8-2011

A Method for Evaluating Manufacturing Change in Engineering Design

Christopher Brooks
Clemson University, cbrooks@clemson.edu

Recommended Citation

Brooks, Christopher, "A Method for Evaluating Manufacturing Change in Engineering Design" (2011). *All Theses*. 1196.
https://tigerprints.clemson.edu/all_theses/1196

A METHOD FOR EVALUATING MANUFACTURING CHANGE IN ENGINEERING DESIGN

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

---

by
Christopher Brooks
August 2011

Accepted by:
Dr. Gregory Mocko, Committee Chair
Dr. Joshua Summers
Dr. Georges Fadel

ABSTRACT

Design changes are a frequent occurrence over the life of a product that may be initiated by an update to the product functionality, new customer needs, or generational improvements. The costs associated with these changes are undesirable, and are often times greatly inflated by additional, unanticipated changes that result from change propagating throughout the system. Propagation paths occur when an initiating change to a component necessitates subsequent changes to coupled components, as the change continues to propagate throughout the product architecture. The nature of this change propagation is challenging to characterize and accurately predict. To address this issue, a change prediction method is developed that builds upon current change management strategies. The method is comprised of: (1) a design structure matrix (DSM) to model the relationships and connectivity within a system, (2) coupling index (CI) values (ranging from 0 to 1) that assess the likeliness of a change to one component/feature affecting another, and (3) design for manufacturing (DFM) information to provide an estimate of the cost and impact of a change.

The method can either be applied at the component level, or through further decomposition, at the interfacing feature level. Modeling the relationships between interfacing features, as opposed to components, offers a more detailed representation of change, but requires more knowledge of the system that may not be available in the earlier stages of design. When evaluating a propagation path, the coupling index values are multiplied together as the path extends, to produce a decreased probability for higher orders of coupling. The proposed change prediction method is applied on three industry examples: BMW X5 headliner and center console assemblies, and a Ryobi drill assembly. The method is shown to produce viable results that allow for informed decisions during change management. These results show that the objective measures of coupling and manufacturing cost of change are effective approximations. A comparison of the results from the component and feature based methods show that a feature level analysis offers improvements in accuracy, and sensitivity to uncertainty and path representation. Furthermore, the method proves to be a valuable tool during the initial design of a product, as it can be used to identify features, interfaces, and manufacturing types that will lower a product's overall ease of change.

ACKNOWLEDGMENTS

I would like to thank my family for their support and encouragement. I would also like to thank my advisor, Dr. Mocko, for his guidance and willingness to help throughout this thesis process.

TABLE OF CONTENTS

Page

CHAPTER

Table of Contents (Continued)

Page

LIST OF TABLES

Table Page

List of Tables (Continued)

Table Page

List of Tables (Continued)

Table Page

LIST OF FIGURES

Figure Page

List of Figures (Continued)

Figure Page

List of Figures (Continued)

Figure Page

List of Figures (Continued)

List of Figures (Continued)

Figure Page

CHAPTER ONE

RESEARCH MOTIVATION

The principle objective of this thesis ***is to develop a change prediction method to better model the change propagation within a system, and assess the difficulty and cost of initiating changes***. Specifically, this research aims to develop a change prediction method that is based on objective measures of component/system coupling and manufacturing change costs.

The motivation for this research derives from the costs that are accrued yearly in industry due to a lack of understanding of the effects of an initiating change on the product architecture [1, 2]. Changes to existing designs are a frequent occurrence in industry that may be required to update the product functionality, meet new customer needs, or realize changes in requirements [3]. The costs associated with these changes are undesirable, and often times far greater than necessary. An initiating change to a component can cause subsequent changes to coupled components, as the change propagates throughout the system. The nature of this change propagation is challenging to characterize, and can inflate costs far past that of the initiating change. The direct effects of a change are difficult to account for, but the challenge is furthered by trying to predict the indirect changes that occur. The indirect changes, in particular, are often unforeseen, as industry engineers estimate that typically 5% to 50% of changes are unexpected [4]. An accurate means of predicting how change propagates though a product architecture will allow for an informed decision on where changes should occur, and may encourage designers to make necessary changes. This could lead to cost savings, and allow designers to account for change flexibility in initial designs. Further, it may enable designers to make strategic decisions about their designs to make them easier to change, saving time and money down the road when changes are required.

1.1 Summary of Current Change Management Strategies

The first step to understanding and characterizing change propagation is to develop a visualization or representation of the connectivity and propagation paths within a system. The first representation commonly used in change prediction models is a design structure matrix (DSM) [5]. A traditional DSM models the direct links in a system using numerical or binary representations [6, 7]. The advantage of a matrix-based model is that it offers an intuitive and concise means of data representation that is easy to populate. It is also easily integrated into software, which reduces the required computational effort, and allows for the analysis of more complex systems. A limitation to the DSM is that it cannot visually model the indirect linkages in a system. To help address the limited information capacity of a traditional DSM, color coding and symbols can be added, such as in the change risk plot developed by Jarratt and colleagues [8]. The change risk plot models a system's connections using rectangles, in which the rectangle's width represents the likelihood of change, height represents the relative impact of change, and area represents the overall risk of change.

Propagation networks and trees provide a graphical model of a system that visually lays out all the direct and indirect links in a propagation path [9, 10]. Each network or tree is centered around a root component from which all the propagation paths originate. The radial distances between the root component and the other components can be used to represent the combined risk or level-distance values [11]. The advantage of a graphical representation is that it can visually model the indirect links, meaning that the full extent of the propagation paths are shown. This comes with a limitation, however, as they can become cumbersome and time consuming when modeling more complex systems. A graphical representation is also more difficult to integrate into software, which increases the required computational effort.

There are many different approaches and strategies that are used to manage change in current literature. Clarkson and colleagues present a change prediction method (CPM) that assesses the overall risk of a change to a component in terms of its effect on the entire system [4, 12]. A product is first decomposed, and a DSM is used to model the dependency between components. Using the established relationships, two DSMs are generated to model the direct likelihood and impact between component changes. The values populated within the DSMs are based on historical data and subjective estimations of the average probability that a change in one sub-system will lead to a change in another, and the average proportion of design work that will result from the change [4]. Propagation trees are then used to model the full extent of the propagation paths between components, which allows for predictive likelihood and impact of change matrices to be produced. Combining these matrices yields a risk of change matrix, which provides a measure of a component's change influence and susceptibility [4, 12].

Bashir and Thomson propose a method to estimate product complexity and predict design effort using historical data from similar designs [13-15]. The method predicts the design effort of a future product by assessing the change in “productivity” from similar past designs to the current design. Productivity is scaled up or down based on factors such as product complexity, severity of requirements, and the efficiency of the design team and the processes used [13]. Some of these factors, such as the product complexity [16], are based on defined measures, but for the most part, they are subjectively assessed by experienced engineers.

Giffin and colleagues present an analysis that can be used to model change propagation in complex technical systems [1]. Larger, more complex systems are challenging to evaluate with the majority of change management strategies because of the amount of information that must be processed and analyzed. Three measures are proposed that use the data from previous changes to yield insight into the nature of change propagation in a system. These measures evaluate whether a component is generally accepting of change (CAI) or tends to reflect change (CRI), along with assessing its propensity for change (CPI) [1, 17]. The values produced by the measures indicate whether a component is generally an originator or absorber of change, and can be used to target areas for redesign.

1.2 Challenges and Research Opportunities

The challenges associated with developing a change prediction method, as identified in the review of current change management strategies, are summarized as:

- The development of a method to model the relationships within a product that is based on a systematic, objective process.
- Evaluation of the manufacturing cost of changes that is not reliant on human interpretation or historical change data.
- The development of a representation to capture the nature of change propagation in a system.
- The development of a method that is expansive and accurate, while still being computationally practical.

1.3 Research Questions and Hypotheses

To accomplish the principle objective of developing a change prediction method to assess the difficulty and cost of initiating changes, a set of requirements must be established that address the identified challenges. These requirements are then mapped to three research questions in Table 1.

Table 1: Mapping the requirements to research questions

Requirements	Research Questions
• Evaluate the level of coupling between components to assess the probability of change propagating from one component to another • Assess the manufacturing costs associated with changes	**RQ1a:** What factors affect change propagation and impact, and how can they be incorporated into a simple and effective method of predicting change?
• Model the connectivity within a system, including the direct and indirect coupling, and the resulting propagation paths • Identify the sub-systems that should and should not be targeted for change • Evaluate the relative design effort required for redesigns • Be computationally practical • Be easily integrated into software	**RQ1b:** What form of modeling will be most efficient in incorporating the determining factors? **RQ3:** What are the benefits and costs of modeling a product at the feature level over the component level?
• Identify areas and means for improving the overall ease of change of a system	**RQ2:** Can the proposed method be used as a tool during the initial design of a product to optimize its overall ease of change?

The three research questions that are formulated in Table 1 are then summarized into a primary research question. Primary and supporting hypothesis are developed to address the research questions based on the knowledge gained from the assessment of current change management strategies. The primary and supporting research questions, along with the correlating hypotheses are shown in Table 2.

Table 2: Research questions and hypotheses

Research Questions	Research Hypotheses
Primary Research Question: How can change propagation within a system be modeled to better predict the difficulty and cost of initiating changes?	**Primary Hypothesis:** A DSM based approach will provide a simple and concise means of modeling the connectivity and propagation paths within a system. Objective level of coupling and manufacturing assessments will increase the accuracy and reliability of the difficulty of change estimates.
RQ1a: What factors affect change propagation and impact, and how can they be incorporated into a simple and effective method of predicting change?	**Hypothesis 1a:** The level of coupling between components affects how change propagates through a system, and the cost associated with a manufacturing change to the components will allow for an overall assessment of the difficulty or impact of a change.
RQ1b: What form of modeling will be most efficient in incorporating the determining factors?	**Hypothesis 1b:** A DSM will offer a model that is easily populated and visualized, and can be integrated into software to allow for efficient calculations.
RQ2: Can the proposed method be used as a tool during the initial design of a product to optimize its overall ease of change?	**Hypothesis 2:** The proposed method will provide recommendations of features, interfaces, and manufacturing types that will lower a product's overall ease of change.
RQ3: What are the benefits and costs of modeling a product at the feature level over the component level?	**Hypothesis 3:** A more detailed model of change that focuses in on the relationships between interfacing features, as opposed to components, will result in a better estimate of change difficulty, along with identifying specific aspects of a product to study. This will come at the cost of being more time consuming, and requiring more knowledge of the system that may not be available during earlier design stages.

1.4 Outline of Thesis

An illustration of the organization and content of the thesis is provided in Figure 1. The major themes of each chapter are specified, along with their relevance to the overall research.

