspace to disassemble the products, and tools for product disassembly. All participants were required to attend a training session where the reverse engineering process was explained and demonstrated. A set of software tools was demonstrated using a basic example.

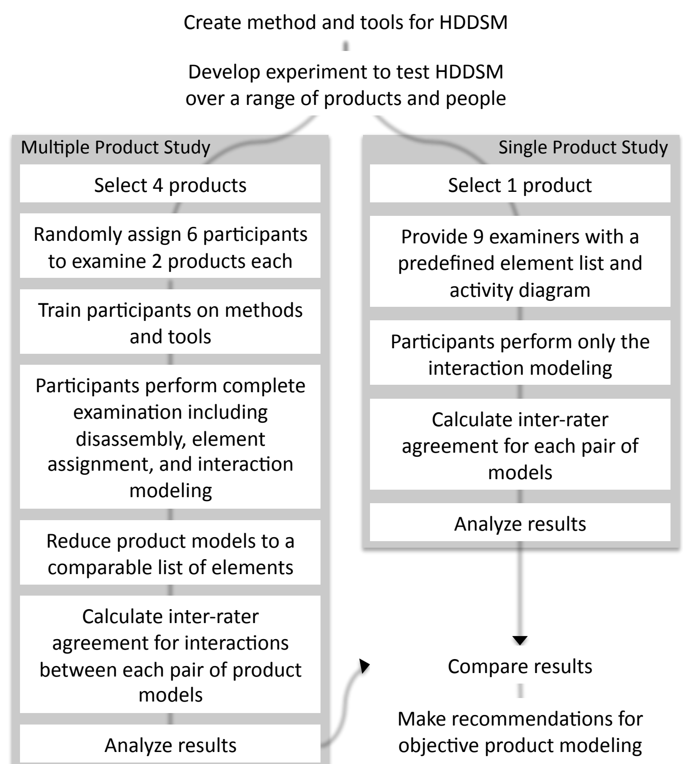


Figure 4: Research method

Each participant followed a standard reverse engineering process. Participants familiarized themselves with a product by examining the product packaging and operating manual and by using the product. The first output created by each participant was an activity diagram as described by Otto and Wood [24]. The participant identified the primary operation state of the product and focused on modeling interactions present in that state.

After completion of the activity diagram, each participant began disassembly. During disassembly, a Bill of Materials (BOM) was created that identifies each unique component used in the product. On the BOM, identifying characteristics of the components such as material and color are noted. After completion of the BOM, each participant followed the HDDSM modeling process described by Tilstra et al. [5]. The process requires the examiner to carefully consider the input and output flows for each component. Then every pair of elements that could possibly interact is examined, and possible interactions between the elements are recorded.

Consumer products were selected as the data set for this research study based on the availability of multiple products and the familiarity of the products to the participants. Products were selected based on a set of criteria:

- Energy conversion takes place within the product
- Product has nearly continuous operation
- Product has more than 20 easily disassembled parts

In addition, products were selected to cover a range of working principles such as mechanical and thermal systems. Consumer products provide a rich set for studying product architecture because many products can be found in the marketplace that perform nearly the same functions but are distinct in how those functions are mapped to the physical components. The four products used are:

- Black and Decker® Cordless Power Scissors
- Counter Cook™ 10-cup Coffee Maker
- Revolutionary Cooling Systems Cooper Cooler™
- Black and Decker® Lids Off™ Jar Opener

Participants were randomly assigned to examine two products as shown in Table 1. Consequently, three HDDSM models are created for each product in the study. This design allows for three comparisons of agreement to be made between pairs of examiners for each product as indicated in the last row of Table 1.

Table 1: Products and examiners

	Power Scissors	Coffee Maker	Cooper Cooler	Jar Opener
Examiner 1	X	X		
Examiner 2		X	X	
Examiner 3			X	X
Examiner 4	X			X
Examiner 5	X	X		
Examiner 6			X	X
Inter-rater Agreement	$\kappa_{PS1,4}$; $\kappa_{PS1,5}$; $\kappa_{PS4,5}$	$\kappa_{CM1,2}$; $\kappa_{CM1,5}$; $\kappa_{CM2,5}$	$\kappa_{CC2,3}$; $\kappa_{CC2,6}$; $\kappa_{CC3,6}$	$\kappa_{JO3,4}$; $\kappa_{JO3,6}$; $\kappa_{JO4,6}$

Figure 5: Products used in multiple product study

3.2 HDDSM Single Product Repeatability Study

While the first study required participants to complete the entire reverse engineering process, a second study was commissioned to focus solely on the task of interaction modeling. In this study, nine graduate students (six male and three female) were asked to identify the interactions between 14 elements of a consumer cordless drill, shown in Figure 6. The product for this study was selected based on the same criteria as those in the multiple product study. A template of the HDDSM was created based on the elements shown in Figure 6 and provided to each participant on a computer pre-loaded with the modeling software.

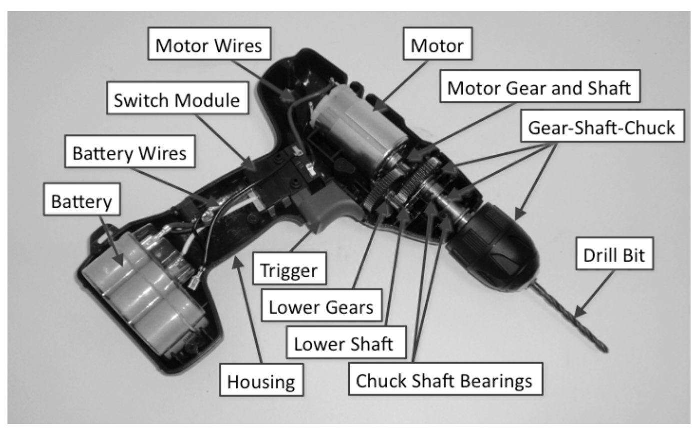


Figure 6: Product used in single product study

Before modeling the interactions independently, the participants were allowed to ask questions and discuss the definition of the interactions in an open forum. The participants were provided with an activity diagram for the cordless drill indicating the activity to be considered, the labeled picture of elements above, and the physical drill as shown in the picture. As before, the models created were compared, and a kappa index of agreement was calculated for each pair of examiners. Since nine examiners participated in the study, there were 36 pairs of examiners to compare. After completing the study, the students were asked to answer a questionnaire investigating their understanding of the modeling process and interaction definitions.

3.3 Agreement Analysis Methods

For each pair of HDDSM models obtained from the study, the similarity of the models was assessed using inter-rater agreement techniques adapted from Tinsley's research [25]. The inter-rater agreement is calculated separately for each individual layer of interaction recorded in the HDDSM. While the HDDSM records directional interactions between element pairs, the data can be generalized to a non-directional model by combining each interaction layer matrix with its transpose. The kappa index, κ, provides a measure of agreement between experimental raters by comparing actual agreement to the level of agreement predicted by chance alone.

$$\kappa = (P_a - P_c) / (1 - P_c) \qquad \text{Eq. 1}$$

P_a: Proportion of cells for which examiners agree
P_c: Proportion of expected agreement based on chance

Adapting the kappa index to this study, a single Design Structure Matrix can be viewed as a series of tests in which the examiner is rating an element pair as either interacting, or not interacting. A kappa index of 1.0 means that the two examiners entered exactly the same interactions in all cells of the DSM. A kappa index of 0.0 indicates that the proportion of cells that are the same between the two examiner's DSMs is exactly the same proportion that would be expected due to chance alone. A kappa value less than 0.0 indicates that there was a concerted effort by the two examiners to create different DSMs. The expected chance agreement, P_c, is calculated based on the product of marginal proportions of the ratings given by each examiner as follows in Equation 2.

$$P_c = (P_{01} * P_{02}) + (P_{11} * P_{12}) \qquad \text{Eq. 2}$$

P_{01}: Proportion of cells marked '0' by first examiner
P_{02}: Proportion of cells marked '0' by second examiner
P_{11}: Proportion of cells marked '1' by first examiner
P_{12}: Proportion of cells marked '1' by second examiner

Equation 2 gives a reasonable expected chance agreement that automatically adjusts for the sparseness of the DSM models being compared. Although the kappa index usually ranges between zero to one, it should not be over-simplified as a percentage of agreement. Acceptable levels of agreement are based on ranges given in literature such as the ranges provided by Landis and Koch [26].

4. RESULTS OF MULTIPLE PRODUCT STUDY

As shown previously in Table 1, three HDDSM models were independently created for each of the four products. The HDDSM models were collected and reduced to a common, comparable list of elements for each product studied. Since each examiner was required to disassemble each product and create a bill of materials independently, some of the models were created to different levels of detail. The number of elements used in the comparison of each product is shown in Table 2. Each HDDSM model created by an examiner contains 25 interaction matrices as specified by the Interaction Basis (Appendix A). The agreement for each type of interaction between a pair of examiners is determined using Equations 1 and 2 discussed above. Due to the nature of the interactions being modeled, there is a significant difference in the number of marks recorded for different interaction types. For example, many pairs of components will be in proximity to each other within a product, while only a few pairs of components may transfer energy between one another. Figure 7 shows a logarithmic plot of the average number of marks in each interaction matrix for each product. Some types of interactions were not used at all in the products examined. They are included in the HDDSM and in the Functional Basis so that the methods may be readily extended to other types of systems. For the remainder of this paper, those interactions that were not used and those for which there are very few marks are excluded from further discussion.