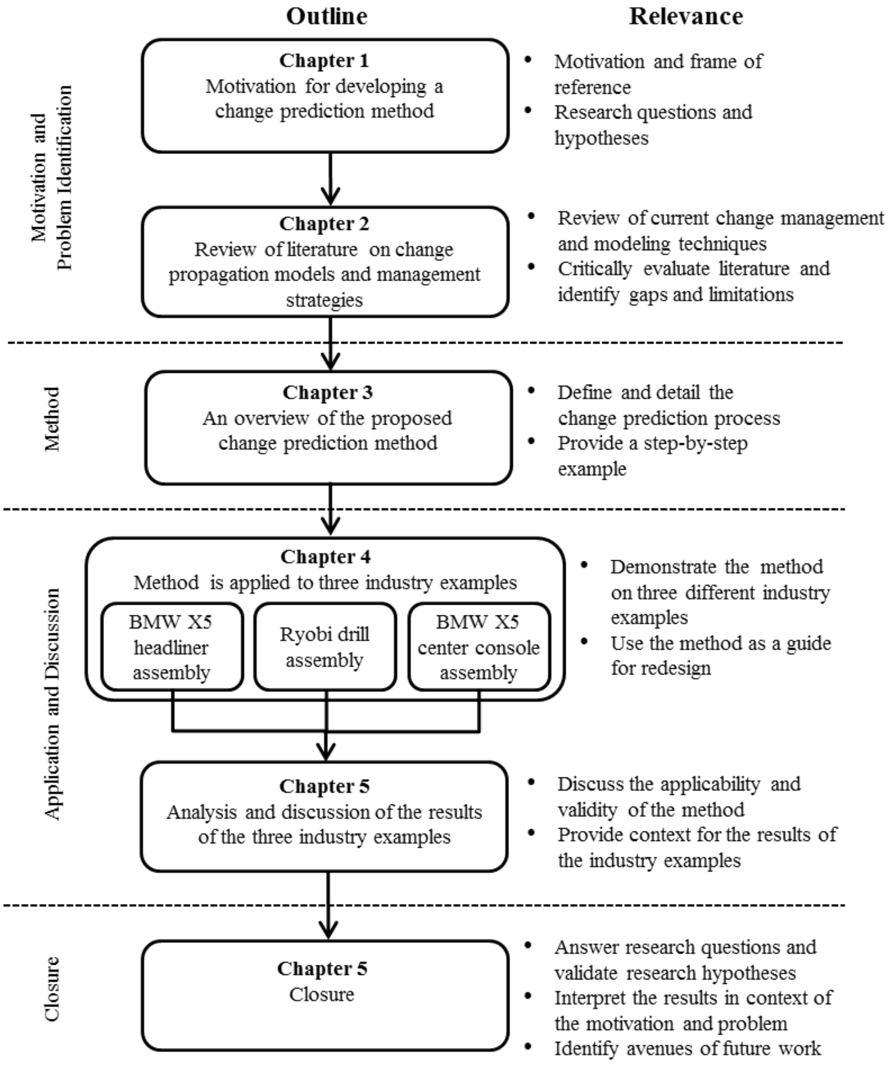


Figure 1: Outline of thesis

CHAPTER TWO

LITERATURE REVIEW

This chapter provides a frame of reference and basis for the proposed change prediction method through a detailed discussion of relevant literature. The research that is presented focuses on defining change propagation and impact, and identifying the determining factors that effect change propagation within a system. The different means of visually representing change propagation within a system are also discussed, along with their respective advantages and disadvantages. Finally, current change prediction methods are discussed, and their limitations are identified to provide a basis for the opportunities for improvement that exist in the change prediction field.

2.1 Change Propagation

Change propagation is generally defined as a progression where a change to one component or element of a system brings about sequential changes to one or more additional components or elements in the system [1, 18]. These additional changes are undesirable, as they can greatly increase the cost associated with the initial change. Research on change management in industry has found that “only 11% of all companies were able to provide a precise list of items affected by a change in the development of a single product” [1]. Thus, a better understanding of change propagation within products can lead to minimizing the unwanted additional changes that occur in complex designs.

To gain a better understanding of change propagation within products, the determining factors must be identified and assessed. The major factor in determining the level of change propagation in a product is the complexity of that product. There are many definitions of complexity [19, 20], but in this research, complexity can be defined as the level and number of connections between components or elements within a product [21, 2, 22-24]. Suh among others stress that product complexity should always be minimized by creating a one-to-one mapping between the physical architecture and the functions of a product, along with minimizing, and if possible, eliminating coupling between the elements of a system [25-27]. This creates minimal information content, and thus minimizes change propagation within a product. However, this represents the ideal layout of a product's architecture, and few products are able to achieve such a goal.

The nature of the coupling between components or subsystems within a product is also a key to understanding change propagation. Coupling between two components occurs when a change to one of the components necessitates a change to the other. This coupling can occur because of a physical connection between components, or because of a functional connection. In this research, only the physical connections will be considered. Different levels of coupling can occur between components, so the level of coupling is generally defined based on the likeliness that a change to one component will change the other [28]. Martin and Ishii [29, 30] address this by developing a Coupling Index (CI), which bases the level of coupling off of a subjective 1-10 rating. A high rating means that there is a high sensitivity between the initiating and receiving components, while a low rating means there is a low sensitivity between the initiating and receiving components.

Components or subsystems can be designated or classified based on their effect on change propagation paths within a product. The general classifications consist of [31]:

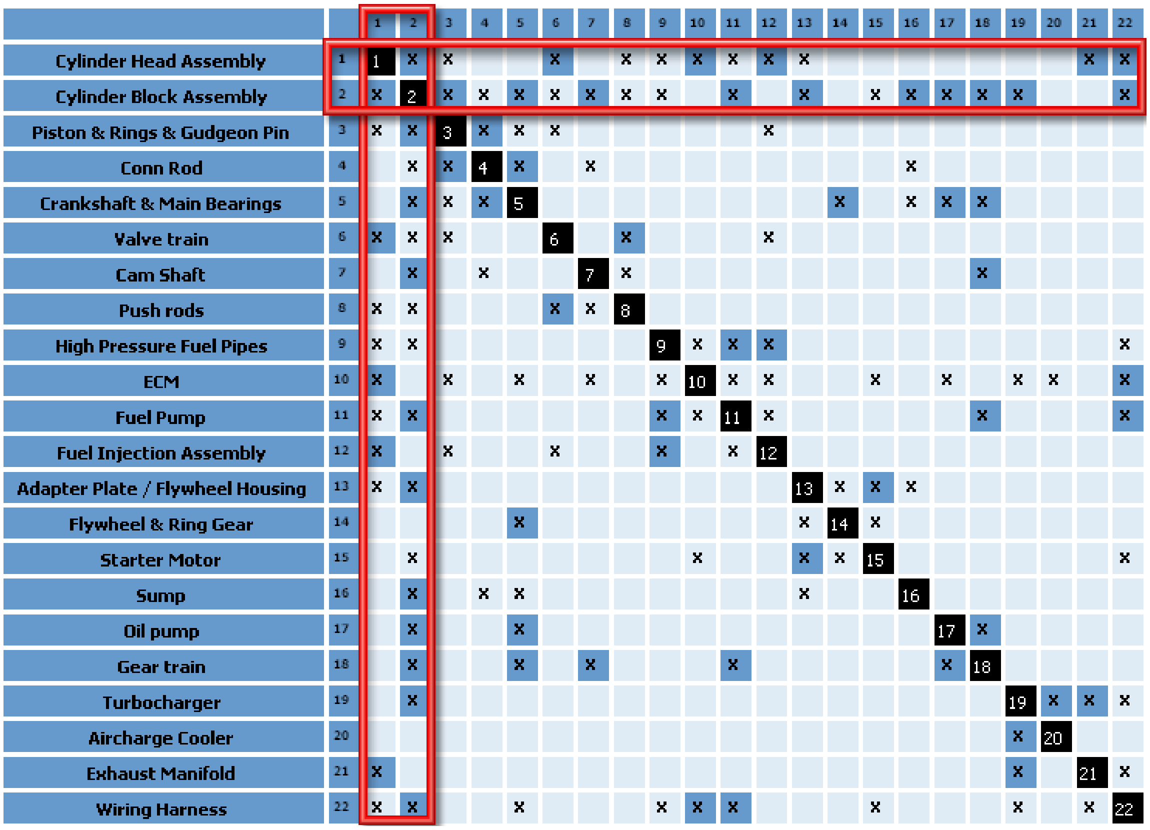
- Constants: Components that have no effect on a change propagation path; they do not absorb change or cause change. Because of this, they have no effect on the degree of change propagation.
- Absorbers: Components that absorb more change than they cause. They reduce the degree of change propagation.
- Carriers: Components that absorb about the same number of changes as they cause. They have little or no effect on the degree of change propagation.
- Multipliers: Components that cause more changes than they absorb. They increase the degree of change propagation.

2.2 Change Propagation Representations

The first step to understanding change propagation within a system is to develop a visualization or representation of how an initiating change will propagate throughout that system. Modeling change propagation in complex products can be challenging, but in general, a change propagation representation must be able to model the coupling between direct and indirect linkages, thus yielding the connectivity and propagation paths within a product. Methods commonly used to model change propagation are design structure matrices (DSMs), propagation networks, and propagation trees.

2.2.1 Design Structure Matrices

Matrix-based forms of modeling are often used in change prediction methods because they offer a simplistic means of analyzing relations within complex engineering systems [5, 32]. Matrices generally offer a more compact, systematic, and less time consuming method for modeling change propagation, in comparison to more extensive models such as propagation networks [33-35]. There are many different classifications and applications of matrix-based modeling [36-38], but the most frequently used modeling method is the design structure matrix (DSM) [39]. Design structure matrices are an effective way to visualize and map the connectivity within a product. In a traditional component-component DSM, the direct links between the components or subsystems are modeled using a numerical or binary representation [6, 40, 7, 41]. This, however, has a limitation in that it cannot display indirect linkages, which can lead to inaccurate models of change propagation especially when analyzing a complex product. To address this issue, more information can be included in the DSMs, such as using a color coding scheme to represent the different linkage types within a product [11]. Figure 2 shows an example of a DSM for a diesel engine in which all the mechanical static links are highlighted.



		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Cylinder Head Assembly	1	1	X	X			X		X	X	X	X	X	X								X	X
Cylinder Block Assembly	2	X	2	X	X	X	X	X	X	X		X		X		X	X	X	X	X			X
Piston & Rings & Gudgeon Pin	3	X	X	3	X	X	X						X										
Conn Rod	4		X	X	4	X		X									X						
Crankshaft & Main Bearings	5		X	X	X	5									X		X	X	X				
Valve train	6	X	X	X			6		X				X										
Cam Shaft	7		X		X			7	X										X				
Push rods	8	X	X				X	X	8														
High Pressure Fuel Pipes	9	X	X							9	X	X	X										X
ECM	10	X		X		X		X		X	10	X	X			X		X		X	X		X
Fuel Pump	11	X	X							X	X	11	X						X				X
Fuel Injection Assembly	12	X		X			X			X		X	12										
Adapter Plate / Flywheel Housing	13	X	X											13	X	X	X						
Flywheel & Ring Gear	14					X								X	14	X							
Starter Motor	15		X								X			X	X	15							X
Sump	16		X		X	X								X			16						
Oil pump	17		X			X												17	X				
Gear train	18		X			X		X				X						X	18				
Turbocharger	19		X																	19	X	X	X
Aircharge Cooler	20																			X	20		
Exhaust Manifold	21	X																		X		21	X
Wiring Harness	22	X	X			X				X	X	X				X				X		X	22

Figure 2: A DSM of a diesel engine [11]

As shown in Figure 2, the DSM allows for a quick identification of the connectivity of a component. In the case of the diesel engine, the cylinder head and block assemblies are identified as having a relatively high level of connectivity.

Another form of DSM, proposed by Jarratt and colleagues [8], is a change risk plot. The change risk plot provides a visualization of the combined risk of a change to one component, if another component is changed. In the DSM, the width of the plotted rectangles represents the likelihood of a change, while the height represents the relative impact of that change. Therefore, the area of each rectangle represents the overall risk, and a color-coding is used to allow for a quick identification of the high-risk connections

[4, 42]. The main drawback to the change risk plot is that it does not provide any visualization of the direct and indirect links, and the overall propagation paths. Figure 3 shows a change risk plot for a diesel engine.