Table 2: Average number of elements in HDDSMs

Product	Number of Elements
Power Scissors	21
Coffee Maker	36
Cooper Cooler	44
Jar Opener	60

The average agreement index is shown for each of a subset of the interactions along with the average number of marks in Figure 8. The 'X' marker shows the average kappa agreement, and the line indicates plus and minus one standard deviation of the kappa indices between pairs of examiners. Here, the average number of marks is not shown on a logarithmic scale to illustrate the extreme difference in frequency between the different types of interactions. As shown in Figure 8, the level of agreement in HDDSM modeling varies greatly depending on the specific type of interaction.

While the setup of this study allowed a variety of products to be compared, the results are heavily dependent on each examiner. As seen in Table 1, if one examiner does a poor job of creating a HDDSM model, it will affect two of the three kappa values created for each product comparison. This significantly pulls down the average agreement for the product. The maximum kappa value observed for each interaction layer is also shown on Figure 8.

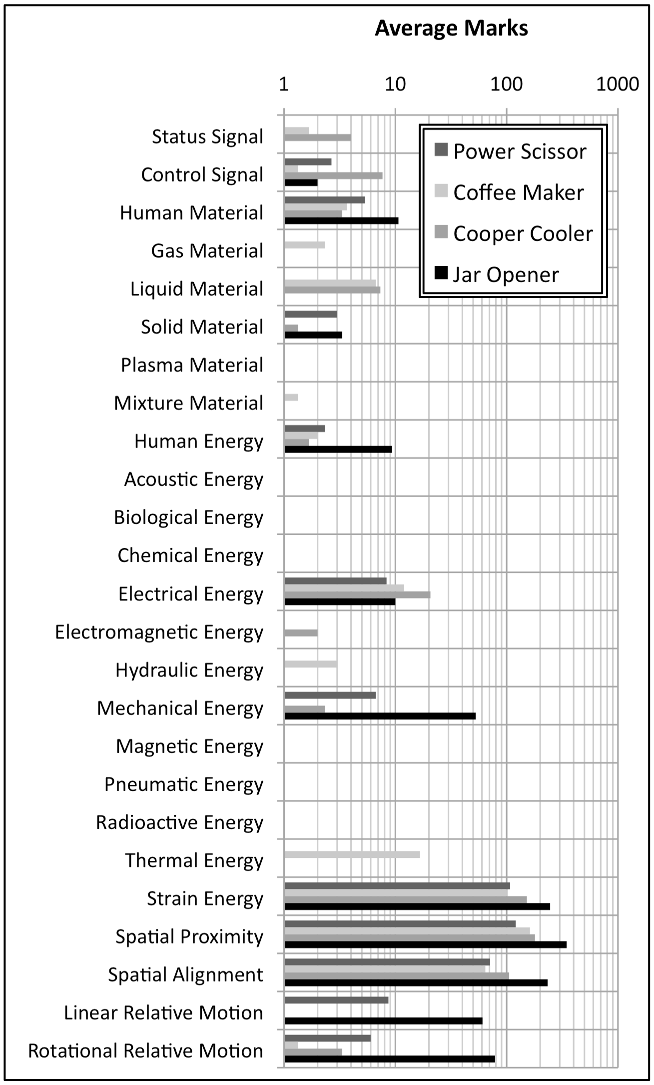


Figure 7: Average marks recorded for each type of interaction layer per product

Across all of the products studied, the best agreement between examiners was found in the "Strain Energy" and "Spatial Proximity" layers. These two types of interaction also have the highest average marks in each of the product HDDSM models. The high level of agreement can be attributed to the obviousness of these interaction types and also to the reduced sensitivity to missing marks due to the higher frequency of occurrence within the products. Strain energy is meant to capture the surface deformation when two components are pressed together. For example, if two plates are bolted together, there is an energy threshold that must be overcome to shear the two plates apart. In the same way, any two elements that are pressed together have a similar, although debatably minor, energy threshold that must be overcome to separate them. Therefore, strain energy captures contact between elements. Proximity was generally defined to the examiners as two elements being near each other such that a reasonable increase in dimension of one element would interfere with the other. Both "Strain Energy" and "Spatial Proximity" are inherently non-directional interactions.