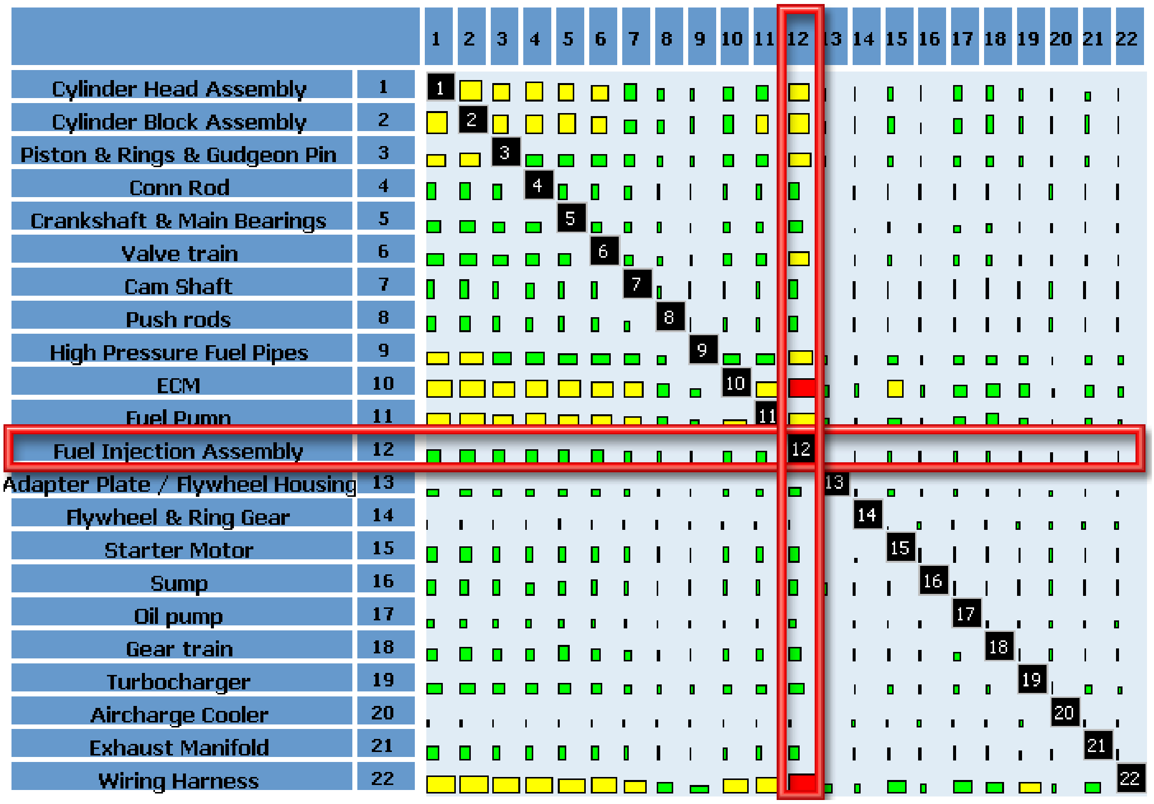


Figure 3: Change risk plot of a diesel engine [11]

The columns in the change risk plot show the risk of a change in each sub-system propagating to the rest of the system. Therefore, the rows show each sub-system's susceptibility to change propagation from the other sub-systems. As shown in Figure 3, the change risk plot identifies the fuel injection assembly as being the largest source of change propagation. It is shown to have numerous high risk connections to both directly and indirectly linked components. Alternatively, it is also shown to be relatively insusceptible to change propagation originating from the other components.

2.2.2 Propagation Networks and Trees

A propagation network or tree provides a visual layout of a system that includes all the direct and indirect links. For each propagation network or tree, a root component is selected as a starting point. The radial distances between the root component and every other component represent the combined risk or level-distance values. This allows for a visualization of the change propagation paths (including direct and indirect links) and a representation of the risk level for every component based on a change in the root component [9, 10]. In more complex products, the size of the propagation network can become cumbersome and difficult to process, so generally a focus component is also chosen in addition to the root component. The focus component, along with any closely connected components, is shown and assessed in greater detail. Many times the focus component will be chosen because it represents the shortest path to the root component. The difference between a propagation network and a propagation tree is that the tree shows multiple propagation paths at the same time. Therefore, components may appear multiple times in the propagation tree representation [11]. An example of a propagation network for the diesel engine assembly is shown below in Figure 4. Figure 5 shows an example of a propagation tree for the same diesel engine assembly with the fuel injection assembly chosen as the initiating component.

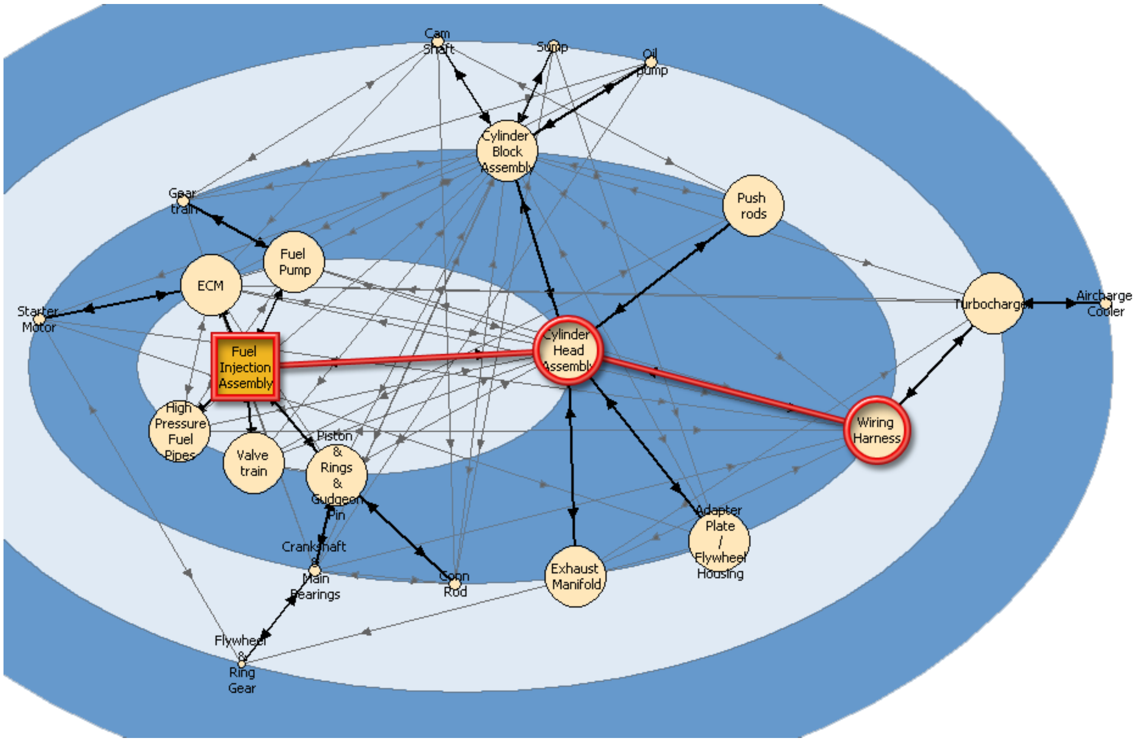


Figure 4: Propagation network of a diesel engine with the fuel injection assembly as the root component [11]

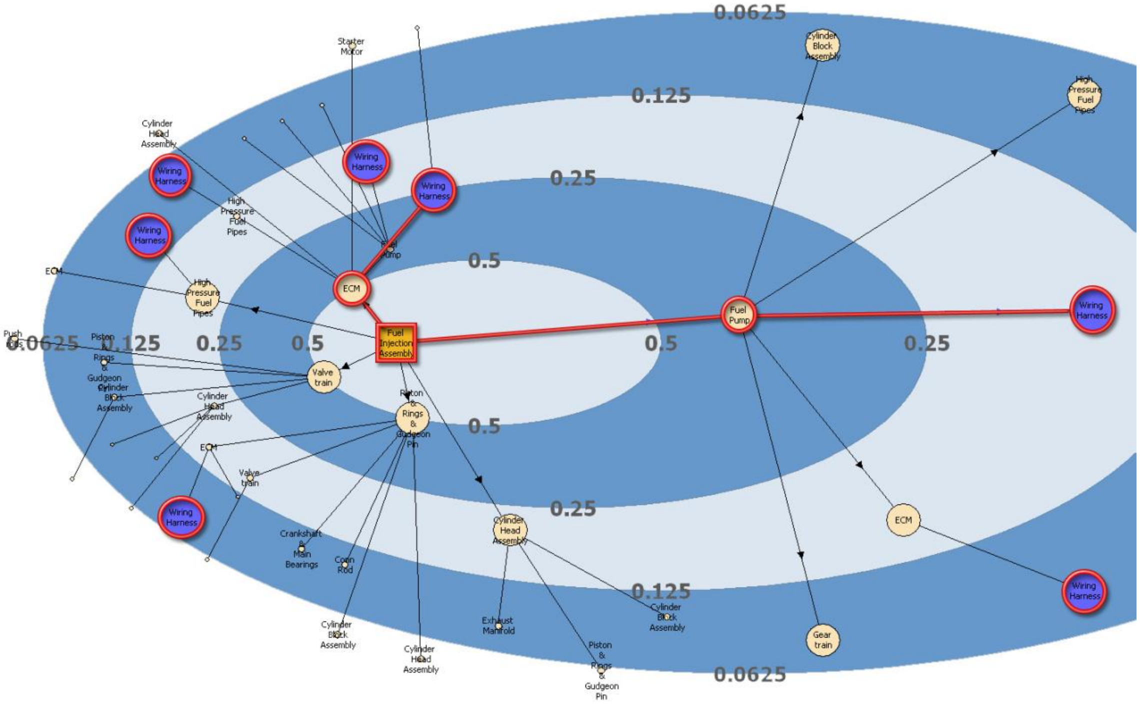


Figure 5: Propagation tree of diesel engine with the fuel injection assembly as the initiating component [11]

The propagation network (refer to Figure 4) offers a more compact representation, which allows for more information to be included. Furthermore, it allows for a better visualization of a component's overall connectivity. The propagation tree (refer to Figure 5), while less compact, offers a better visualization of the propagation paths within an assembly, and allows for an easier integration of the level of coupling between linkages.

2.2.3 Comparison of the Change Propagation Representations

The change propagation representations discussed in the previous sections all offer distinct advantages and disadvantages when it comes to aspects of visualization, software compatibility, and efficiency. A comparison of the capabilities of the four previously discussed representations is shown in Table 3.

Table 3: Comparison of the capabilities of the change propagation representations (adapted from [11])

Criteria	Traditional Component-Component DSM	Change Risk Plot	Propagation Network	Propagation Tree
Models direct linkages	+	-	+	+/-
Models indirect linkages	-	+	+/-	+/-
Allows for visualization of propagation paths	-	-	+/-	+
Allows for visualization of component connectivity	+/-	+/-	+	+/-
Shows level of coupling between linkages	+/-	+	+/-	+
Allows for efficient calculations and software implementation	+	+/-	-	-
Time efficient	+	+/-	-	-

As shown in Table 3, there is not a representation that is clearly better than the others when all the criteria are taken into account. This necessitates that a compromise must be made based on what is required or desired for the particular model that is used for change prediction.

2.3 Change Prediction

An accurate means of predicting how change propagates throughout a product can lead to huge cost savings and better change management in industry. There are many different approaches to predicting change, but in general, a change prediction method must be able to identify the determining factors in change effort and be flexible in its application. Three relevant change management strategies that are discussed are the change prediction method, the analogy-based model for estimating design effort, and the change propagation analysis for complex technical systems.

2.3.1 Change Prediction Method

In order to accurately assess change complexity and costs, Clarkson and colleagues present a change prediction method (CPM) that calculates the probability of change propagation in a system [4, 12]. An illustration of this method is shown below in Figure 6.