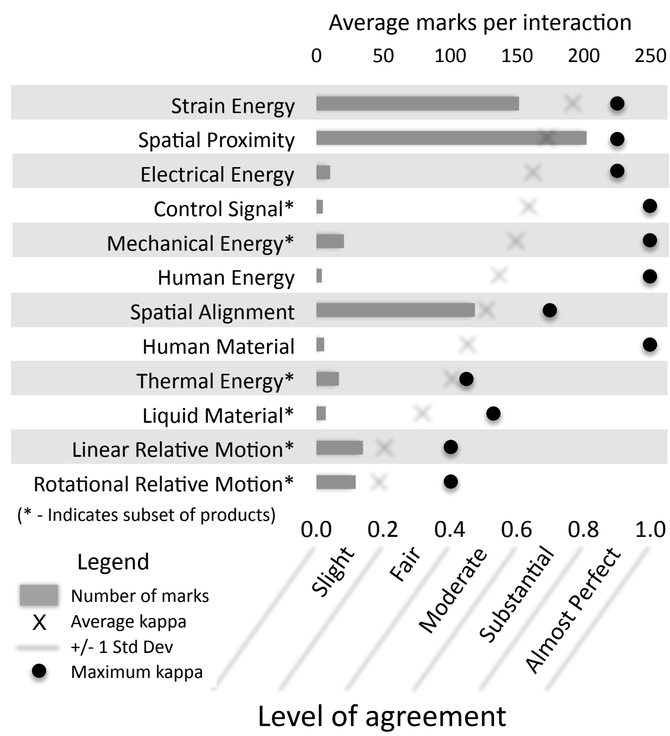


Figure 8: Average level of agreement in interaction layers of the HDDSM for multiple product study

"Spatial Alignment" was described to the examiners as being when the geometry of one element orients the position or path of another element. Despite the significant openness to interpretation, this interaction was still modeled with moderate agreement between the examiners, at the high-end of the moderate range. For both the power scissors and the jar opener products, one pair of examiners had a kappa value of 0.7, which is substantial agreement. When the models where generalized to non-directional interactions and analyzed for agreement, the spatial alignment agreement increased from 0.52 to 0.68. In the comparison of directional models, if one examiner recorded that Element A aligned Element B and the other examiner indicated that Element B aligned Element A, this would be seen as a disagreement. If each model was generalized to be non-directional, both models would show that A aligns B and B aligns A. Therefore the models would be in agreement.

Moderate to substantial agreement was also achieved in interaction layers that had less than ten marks. Interactions of "Control Signal," "Human Energy," "Electrical Energy," and "Mechanical Energy" all had an average kappa agreement index over 0.5 and at least one examiner pair had perfect agreement. To understand the lower levels of agreement in these types of interactions, the individual HDDSM models were reviewed and compared. Disagreement in the "Control Signal" layer of the HDDSM appears to focus on how far to carry the control signal into the product. All examiners' HDDSM models of the Cooper Cooler agreed that a control is input to the front panel buttons, transmitted through a data cable, and then passed to the main circuit board. Two examiners stopped modeling the control interactions at this point in the product while a third examiner modeled the control signal then being passed through the wires to the two different motors.

According to the functional basis, Human Energy is "work performed by a person on a device" [27]. In the HDDSM models created by the examiners, there is disagreement between whether the work being performed is purposeful, such as pressing a trigger, or if work is performed by just being in contact with a device, such as holding the handle. The former was intended when the HDDSM model was specified so that energy flows could be tracked through a system.

The substantial agreement in modeling interactions of "Electrical Energy" is expected given the obviousness of electrical connections in these types of consumer products. The repeatability of the electrical energy interactions is improved immensely by generalizing to a non-directional interaction. As entered by the examiners, the average kappa value was 0.67. When the non-directional model is analyzed for agreement, the average kappa value increases to 0.83, which is in the range of almost perfect agreement.

The wide variation of the agreement in "Mechanical Energy" interactions is due to the HDDSM models of the jar opener product. When considering all four products, the average kappa agreement index is 0.61, but excluding the jar opener increases the average agreement to 0.8, which is almost perfect agreement. The jar opener uses a clamping mechanism to twist-off the lid of a jar (Figure 9) while a similar mechanism is used to hold the base of the jar. Initially, the output from the driveshaft turns a gear that draws in the clamps. As the clamps come into contact with the lid, the torque from the gear continues to act, and the entire mechanism is turned. The motion of the unopened lid turns the jar, which causes the lower mechanism to move and draw in the lower clamps. Once the lower clamps have tightened, the jar is restricted from further rotation and the lid is opened. Each examiner followed the flow of mechanical energy through these components differently.