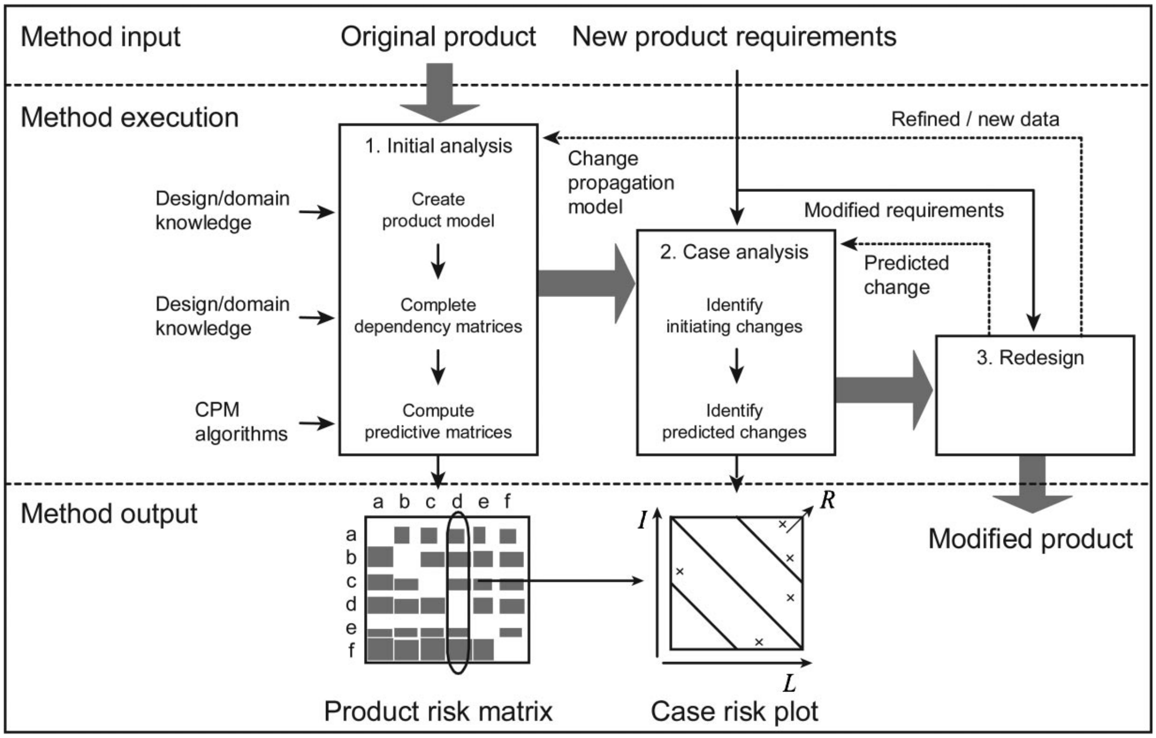
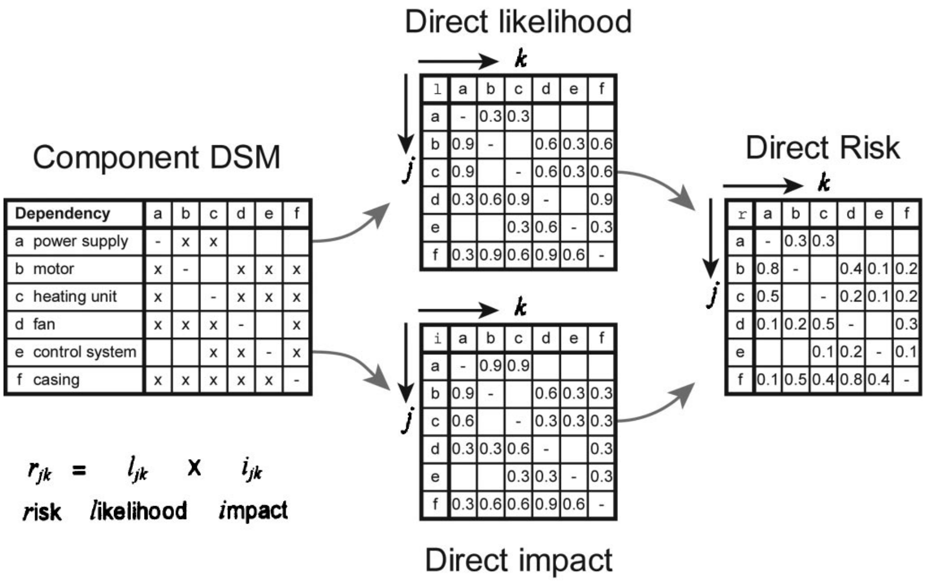


Figure 6: Change prediction method [4]

The first step in this method is to decompose the product into sub-systems based on the level of detail that is desired. The higher the level of detail, the more time consuming the method becomes, so a balance must be maintained. The next step is to create direct likelihood and direct impact design structure matrices to model the direct links in the system [4]. Clarkson and colleagues define likelihood as “the average probability that a change in the design of one sub-system will lead to a design change in another by propagation across their common interface. Likewise, impact is defined as the average proportion of the design work that will need to be redone if the change propagates [4].” The likelihood and impact values that are used to populate the DSMs, are drawn from the history of previous design changes or the knowledge of experienced engineers. The values are assigned on a 0-1 scale. A DSM of the direct risk is then created by taking the product of the direct likelihood and impact [4]. An illustration of this process is shown in Figure 7.



Dependency	a	b	c	d	e	f
a power supply	-	x	x			
b motor	x	-		x	x	x
c heating unit	x		-	x	x	x
d fan	x	x	x	-		x
e control system			x	x	-	x
f casing	x	x	x	x	x	-

l	a	b	c	d	e	f
a	-	0.3	0.3			
b	0.9	-		0.6	0.3	0.6
c	0.9		-	0.6	0.3	0.6
d	0.3	0.6	0.9	-		0.9
e			0.3	0.6	-	0.3
f	0.3	0.9	0.6	0.9	0.6	-

i	a	b	c	d	e	f
a	-	0.9	0.9			
b	0.9	-		0.6	0.3	0.3
c	0.6		-	0.3	0.3	0.3
d	0.3	0.3	0.6	-		0.3
e			0.3	0.3	-	0.3
f	0.3	0.6	0.6	0.9	0.6	-

r	a	b	c	d	e	f
a	-	0.3	0.3			
b	0.8	-		0.4	0.1	0.2
c	0.5		-	0.2	0.1	0.2
d	0.1	0.2	0.5	-		0.3
e			0.1	0.2	-	0.1
f	0.1	0.5	0.4	0.8	0.4	-

$$r_{jk} = l_{jk} \times i_{jk}$$

risk likelihood impact

Figure 7: Direct likelihood, impact, and risk DSMs [4]

Next, predictive matrices are created to model the indirect links in the system, and the change propagation through these links. Change propagation trees are created for each component, with that component being the source of change. This allows for the combined effects to be calculated based on the levels at which the components are indirectly linked. An example of a change propagation tree with sub-system ***a*** as the source of an initiating change and ***b*** as the affected sub-system is shown below in Figure 8.

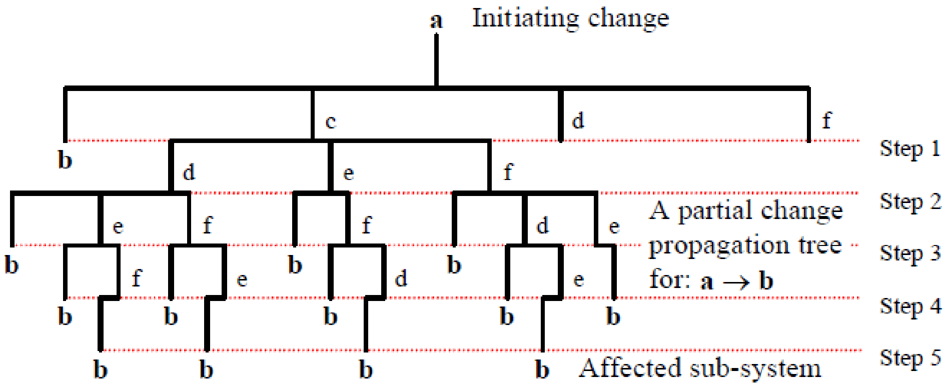


Figure 8: Partial change propagation tree [4]

The propagation trees are then represented mathematically with the horizontal lines defined as $\cap$ (*or*) and the vertical lines defined as $\cup$ (*and*). The combined likelihood (L) is then calculated by summing the *and/or* evaluations starting at the bottom of the tree and ending with the initiating sub-system. The *and* evaluation is mathematically defined using Equation 2.1, and the *or* evaluation is mathematically defined using Equation 2.2 [4].

$$l_{b,u} \cup l_{b,v} = l_{b,u} \times l_{b,v} \tag{2.1}$$

$$l_{b,u} \cap l_{b,v} = l_{b,u} + l_{b,v} - (l_{b,u} \times l_{b,v}) = 1 - ((1 - l_{b,u}) \times (1 - l_{b,v})) \tag{2.2}$$

where $l_{b,u}$ and $l_{b,v}$ are the direct likelihood values between the affected sub-system b and sub-systems u and v. The combined risk of change propagating from one sub-system to another sub-system is then calculated using Equations 2.3 and 2.4 [4].

$$R_{b,a} = 1 - \prod (1 - \rho_{b,u}) \tag{2.3}$$

$$\rho_{b,u} = \sigma_{u,a} l_{b,u} i_{b,u} \tag{2.4}$$

where $R_{b,a}$ is the combined risk of change propagating from a to b, $\rho_{b,u}$ is the risk of change propagating from u to b, $\sigma_{u,a}$ is the likelihood of change reaching sub-system u from a, $l_{b,u}$ is the direct likelihood of change propagating from u to b, and $i_{b,u}$ is the direct impact of change propagating from u to b. Finally, the combined impact (I) of change propagating from a to b is calculated using Equation 2.5 [4].

$$I_{b,a} = R_{b,a} / L_{b,a} \tag{2.5}$$

A summary of this process is shown below in Figure 9.

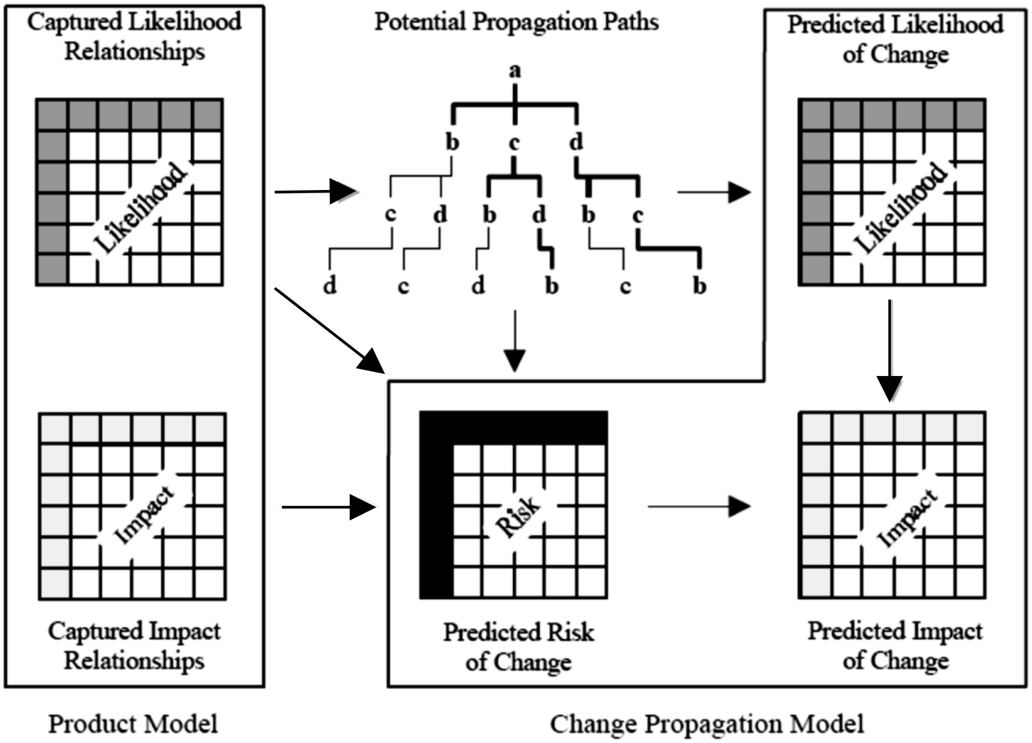


Figure 9: Model of the change prediction method [4]

The predicted likelihood, risk, and impact of change that are produced by the CPM method can then be presented in a change risk plot (as seen in Figure 3), or a risk graph [43].

The change prediction method is shown to have value as a tool that can be used to assist designers in selecting the least costly modifications during redesign. It is generally considered to be one of the most advanced and expansive change prediction methods available [44]. It does, however, have some key drawbacks that offer room for improvement. The most significant drawback to the change prediction method is that it bases all the predictive measures on the initial likelihood and impact relationships, which are assessed based on data from previous changes or the knowledge of experienced engineers [45, 46]. Thus, for a newer product with little or no historical data, the change prediction method may not provide the level of accuracy that is desired. Furthermore, because the likelihood and impact relationships are based on human interpretation, they will inherently contain uncertainty that will propagate to the final predictive measures. A more systematic approach that takes as much of the human interpretation out as possible will yield more consistent and reliable results. Furthermore, it will make the method more flexible, allowing it to be applicable in situations where there is not any previous data or experience. The direct impact values in the method assess the degree to which a component will be affected by a change, but they do not evaluate the cost associated with those changes. A means of modeling the cost sustained during manufacturing due to changes to a component would provide a more accurate and extensive representation of change effort. The change prediction method is also computationally intensive and can become very time consuming when analyzing larger and more complex systems. To further this problem, it is not easily implemented into software, so additional effort is required to make the method computationally feasible.