Interactions of "Thermal Energy" were only recorded by examiners of the coffee maker product. The kappa agreement between examiners is improved by generalizing to a non-directional model. The kappa index as modeled is 0.42, and the non-directional kappa index is 0.53. Disagreements in this interaction also can be attributed to how far the flow of thermal energy is followed. One examiner followed the thermal interaction along with the flow of water as it moved up through the pipes and into the filter basket, while the other examiners only modeled the thermal energy being transferred from the heater into the hotplate and heat exchanger.

While the Cooper Cooler is a product that claims to chill beverages, the product itself does not create or prevent any heat transfer. The reservoir of the product is to be filled with ice and water. The product then pumps the water onto the beverage container while it is being rotated. This is simply an improvement over the natural convection that would be obtained from placing the beverage directly into ice water. However, there are no heat exchangers, Peltier plates, or insulation within the product. So it is not surprising that the examiners did not model any thermal interactions.

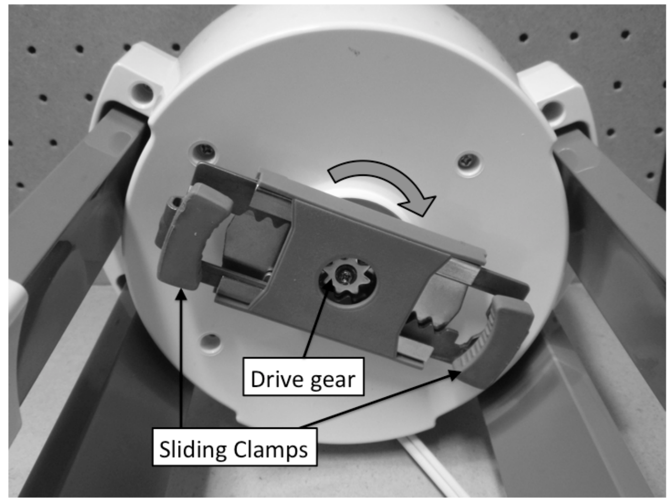


Figure 9: The clamping mechanism of the Black and Decker Jar Opener

Both the "Linear Relative Motion" and the "Rotational Relative Motion" have slight to fair agreement. Generalizing the movement interactions to be non-directional produced a small increase in the agreement between HDDSM models. The models as entered by the examiners had an index of agreement of 0.2 for both linear and rotational relative motion. When the models are generalized to be symmetrical interactions, the agreement increases only to 0.3 for both types of relative motion. There are a few reasons why interactions of motion were problematic for the examiners. Considering the directionality of the interaction was a concern expressed by the examiners. In some products, such as the power scissors, it was clear which components to view as 'fixed' and which components were moving relative to those. However, in the jar opener product, where many components moved together but also relative to each other, it was less clear. In the jar opener product, the relative motion between components changes depending on whether or not the grips have engaged the lid of the jar.

5. RESULTS OF SINGLE PRODUCT STUDY

Nine examiners independently created HDDSM models for the cordless drill, which provides 36 pairs of HDDSM models to be compared for inter-rater agreement. The results are shown in Figure 10. While the product in this study was examined by many more people than the products in the previous study, the results are still strongly influenced by any one examiner who does a poor job of modeling an interaction. Of the 36 kappa values calculated, each examiner will be used in 8 of them, which could significantly influence the average.

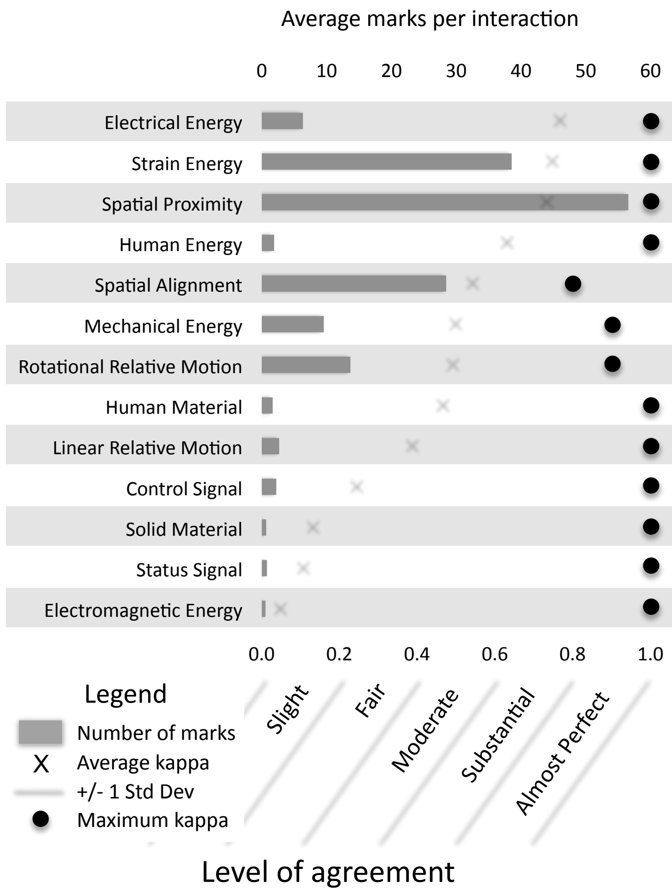


Figure 10: Average level of agreement in interaction layers of the HDDSM for single product study

The maximum inter-rater agreement for each type of interaction is also shown in Figure 10. This quantity offers some assurance that two independent people can indeed be completely in agreement for many of the interaction types. However, the overall purpose of this research study is to find insights that can improve the HDDSM model; so, more focus is given to understanding the lower levels of average agreement.

Figure 11 shows the responses to a survey filled out by the participants after completion of the modeling exercise. The participants were asked to rate their level of understanding for the types of interactions that were used by them during the study. Comparing the results of the survey with the agreement of the participants' HDDSM models reveals that lower levels of agreement cannot necessarily be predicted by the examiners' perceived understanding of the interactions. This is especially apparent for the functional flows of energy, signals, and materials due in part to the low number of marks recorded for these types of interactions. For example, 'Human Energy' was rated as the most well understood type of interaction by the nine examiners. However, the agreement seen in the actual models varied greatly for reasons similar to those discussed in the previous study. Examiners indicated a lower understanding of the 'Status Signal' and 'Control Signal' interactions, which have correspondingly low levels of agreement in the models.

These results have implications for the effectiveness of examiner training. Specifically, if each individual examiner assumes that he/she has an 'Excellent' understanding of the interaction types, he/she may not be receptive to further instruction. It could also lead to two types of errors that can decrease the use and transferability of product models.

- Type A Error: Examiners think that they have a good understanding of the interaction's definition, but in reality individual examiners do not have a consistent definition.
- Type B Error: Examiners know that they have a unique understanding of the interaction's definition, but the model standard doesn't allow them to communicate their unique interpretation.

The Type A Error is a problem of false confidence. For example, consider the interaction of Human Energy. All of the participants indicated that they had a Good to Excellent understanding of this interaction, yet the distribution of agreement between examiners is very large, ranging from Fair to Almost Perfect agreement. The danger with this type of error is that the inconsistency of the definition held by each examiner may never be discussed. If a large system was to be created by merging the HDDSM models of subsystems created by different people, the inconsistencies between the way an interaction was captured in the subsystem models may go unnoticed because everyone thinks the interaction is well understood.

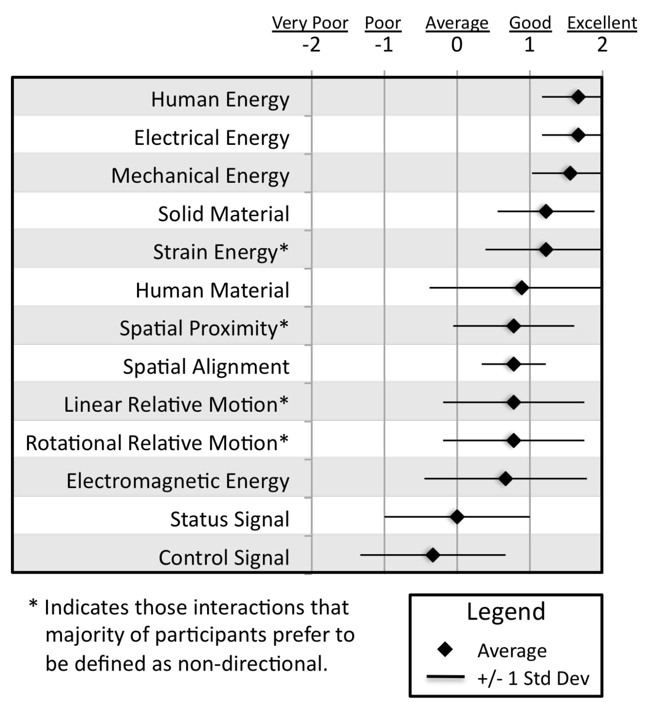


Figure 11: Participant response to self assessment on level of understanding for each interaction