2.3.2 Analogy-based Model for Estimating Design Effort

Bashir and Thomson introduce a way to estimate complexity and finally a way to predict design effort by using historical data from similar designs [13-15]. The past designs that are used as a point of reference should be as similar as possible, in terms of influencing factors. The key to determining the design effort for a future product is to look at the "productivity" of similar past designs, and scale it up or down based on multiplying factors such as design complexity and severity of requirements [13]. The equation for productivity is shown below Equation 2.6 [13].

$$P_r = O_r / E_r \tag{2.6}$$

where P_r is the productivity of the reference project, E_r is the input of the reference project (# of man-months spent on design), and O_r is the output of the reference project. The output is measured using the product complexity (*PC*) [16], which is shown in equation 2.7 [13].

$$PC = \sum_{j=1}^{l} F_j j \tag{2.7}$$

where F_j is the number of functions at level j, and l is the number of levels. In order to scale the reference product to the new product, a multiplying factor is introduced to take into account changes in productivity. The major factors in changes to the productivity from one design to the next are product complexity, severity of requirements, and the efficiency of the design team and the processes used [47]. To compute the multiplying factor, a 0-9 scale is utilized that ranks the severity of the influence of productivity from one project to the next (1 being equal influence, 9 being extremely severe influence) [13]. Using this scale, a pairwise comparison table is created as shown below in Table 4.

Table 4: Project comparisons with respect to severity of requirements [13]

Project number	1	2	3	4	5	Relative influence
1	1	1/2	2	1	1/2	0.36
2	2	1	1/2	1/2	1/2	0.33
3	1/2	2	1	1/2	1/3	0.30
4	1	2	2	1	1	0.51
5	2	2	3	1	1	0.64

The principal eigenvector of the matrix is then computed using Equation 2.8 [13].

$$Aw = \lambda_{max} w \qquad (2.8)$$

where A is the pairwise matrix, λ_{max} is the maximum eigenvalue, and w is the extracted weight. This weight (w) is then used to calculate the multiplier using Equation 2.9 [13].

$$M_{rf} = w_{rf} \,/\, w_{uf} \qquad (2.9)$$

where M_{rf} is the multiplier, w_{rf} is the extracted weight corresponding to the reference project, and w_{uf} is the extracted weight corresponding to the upcoming project u. With this the estimated productivity for the upcoming project (P_{ur}), using the reference projects (r), can be calculated using Equation 2.10 [13].

$$P_{ur} = P_r \prod_{f=1}^{m} M_{rf} \qquad (2.10)$$

where m is the number of influencing factors. Finally, the estimated effort for the upcoming project (E_u) can be calculated using Equation 2.11 [13].

$$E_u = (1 / nr)\sum_{r=1}^{nr} E_{ur} \tag{2.11}$$

where nr is the number of reference projects and $E_{ur} = O_u/P_{ur}$, where O_u is the upcoming project output.

The analogy-based model is a tool that can be used to predict design effort in initial designs and all levels of redesign. Its value, however, is somewhat limited, as it requires a set of historical projects with similar influencing factors to produce a design effort prediction with any kind of accuracy. Therefore, this model would not be ideal for a new, novel project. Furthermore, the model relies on the experience of designers to develop the pairwise comparison table, and make accurate assessments of the level of influencing factors. Relying on human interpretation inherently introduces uncertainty into the model and reduces accuracy. Finally, as the bank of reference projects grow, the amount of data that needs to be processed causes the implementation of the model to be very time consuming.

2.3.3 Change Propagation Analysis for Complex Technical Systems

Giffin and colleagues present a study on change propagation in large complex systems [1]. The system studied was designed over an eight year period, and consists of more than 41,500 proposed changes. Larger, more complex systems present a problem with the majority of change prediction methods due to the huge amount of information that must be processed and analyzed. One means of identifying an area or component to focus on for change, in such a complex system, is by calculating the propensity for change (denoted as *CPI*) [1, 17, 48]. Two additional evaluations that can be used to gain insight on the nature of change propagation in a system are whether areas are generally accepting of change or tend to reflect change. These evaluations are quantified using the *CAI* and *CRI* ratios [1]. The *CAI*, *CRI*, and *CPI* of a component are calculated using Equations 2.12, 2.13, and 2.14 [1].

$$CAI_i = \frac{\text{total number of implemented changes in area } i}{\text{total number of changes originally proposed in area } i} \tag{2.12}$$

$$CRI_i = \frac{\text{total number of rejected changes in area } i}{\text{total number of changes originally proposed in area } i} \tag{2.13}$$

$$CPI\ \ i\ \ = \frac{C_{out}\ \ i\ - C_{in}(i)}{C_{out}\ \ i\ + C_{in}(i)} \tag{2.14}$$

where C_{in} is the sum of all the changes, including self-changes, that affect area *i*, and C_{out} is the sum of all the areas that are affected by a change to area *i*. A *CPI* value between 0 and 1 indicates that the area is a multiplier, with a value of 1 signifying a perfect multiplier. A value between -1 and 0 indicates an absorber, with a value of -1 signifying a perfect absorber. A *CPI* of 0 is a carrier. A multiplier is an area that originates more change than it has incoming change, and an absorber has more incoming change than it originates. A carrier is an area that has an equal amount of incoming and outgoing change. Identifying which areas are multipliers and absorbers can be valuable during the redesign of a product, or during the design of subsequent generations of a product. Areas that are identified as multipliers can be designed with more built-in flexibility, potentially saving time and effort down the road when changes are required. Also, if an absorber is a potential area for change, it would be a better choice than a multiplier as it will have less of an effect on other areas [1].

The change propagation analysis for complex systems provides an evaluation that can be used for change management in large, complex systems. The analysis is not as computational intensive as the previous methods, but it does require an initial amount of change history data to base the subsequent calculations on. Another drawback to the analysis is that when identifying key areas for change, it does not take into account the number of changes required or the effort involved in the change (i.e. one component may require more effort to change than another for reasons such as manufacturing). Additionally, different types of changes could cause areas/components to behave in different manners. For instance, for one change a component may act as a multiplier but for another it acts as an absorber.

2.4 Current Opportunities in Change Management

In light of the research questions posed in Chapter 1, a change prediction method must address the following requirements:

- Model the connectivity within a system, including the direct and indirect coupling, and the resulting propagation paths [11].
- Evaluate the level of coupling between components to assess the probability of change propagating from one component to another [4, 29].
- Assess the manufacturing costs associated with changes [4].
- Identify the sub-systems that should and should not be targeted for change [1, 4].

- Evaluate the relative design effort required for redesigns [4, 13].
- Identify areas and means for improving the overall ease of change of a system.
- Not require any previous experience or historical change data.
- Be a systematic process that is based on objective information.
- Be computationally practical.
- Be easily integrated into software.

A review of relevant literature establishes that no existing change management strategies fully address the requirements for change prediction as focused in this research. A list of important characteristics of a change prediction method, and evaluation against current tools, is provided in Table 5.

Table 5: Evaluation of the reviewed change management strategies against the prescribed requirements

Requirements	Change prediction method	Analogy-based model for estimating design effort	Change propagation analysis for complex technical systems
Identifies the sub-systems that should and should not be targeted for change	X		X
Evaluates the relative design effort required for redesigns	X	X	
Systematic process that is based on objective information			X
Does not require any previous experience or historical change data			
Computationally practical			X
Easily integrated into software			X
Assesses the manufacturing costs associated with changes			

A review of current change management strategies has identified several gaps and limitations that offer room for improvement. The limitations that are addressed in this research are summarized as:

- Reliance on human experience and historical change data for the population of component/system coupling.
- Impact of change assessments rely on subjective information and interpretation, independent of component characteristics.

- Cost of change is not explicitly modeled.
- Manufacturing information is not taken into account or included.

In light of the identified limitations, a change prediction method is developed that integrates a systematic and objective assessment of level of coupling, along with incorporating design for manufacturing (DFM) information to model the cost and impact of change. The proposed method is detailed and discussed in Chapter 3.

CHAPTER THREE

PROPOSED CHANGE PREDICTION METHOD

The proposed change prediction method is based off of a traditional component-component design structure matrix. A DSM is chosen because it offers a concise and simple representation [33], while allowing for software integration for computations. In order to produce a more accurate assessment of the difficulty of change, the manufacturing costs, in terms of the relative manufacturing hours required for a change, are included. In addition to the traditional approach of modeling the linkages between the components, a more detailed assessment is performed by breaking the components down to interfaced features. The interfaced features are what will actually be affected by change, so the DSM is able to model the coupling between the interfaced features and evaluate the manufacturing costs of a change to each feature. A flow chart of the proposed change prediction method is shown in Figure 10.

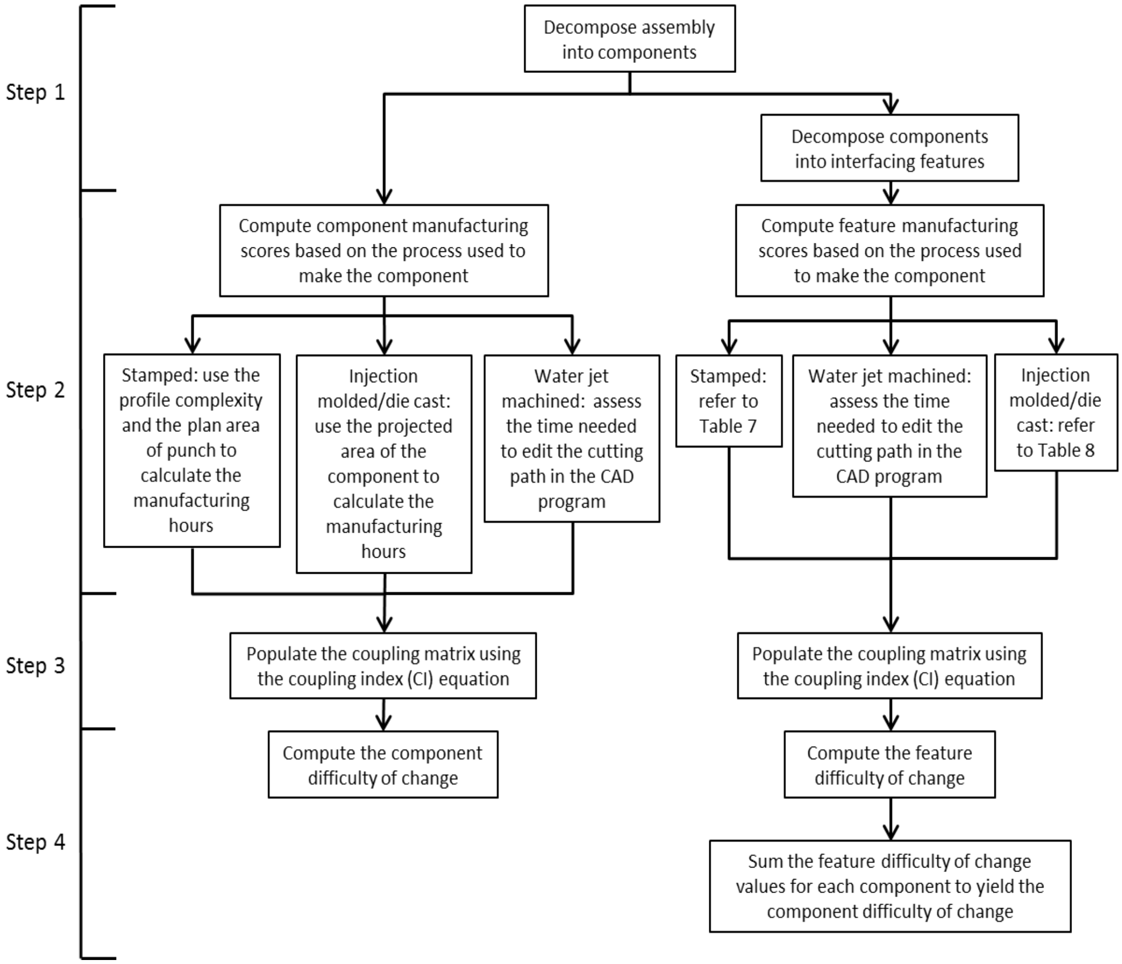


Figure 10: Flow chart of the proposed change prediction method

3.1 Step 1: Decompose the System

The system must first be decomposed into components so that the connectivity within the system can be modeled. It is preferable that the system be decomposed as far as possible, because it is more difficult to assess the manufacturing costs of subassemblies. For simplicity, it is only necessary to include the important components that offer an opportunity for change. For the feature-based method, the components are further decomposed to the interfacing feature level. In some instances, it may not be possible to easily identify the interfacing features within an assembly, and if so, the analysis should only be performed at the component level. It should be noted, that the decomposition process is based on an engineer's interpretation of a system, and thus may vary from engineer to engineer. This challenge is identified, but is out of the scope of this research.

3.2 Step 2: Estimate/Compute Manufacturing Costs

The cost of geometrical changes for stamping, injection molding, die casting, and water jet machining are evaluated due to their wide use in industry. A system is first evaluated on a component level, basing the manufacturing cost of a change on the overall size of each component. Then, if the interfaces between the components can be clearly broken down to a feature level, the manufacturing cost of a change is based on each individual, interfaced feature.

3.2.1 Component Level

To evaluate the relative cost of change on a component level, size is chosen as the determining factor. A larger part is more expensive to manufacture, and thus will cost more to change. The relative cost for injection molded, die cast, and stamped components are determined using design for manufacturing assessments that relate aspects of a part's size to the required manufacturing hours.

The relative manufacturing hours for injection molded and die cast components are determined based on the projected area of the part. The projected area is the area of the part at a right angle to the direction of molding. The relationship between a part's projected area and its resulting manufacturing hours is developed by Boothroyd and Dewhurst [49, 50], and is seen in Equation 3.1.

$$M_h = 5 + 0.085 A_p^{1.2} \tag{3.1}$$

where M_h is the manufacturing hours and A_p is the part projected area (cm^2). The results of the manufacturing hours calculation for each component are then entered into the component-component DSM.

The relative manufacturing hours for stamped components are determined based on the size relationships developed by Boothroyd and Dewhurst for the blanking operation of a stamped part [49]. For simplicity, only the blanking operation is evaluated, as it is the main determining factor in the overall size of the part. First, the profile complexity (X_p) of the component is calculated using Equation 3.2 [49].

$$Xp = P^2 \, / \, (LW) \tag{3.2}$$

where P is the perimeter length to be sheared (cm^2) and L and W are the length and width of the smallest rectangle that surrounds the punch (cm). The basic manufacturing points (M_{po}) associated with the calculated profile complexity are then assessed using Figure 11.

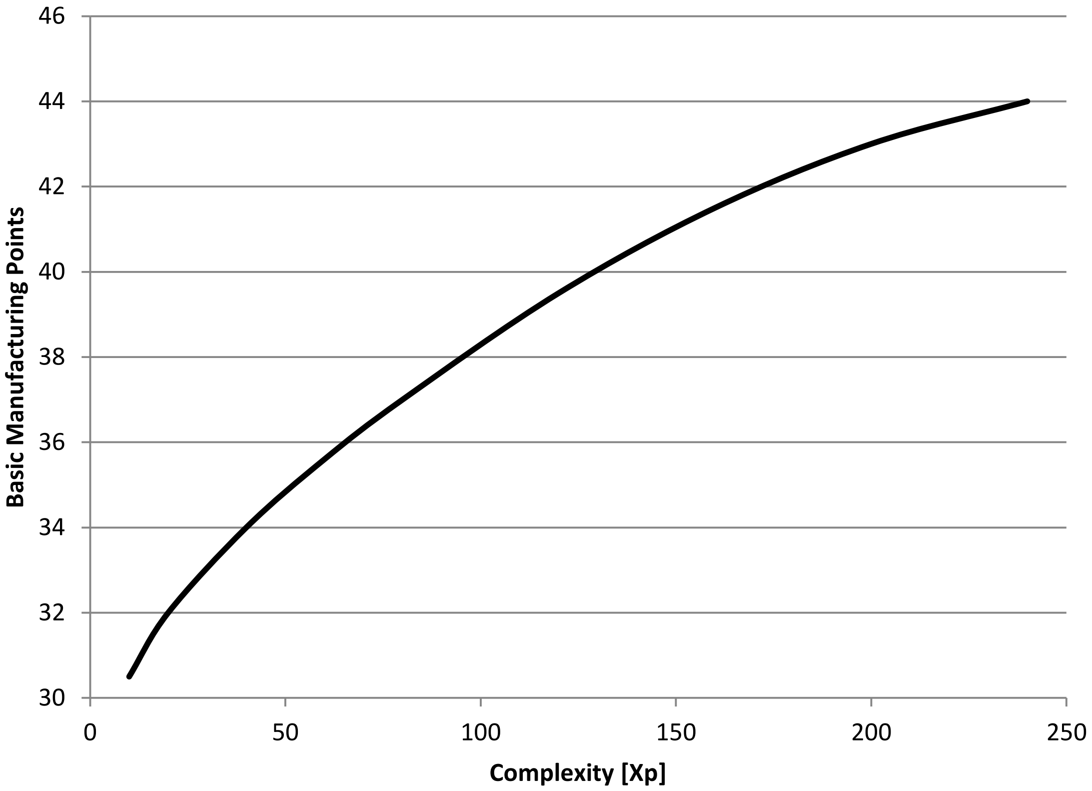


Figure 11: Basic manufacturing points for blanking die [49]

The final factor in the overall manufacturing hours calculation is the area correction factor (f_{1w}), which is found using Figure 12.

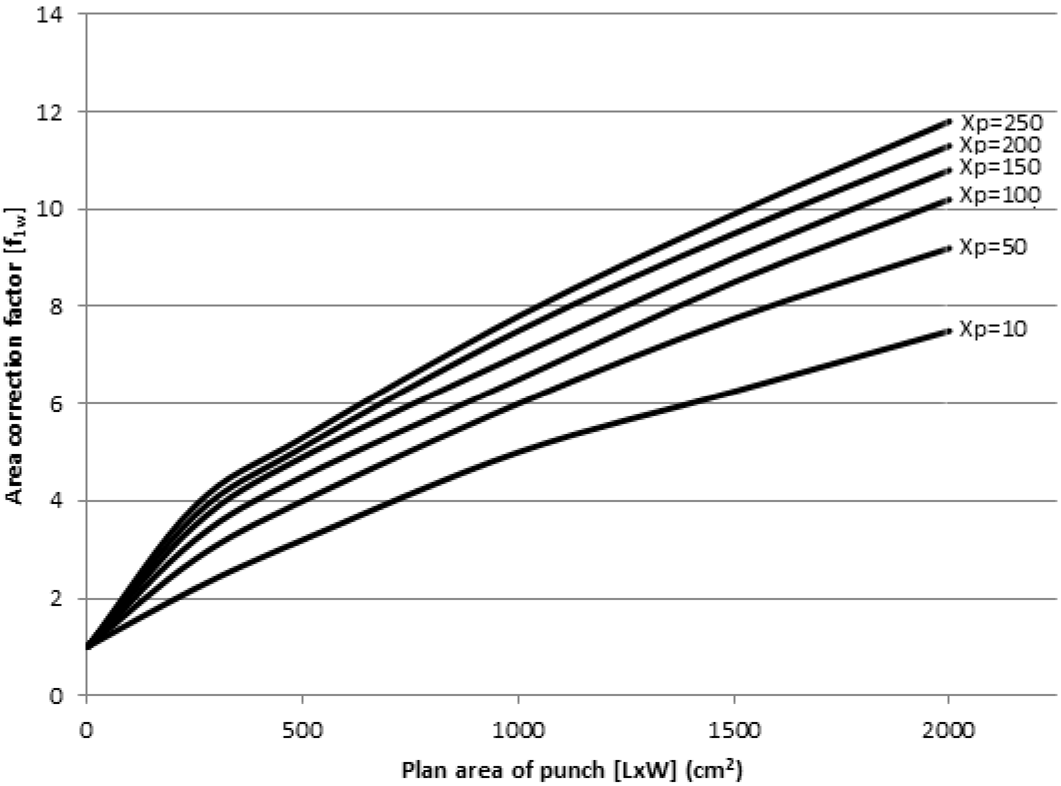


Figure 12: Area correction factor [49]

The overall manufacturing hours (M_h) for a stamped part are then calculated using Equation 3.3 [49].

$$M_h = f_{1w} M_{po} \tag{3.3}$$

The results of the manufacturing hours calculation for each component are then entered into the component-component DSM.

3.2.2 Feature Level

A higher fidelity analysis can be completed by decomposing the components into the interfacing features. This presents a challenge, however, as a component can be viewed at the feature level from multiple perspectives. This is out of the scope of this research. To assess the relative cost, the hours needed to machine and design the changed features are tabulated to provide a simple referencing system. The manufacturing hours for each interfaced feature are then inserted into the DSM. The tabulated relative manufacturing hours can be seen in Table 7 for stamped components and Table 8 for injection molded and die-cast components.

The relative manufacturing hours for the stamped features (Table 7) are adapted from Poli's design for manufacturing analysis [51]. The tabulated hours account for the time needed to machine the added features into the die/punch, along with the time needed to design any changes to the stations. The relative manufacturing hours for the injection molded and die-cast features (Table 8) are adapted from Boothroyd and Dewhurst's process for calculating mold manufacturing hours [49]. The cost of a change to an existing feature is evaluated by determining the changes to mold complexity. The additional mold machining hours, as a result of the changes to mold complexity, is then calculated based on the additional surface patches that are added. A surface patch is defined as a separate surface segment. The approximate number of surface patches per feature can be seen below in Table 6 [49].

Table 6: Surfaces patches per feature

Feature		Surface Patches/Feature
Hole	Circular	1
	Rectangular	4
	Irregular	6
Cylindrical Boss	Solid	2
	Hollow	3
Rectangular Boss	Solid	5
	Hollow	12
Rib, Wall		3
Side Shutoff	Simple	3
	Complex	12

Using the additional surface patches due to the changes to a feature, the added mold complexity can be calculated using Equation 3.4.

$$X_i = 0.1N_{sp} \tag{3.4}$$

where X_i is the added mold complexity and N_{sp} is the number of surface patches. This measure of added mold complexity then allows for the calculation of the added mold manufacturing hours (M_x) due to the geometrical changes to a feature using Equation 3.5 [49].

$$M_x = 5.83X_i^{1.27} \tag{3.5}$$

The resulting relative manufacturing hours required for a change to injection molded and die cast features are seen in Table 8.

Table 7: Relative manufacturing hours required to change stamped features (adapted from [51]).

Feature Operation	Hours
Blanking	40
Semi-perf	25
Piercing, Standard Hole	30
Lancing, Notching, Forming, Coining, Embossing	40
Embossing Near Part Periphery	113
Nonstandard Hole	45
Extruded Hole	50
Drawing	55
Tab	65
Side-Action Feature	95
Curl, Hem	120
Bend	40
Overbend (>105 deg, add 20 hrs)	80

Table 8: Relative manufacturing hours required to change injection molded and die-cast features (adapted from [49]).

Feature		Hours
Hole	Circular	0.31
	Rectangular	1.82
	Irregular	3.05
Cylindrical Boss	Solid	0.76
	Hollow	1.26
Rectangular Boss	Solid	2.42
	Hollow	7.35
Rib, Wall		1.26
Side Shutoff	Simple	1.26
	Complex	7.35

The manufacturing hours required for a change to a component machined using a water jet are based on the time it takes to edit the geometrical change in the CAD program. This is usually very low, but depends on the complexity of the feature being changed and must be assessed on a case by case basis. For flexible components, a corresponding mold may be required to ensure that the component's shape is maintained during the cutting process. If this is the case, the time required to machine the corresponding changes into the support mold must also be assessed. The machining process of a support mold is very similar to that of an injection mold, so the relative manufacturing hours required for a change to an injection molded feature (Table 8) can also be used to evaluate a change to the support mold [52].

3.3 Step 3: Compute the Level of Coupling

Design structure matrices traditionally only model the direct coupling in a product. This is a huge limitation as the cost accrued due to unanticipated changes in indirectly coupled components can be substantial. The proposed method incorporates all degrees of coupling for each component, not just the first order coupling. Furthermore, the proposed method evaluates the level of coupling between each component.

To evaluate the level of coupling between directly coupled components a coupling index (CI) is formulated. The coupling index assesses the degree of coupling between the interfaced features/components using a ratio of the sum of the level of constraint of each parameter over the total number of parameters. The equation for the coupling index is seen below in Equation 3.6.

$$CI = \frac{\sum_{1}^{n} L_c}{T_p} \qquad (3.6)$$

Level of Constraint (L_c) =
0 for no dimensional constraint
0.5 for dimensional constraint in one direction (increasing or decreasing)
1 for dimensional constraint in both directions

where n is the number of constrained parameters and T_p is the total number of parameters. The CI calculations produce what is effectively the probability that a change to one interfaced feature or component will affect the other. The result is a value between 0 and 1, with 1 meaning that a change to a feature/component will always affect the other feature/component and a 0 indicating that the features/components are not coupled. The values from the CI calculations are used to populate the DSM.