The Type B Error will lead to problems when models are transferred between disconnected groups of people. Type B errors will be especially problematic in the use of knowledge bases or repositories where people are asked to submit models in a common format. The model created by an examiner under Type B Error will still be useful for that examiner since they understand the limitations and nuances of the model and how it may effect any conclusions drawn from the model. However, if a different person wishes to use that model along with a number of other models, all created by different examiners, any conclusions will be marred by the inconsistent definition between the independent examiners.

6. DISCUSSION OF RESULTS

The HDDSM restricts examiners to make a binary decision about the existence of an interaction between a pair of elements. This requires the examiner to set a threshold that determines the cutoff between an interaction existing or not existing. For example, when capturing interactions of Spatial Proximity, examiners were told that they could test for proximity in the following way:

> If a reasonable increase in a dimension of element A causes it to contact or interfere with element B, then B is in the proximity of A.

In this study, no firm threshold was given to the examiners. As a result, one examiner may have defined "a reasonable increase in dimension" to be one millimeter while another examiner may have defined it to be an increase in length of five percent. During the studies, no examiner used or asked to use calipers to measure the distance between components. This implies that examiners used their instincts without necessarily setting a hard and fast threshold. Despite the lack of being given or stating a concrete threshold, the agreement for Spatial Proximity was quite high.

Other types of interaction were more difficult for setting a threshold. There was only slight agreement for interactions of Status Signals, and the survey results show that examiners found it somewhat difficult to set a threshold. The Status Signal is intended to capture information about the state of the system being passed from one element to another. For the cordless drill studied, there are a number of ways a user can get information about the state of the system. Some possible ways a user might infer about the status of the drill are listed below.

- Visible rotation of the chuck
- Visible rotation of the drill bit
- Visible position of the trigger
- Sound of the motor
- Sound of the gears
- Vibration transmitted through the housing
- Reaction torque transmitted to the hand

After the interaction modeling was completed, all examiners agreed that these existed but debated about the significance of including all of them in the same model. This may suggest a challenge in extending the functional basis to product architecture models. In a functional model, all of the status signals listed above may be generally recorded by a "Provide status" function. However, there is no way to generically capture the status signals in a product architecture model; instead, they must be mapped to specific components. Similar issues can be seen in the product models from both studies. For example, only one of three examiners recorded that the translucent plastic lid of the Cooper Cooler allowed the user to receive status signals about the product's operation.

Examiners also expressed difficulty in knowing how far to carry some of the interaction flows. Many examiners agreed that a Control Signal was received by the trigger from outside of the product. This control signal was accompanied by an interaction of Human Energy which provided the force necessary to move the trigger. However, there was disagreement in whether the Control Signal continued to flow into and through the system. Some examiners stopped the control signal at the trigger, a few carried the control signal from the trigger into the electric switch, and a few carried the control signal all the way through the electrical wires to the motor.

7. CONCLUSIONS AND FUTURE WORK

Based on the results of this research, the following conclusions are made:

- The repeatability of interaction modeling is determined by the concreteness of the definition for the interaction.
- The repeatability is improved by defining interactions as non-directional when appropriate.
- The repeatability is improved by clearly specifying the activities to consider because the interactions between elements of a product, and even the elements themselves, may change significantly during different activity states.

The first conclusion is strongly supported by the range of kappa agreement values in both studies and from the feedback gathered from participants. More agreement can be expected between examiners for interactions that have objective definitions and clear thresholds. This conclusion validates findings from other researchers. Jarratt et al. [11] found that when creating a model for change propagation in a diesel engine, people "largely agreed on geometric connections between parts," but "dynamic links, electrical and thermal links were interpreted quite differently." A deeper insight that could be drawn from this conclusion is that examiners had difficulty mapping the functional flows that occur within a product to specific components. It is expected that repeatability could be improved by further extending the list of interactions to include more specific types of interactions, such as a return-path for the different types of energies.

For some types of interactions, the direction of the interaction is either trivial or unclear. Therefore interactions should be clearly defined as non-directional when applicable to increase the repeatability of the model created. This was especially true for interactions of "Spatial Alignment." When the HDDSM format was created, "Spatial Alignment" was introduced with the intent of being able to capture the roles that a structural framework and fasteners have in a product. However, when considering the interaction of two elements it is difficult to have a frame of reference (i.e. does the screw align the plate it is holding, or does the hole in the plate align the screw?)