3.4 Step 4: Compute the Difficulty of Change

To determine the overall difficulty of change, the second and tertiary order coupling has to be modeled. To accomplish this, the coupling index values are multiplied together as the order of coupling increases to produce a diminishing probability as the propagation path extends. The equation for the difficulty of change (D_c) is seen in Equation 3.7.

$$D_c = \sum_{1}^{n} CI_{1st} M_h + \sum_{1}^{n} CI_{1st} CI_{2nd} M_h + \sum_{1}^{n} CI_{1st} CI_{2nd} CI_{3rd} M_h \tag{3.7}$$

where M_h is the manufacturing hours required for a change and n is the number of interfaced features/components. This equation calculates to third order coupling, but it can be extended to as high a degree of coupling as necessary by continuing to multiply the sequential coupling indexes together. When calculating the difficulty of change, it is important to identify when redundant coupling occurs, because only the most probabilistic occurrence of coupling between two components/features should be included in the calculations. An example of a connectivity tree for feature A is shown below in Figure 13.

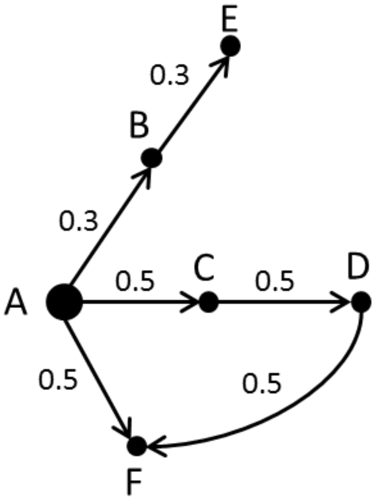


Figure 13: Connectivity tree for feature A.

The resulting difficulty of change calculation for feature A is seen below in Equation 3.8.

$$\begin{aligned} D_c(A) = M_h(A) + CI_{AB}M_h(B) + CI_{AC}M_h(C) + CI_{AF}M_h(F) \\ +CI_{AB}CI_{BE}M_h(E) + CI_{AC}CI_{CD}M_h(D) \end{aligned} \tag{3.8}$$

It is important to note that the feature difficulty of change calculation only models the path of highest probability between the root feature and other features. Thus, the measure only includes the highest coupling value between two features that exists within the connectivity tree. For instance, in the above example features A and F are connected by two different paths, both first order coupling and third order coupling. However, only the first order coupling is included in the feature difficulty of change calculation because it represents the path of highest probability. It should be noted, that this path representation assumes that if there are two paths to the same end node, that the hypothetical changes will be the same.

3.5 Demonstration of the Change Prediction Method

To further the understanding of the proposed change prediction method, a ball-point pen assembly is analyzed step by step. The ball-point pen assembly, seen in Figure 14, is a geometrically simplified representation, and all components are assumed to be manufactured using injection molding.

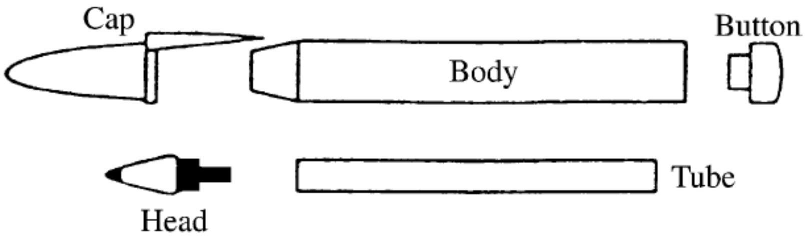


Figure 14: Ball-point pen assembly [53]

The assembly is first assessed on a component level, basing the manufacturing hours for a change to each component on their overall size using Equation 3.1. Table 9 lists each component's projected area and the resulting manufacturing hours required for a change.

Table 9: Manufacturing hours for each component

Component	***Part Projected Area [A_p] (cm^2)***	***Manufacturing Hours***
Cap	3.13	5.33
Body	12.69	6.79
Button	0.81	5.07
Head	1.75	5.17
Tube	8.25	6.07

The level of coupling between each component is then assessed using the coupling index (Equation 3.6). All of the components are simplified as cylinders and thus have two parameters, length and diameter. The level of constraint for each of the component's parameters is then evaluated by determining whether an increase or decrease in the parameter affects the other component. For instance, the coupling index between the tube and body is calculated below in Equation 3.9.

$$CI = \frac{0.5 + 0.5}{2} = 0.5 \tag{3.9}$$

The length and diameter of the tube can both be decreased without affecting the body, while an increase in either will have an effect. This leads to a 0.5 for the level of constraint of both parameters, and a result of 0.5 for the coupling index. Table 10 lists the coupling index equations for all the components.

Table 10: Coupling index calculations

	Cap	**Body**	**Button**	**Head**	**Tube**
Cap	1	(0+1)/2	(0+0)/2	(0.5+0)/2	(0+0)/2
Body	(0+1)/2	1	(0+1)/2	(0+1)/2	(0.5+0.5)/2
Button	(0+0)/2	(0+1)/2	1	(0+0)/2	(0+0)/2
Head	(0.5+0)/2	(0+1)/2	(0+0)/2	1	(0+1)/2
Tube	(0+0)/2	(0.5+0.5)/2	(0+0)/2	(0+1)/2	1

The coupling index calculations in Table 10 are then entered into the body of the DSM, and the final component difficulty of change calculations are performed using Equation 3.7. The final DSM for the ball-point pen assembly is seen below in Table 11. The DSM contains the equations used to calculate the component difficulty of change, along with the final results.

Table 11: Ball-point pen DSM with component difficulty of change calculations

	Man. Hrs.	**Comp. #**	**1**	**2**	**3**	**4**	**5**	**Component Difficulty of Change**
Cap	5.33	**1**	1	0.5	0	0.25	0	12.8
Body	6.79	**2**	0.5	1	0.5	0.5	0.5	17.6
Button	5.07	**3**	0	0.5	1	0	0	12.6
Head	5.17	**4**	0.25	0.5	0	1	0.5	14.2
Tube	6.07	**5**	0	0.5	0	0.5	1	14.7

The results of the change prediction method show that the button and the cap are the components which offer the greatest ease of change, while the body is shown to have the highest difficulty of change. Since the manufacturing hours for the five components are mostly similar, the discrepancy between the final results is largely attributed to differing levels of connectivity. Looking at the coupling values in the body of the DSM, it can be seen that the body has the highest overall level of coupling, while the cap and the button have the lowest.

A more detailed analysis of the ball-point pen assembly is completed by decomposing to the feature level. Once the interfacing features are identified, the relative manufacturing hours required for a change are then evaluated using Table 8. Table 12 lists the components, the corresponding interfacing features, and the resulting manufacturing hours required for a change.

Table 12: List of the components, interfacing features, and resulting manufacturing hours

Components	Interfacing Features	Manufacturing Hours
Cap	Inside diameter	0.31
Body	Inside diameter	0.31
	Outside diameter	0.31
Button	Outside diameter	0.31
Head	Small diameter	0.31
	Large diameter	0.31
Tube	Inside diameter	0.31
	Outside diameter	0.31

The level of coupling between each of the interfacing features is then calculated using the coupling index (Equation 3.6). For this example, with all the interfacing features being one of the components' diameters, the only parameter that is evaluated in each of the coupling index calculations is the diameters themselves. The results of the coupling index calculations are entered into the body of the DSM, and can be seen below in Table 13. It should be noted, that for many of the level of constraint evaluations the diameters of the coupled features are considered to be fully constrained based on maintaining the functionality of the pen, not because both an increase and decrease in the diameter would interfere with the other coupled diameter. For instance, when evaluating the coupling between the inside diameter of the cap and the outside diameter of the body, increasing the diameter of the cap would not directly interfere with the outside diameter of the body, but in order to maintain the functionality of the pen assembly the outside diameter of the body must also be increased.

Table 13: Coupling index calculations

Comp.	**Interfacing Features**	**Comp. #**	**1**	**2.1**	**2.2**	**3**	**4.1**	**4.2**	**5.1**	**5.2**
Cap	Inside diameter	**1**	1	0/1	1/1	0/1	0/1	0/1	0/1	0/1
Body	Inside diameter	**2.1**	0/1	1	0/1	1/1	0/1	1/1	0/1	0.5/1
	Outside diameter	**2.2**	1/1	0/1	1	0/1	0/1	0/1	0/1	0/1
Button	Outside diameter	**3**	0/1	1/1	0/1	1	0/1	0/1	0/1	0/1
Head	Small diameter	**4.1**	0/1	0/1	0/1	0/1	1	0/1	1/1	0/1
	Large diameter	**4.2**	0/1	1/1	0/1	0/1	0/1	1	0/1	0/1
Tube	Inside diameter	**5.1**	0/1	0/1	0/1	0/1	1/1	0/1	1	0/1
	Outside diameter	**5.2**	0/1	0.5/1	0/1	0/1	0/1	0/1	0/1	1

The feature difficulty of change is based on the coupling index values in the body of the DSM along with the manufacturing hours for each interfaced feature, and is calculated using Equation 3.7. The final component difficulty of change value is then found by summing the feature difficulty of change values for each component. The final DSM for the ball-point pen assembly is seen below in Table 14. The DSM contains the equations and results for each of the feature difficulty of change calculations, along with the subsequent component difficulty of change values.

Table 14: Ball-point pen DSM with feature difficulty of change calculations

Comp.	Interfacing Features	Man. Hrs.	Comp. #	1	2.1	2.2	3	4.1	4.2	5.1	5.2	Feature Change Diff.	Comp. Change Diff.
Cap	Inside dia.	0.31	**1**	1	0	1	0	0	0	0	0	0.62	0.62
Body	Inside dia.	0.31	**2.1**	0	1	0	1	0	1	0	0.5	1.09	1.71
	Outside dia.	0.31	**2.2**	1	0	1	0	0	0	0	0	0.62	
Button	Outside dia.	0.31	**3**	0	1	0	1	0	0	0	0	1.09	1.09
Head	Small dia.	0.31	**4.1**	0	0	0	0	1	0	1	0	0.62	1.71
	Large dia.	0.31	**4.2**	0	1	0	0	0	1	0	0	1.09	
Tube	Inside dia.	0.31	**5.1**	0	0	0	0	1	0	1	0	0.62	1.4
	Outside dia.	0.31	**5.2**	0	0.5	0	0	0	0	0	1	0.78	

The results of the feature and component difficulty of change calculations show that the body and head present the greatest difficulty of change, while the cap and the button offer the greatest ease of change. Since the manufacturing hours for all the interfacing features are the same, the separation in the results is mostly due to the body, head, and tube having multiple interfacing features. In some instances, the interfacing features of the higher scoring components can also be seen to have a higher level of connectivity than those of the cap and button. A comparison of the results of the component and feature based methods is seen below in Table 15.

Table 15: Ease of change rankings for the ball-point pen assembly using the component and feature based methods

Component	*Component-based ranking*	*Feature-based ranking*
Cap	2	1
Body	5	4
Button	1	2
Head	3	4
Tube	4	3

The rankings produced by the two methods have the same overall trend, with only a couple of the component rankings switched. Both methods identify the cap and button as the components which offer the greatest ease of change. It should be noted, this does not identify a single component, but rather directs the attention of the designer.

CHAPTER FOUR

APPLICATION OF THE PROPOSED METHOD

4.1 BMW X5 Headliner Assembly

The BMW X5 model is experiencing significant time delays and quality issues during assembly due to alignment issues during the headliner installation. The headliner assembly, seen in Figure 15, contains four adaptor plates (8, 20), each with two clips (10), which are inserted into the body of the car to secure the headliner (1) and handles (4, 18). During the initial installation, the clips never align properly, which necessitates an additional step to re-align and secure the headliner. This extra step results in significant time losses during assembly, costing thousands of dollars. To fix this problem, a component, or multiple components, must be selected for re-design. In order to minimize the cost impact of this re-design, a change impact analysis will be performed to identify the component(s) with the greatest ease of change. To accomplish this, a component-component matrix is used with the proposed model of coupling. This industry example will allow for the assessment of the overall effectiveness of the change prediction scheme. For simplification, only the components which offer an opportunity for change are included in the analysis. Furthermore, the functional importance of the components is not considered.