The repeatability of the HDDSM method could be improved with rigorous training and testing of examiners. However, rigorous training was not provided to the participants because the purpose of the study was not to test the examiners' ability to replicate observed examples. Although there was some discussion of the interaction basis, the examiners were largely required to rely on their familiarity with the functional basis and their interpretation of the definitions provided to them. Showing repeatability among a group of examiners with limited training will facilitate the more wide-spread use of the method. Ideally, the HDDSM or any other model of product architecture can be defined in a way that is naturally repeatable without the need for excessive training beyond the customary education of mechanical engineering.

It was anticipated before the study began that repeatability could be severely reduced if examiners did not consider the same activity state of the product.. We attempted to control for this issue by selecting products that have nearly continuous operation (thus making it easier to imagine the quasi-steady state of the product during operation) and also by having each examiner create an activity diagram and recognize the single activity of operation. However, there was still evidence to support that the specification of the activity to be modeled is very important in creating a repeatable model. Rather than trying to restrict the examiner to a specific activity, an alternative approach would be to define distinct layers of interaction where different activities may conflict.

The High Definition Design Structure Matrix was created to address the need for an objective model that could be used for the quantitative evaluation of characteristics of evolvable design and other analysis and design activities related to product architecture. The format for the HDDSM is based on combining the power and simplicity of DSM methods with the language defined for functional modeling. Therefore, implications of this study can be drawn for research related to both topics as well as product representation in general.

Overall, the study provided great insight into the strength and weaknesses of the HDDSM for representing product architecture. One advantage of the DSM is that it forces the examiner to think about every possible interaction, which may expose some interactions that would otherwise be missed. The participants in both research studies commented that the HDDSM modeling process forced them to think critically about the design of the product.

When possible, it is most useful to have a team of people collaborating on the creation of the model since some people may identify interactions others have not [7, 11]. However, the team approach may require a significant investment of time and cost when creating a HDDSM model of a system. The results found in this study suggest that with the careful definition of interaction types, an objective HDDSM could be created. This may require the extension of the Interaction Basis to allow for multiple distinct flows of an interaction to be captured separately.

Whether product models will be kept proprietary within an organization or will be posted to a public repository, there are immense benefits to having a repeatable product model. When using a team approach, a repeatable model may require less cost and resources to create due to increased initial agreement among those involved. A repeatable model will also allow experts to independently create the model for the part of the system that they are most familiar and then combine the independent models. If repeatable models can be created within an organization, then those models could be reused for analysis or comparison long after the original team that created them has dispersed.

When testing the accuracy and usefulness of new analysis methods for design methodology, such as those being developed for product evolvability, there is a difficult challenge in acquiring a significant data set. An objective, repeatable model will allow for a collection of models to be used when evaluating new methods for analysis. The agreement analysis used in this work could be useful during the training of examiners to evaluate their understanding compared to a control model.

Future work will focus on improving the HDDSM format and process based on the findings of this study. While the Interaction Basis may be sufficient for simple products, the HDDSM will be expanded to allow multiple, more specific instances of those interactions to be captured separately. Work will also be done to improve definitions of the interaction types. Ideally, all interactions should be as straightforward as the participants found Electrical Energy and Strain Energy to be. Based on feedback from participants, more examples of each type of interaction will be specified in a reference document. Making this document available to examiners during the modeling process is expected to help improve the repeatability of the models. The HDDSM is also being used to seed more analysis-specific models. For example, the HDDSM of a given product can be used to generate an initial graph that can then be reviewed and augmented with more specific information such as disassembly processes. The same HDDSM could then be augmented with information necessary for change propagation or for the analysis of design guidelines.

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APPENDIX A: THE INTERACTION BASIS

General	Specific
Information	Status
	Control
Material	Human
	Gas
	Liquid
	Solid
	Plasma
	Mixture
Energy	Human
	Acoustic
	Biological
	Chemical
	Electrical
	Electromagnetic
	Hydraulic
	Mechanical
	Magnetic
	Pneumatic
	Radioactive
	Thermal
	Strain Energy
Spatial	Proximity
	Alignment
Movement	Linear
	Rotational

APPENDIX B: HDDSM FOR CORDLESS DRILL EXAMPLE

The DSMs below represent the specific layers of interaction recorded in the HDDSM for the cordless drill discussed in Section 2 and used in the single product repeatability study. A labeled picture of the elements is provided in Figure 6.