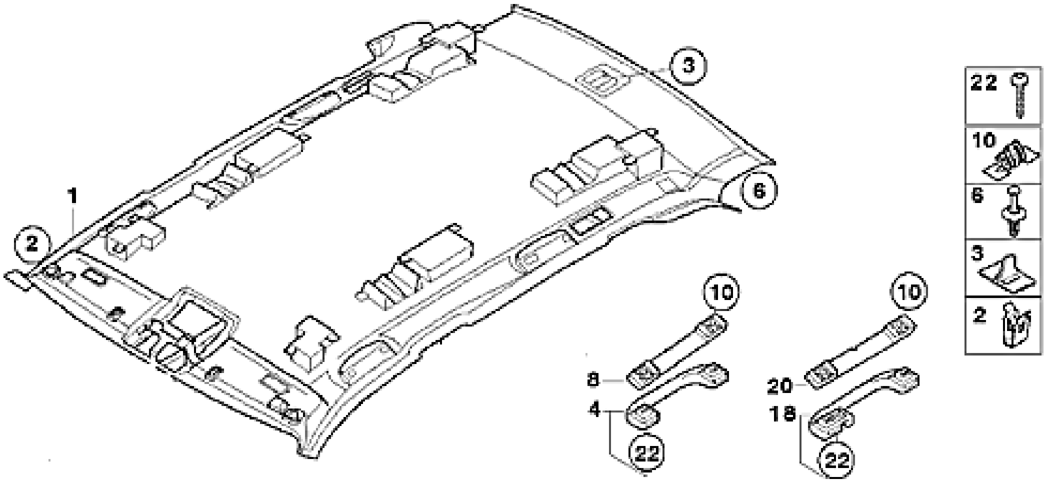


Figure 15: Schematic of the headliner assembly (from www.realoem.com)

4.1.1 Component-based Method

The resulting design structure matrix with the component difficulty of change calculations for the BMW X5 headliner assembly is seen below in Table 16. The body of the DSM is populated with the coupling index calculations for each component versus every other component in the assembly. The manufacturing hours for the molded roof lining are based only on the sections that are in contact or interface with the other components in the assembly. This yields a more accurate representation because even though the headliner is much larger than the other components in the system, only a small part of it interfaces with the rest of the assembly.

Table 16: DSM for the BMW X5 headliner assembly

Component	**Man. Process**	**Total Man. Hrs.**	**Comp. ID**	**1**	**4**	**8**	**10**	**14**	**18**	**20**	**Comp. change difficulty**
Molded roof lining	waterjet	60.6	**1**	1	0.5	0	0	0	0.5	0	177.5
Front handle (left/right)	injection molding	61.4	**4**	0.5	1	0.5	0	0	0	0	176.4
Adaptor plate, front handle grab (left/right)	injection molding	28.3	**8**	0	0.5	1	0.5	0	0	0	171.5
Clip, front handle grab	stamping	165.4	**10**	0	0	0.5	1	0	0	0	209.8
Clip, rear handle grab	stamping	165.4	**14**	0	0	0	0	1	0	0.5	209.8
Rear handle (left/right)	injection molding	61.4	**18**	0.5	0	0	0	0	1	0.5	176.4
Adaptor plate, rear handle grab (left/right)	injection molding	28.3	**20**	0	0	0	0	0.5	0.5	1	171.5

The results of the component difficulty of change calculations show that the clips are the most difficult to change, while the adaptor plates offer the greatest ease of change. Comparing the component difficulty of change scores and the manufacturing hours for each component, it can be seen that a trend exists between the two. The manufacturing scores have three distinct groupings, with the clips being the highest, the handles and molded roof lining being in the middle, and the adaptor plates being the lowest. Likewise, the resulting component difficulty of change scores follow the same trend, with the same three distinct groupings. The reason for this trend is partly because of the large separation between the components' manufacturing scores, but mostly because the level of connectivity for all four components is very similar.

4.1.2 Feature-based Method

The BMW X5 headliner assembly is further broken down into the interfacing features for each component. The resulting component and manufacturing information, coupling index DSM, and change difficulty for the BMW X5 headliner assembly are included in Table 17, Table 18, and Table 19.

Table 17: Component, interface, and manufacturing hours information for the BMW X5 headliner

Component	Interfacing Features	# Features	Man. Hours	Total Hours	Feature ID
Molded roof lining	holes	8	2	16.00	1
front handle (left)	rectangular boss	2	2.42	4.84	4
front handle (right)	rectangular boss	2	2.42	4.84	5
adapter plate, front handle grab (left)	rect. boss (bottom slots)	2	2.42	4.84	8.1
	rect. boss/slot (top, big)	2	2.42	4.84	8.2
	cylindrical boss	4	0.76	3.04	8.3
	rect. boss (top, small)	4	2.42	9.68	8.4
adapter plate, front handle grab (right)	rect. boss (bottom slots)	2	2.42	4.84	9.1
	rect. boss/slot (top, big)	2	2.42	4.84	9.2
	cylindrical boss	4	0.76	3.04	9.3
	rect. boss (top, small)	4	2.42	9.68	9.4
clip (front, left, 1)	slot	2	80	160.00	10.1
	change to blanking	1	40	40.00	10.2
clip (front, left, 2)	slot	2	80	160.00	11.1
	change to blanking	1	40	40.00	11.2
clip (front, right, 1)	slot	2	80	160.00	12.1
	change to blanking	1	40	40.00	12.2
clip (front, right, 2)	slot	2	80	160.00	13.1
	change to blanking	1	40	40.00	13.2
clip (back, left, 1)	slot	2	80	160.00	14.1
	change to blanking	1	40	40.00	14.2
clip (back, left, 2)	slot	2	80	160.00	15.1
	change to blanking	1	40	40.00	15.2
clip (back, right, 1)	slot	2	80	160.00	16.1
	change to blanking	1	40	40.00	16.2
clip (back, right, 2)	slot	2	80	160.00	17.1
	change to blanking	1	40	40.00	17.2
rear handle (left)	rectangular boss	2	2.42	4.84	18
rear handle (right)	rectangular boss	2	2.42	4.84	19
adapter plate, rear handle grab (left)	rect. boss (bottom slots)	2	2.42	4.84	20.1
	rect. boss/slot (top, big)	2	2.42	4.84	20.2
	cylindrical boss	4	0.76	3.04	20.3
	rect. boss (top, small)	4	2.42	9.68	20.4
adapter plate, rear handle grab (right)	rect. boss (bottom slots)	2	2.42	4.84	21.1
	rect. boss/slot (top, big)	2	2.42	4.84	21.2
	cylindrical boss	4	0.76	3.04	21.3
	rect. boss (top, small)	4	2.42	9.68	21.4

Table 18: Coupling index between component features represented in the DSM for the BMW X5 headliner

Feature ID	1	4	5	8.1	8.2	8.3	8.4	9.1	9.2	9.3	9.4	10.1	10.2	11.1	11.2	12.1	12.2	13.1	13.2	14.1	14.2	15.1	15.2	16.1	16.2	17.1	17.2	18	19	20.1	20.2	20.3	20.4	21.1	21.2	21.3	21.4
1	1	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0
4	0.5	1	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0.5	0	1	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.1	0	0.33	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.2	0	0	0	0	1	0	0	0	0	0	0	0	0.17	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.3	0	0	0	0	0	1	0	0	0	0	0	0.25	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.4	0	0	0	0	0	0	1	0	0	0	0	0	0.17	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.1	0	0	0.33	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0.17	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0.25	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.4	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0.17	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.1	0	0	0	0	0	0.5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.2	0	0	0	0	0.17	0	0.33	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.1	0	0	0	0	0	0.5	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.2	0	0	0	0	0.17	0	0.33	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.1	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.2	0	0	0	0	0	0	0	0	0.17	0	0.33	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13.1	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13.2	0	0	0	0	0	0	0	0	0.17	0	0.33	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0
14.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.17	0	0.33	0	0	0	0
15.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0
15.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0.17	0	0.33	0	0	0	0
16.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0.5	0
16.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.17	0	0.33
17.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.5	0
17.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0.17	0	0.33
18	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0.33	0	0	0	0	0	0	0
19	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.33	0	0	0
20.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	1	0	0	0	0	0	0	0
20.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0.17	0	0	0	0	0	0	0	1	0	0	0	0	0	0
20.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0.25	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
20.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0.17	0	0	0	0	0	0	0	0	0	1	0	0	0	0
21.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	1	0	0	0
21.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0.17	0	0	0	0	0	0	0	1	0	0
21.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0.25	0	0	0	0	0	0	0	0	0	1	0
21.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0.17	0	0	0	0	0	0	0	0	0	1

The DSM contains the headliner components, which are then further decomposed into the interfaced features and assigned an ID number (see Table 17). Based on the type of feature and the manufacturing process used for the component, the manufacturing hours are determined by referring to Table 7 and Table 8. This yields the total hours calculation that is based on the number of features. The body of the DSM contains the values from the coupling index, which are calculated for each interfaced feature versus every other feature through Equation 3.6 (see Table 18). The feature difficulty of change and overall component difficulty of change are shown in Table 19. The overall component difficulty of change is found by summing all the feature difficulty of change values for each component.

Table 19: Feature and component difficulty of change calculations

Components	Interfacing Features	Feature ID	Feature change difficulty	Component change difficulty
Molded roof lining	holes	1	28.9	28.9
front handle (left)	rectangular boss	4	19.3	19.3
front handle (right)	rectangular boss	5	19.3	19.3
adapter plate, front handle grab (left)	rect. boss (bottom slots)	8.1	10.7	136.1
	rect. boss/slot (top, big)	8.2	19.0	
	cylindrical boss	8.3	83.0	
	rect. boss (top, small)	8.4	23.4	
adapter plate, front handle grab (right)	rect. boss (bottom slots)	9.1	10.7	136.1
	rect. boss/slot (top, big)	9.2	19.0	
	cylindrical boss	9.3	83.0	
	rect. boss (top, small)	9.4	23.4	
clip (front, left, 1)	slot	10.1	181.5	226.7
	change to blanking	10.2	45.2	
clip (front, left, 2)	slot	11.1	181.5	226.7
	change to blanking	11.2	45.2	
clip (front, right, 1)	slot	12.1	181.5	226.7
	change to blanking	12.2	45.2	
clip (front, right, 2)	slot	13.1	181.5	226.7
	change to blanking	13.2	45.2	
clip (back, left, 1)	slot	14.1	181.5	226.7
	change to blanking	14.2	45.2	
clip (back, left, 2)	slot	15.1	181.5	226.7
	change to blanking	15.2	45.2	
clip (back, right, 1)	slot	16.1	181.5	226.7
	change to blanking	16.2	45.2	
clip (back, right, 2)	slot	17.1	181.5	226.7
	change to blanking	17.2	45.2	
rear handle (left)	rectangular boss	18	19.3	19.3
rear handle (right)	rectangular boss	19	19.3	19.3
adapter plate, rear handle grab (left)	rect. boss (bottom slots)	20.1	10.7	136.1
	rect. boss/slot (top, big)	20.2	19.0	
	cylindrical boss	20.3	83.0	
	rect. boss (top, small)	20.4	23.4	
adapter plate, rear handle grab (right)	rect. boss (bottom slots)	21.1	10.7	136.1
	rect. boss/slot (top, big)	21.2	19.0	
	cylindrical boss	21.3	83.0	
	rect. Boss (top, small)	21.4	23.4	

The resulting calculations show that the feature that offers the greatest ease of change is the rectangular slots on the bottom of the adapter plates. Conceptually this makes sense because the slots are easy to change in terms of manufacturing and are only coupled to the handle bosses. The component that offers the greatest ease of change is the handles, primarily because they only contain two interfacing features, both of which are easy to change. The DSM also identified that the clips and anything coupled to the clips presents the greatest difficulty of change. This is because stamped features are significantly harder to change than injection molded features. The highest order of coupling in the system is found to be fourth order.

4.1.3 Comparison of the Component and Feature Based Methods

To further evaluate the results from the component and feature based methods, the overall ease of change rankings for the components of the BMW X5 headliner assembly are presented in Table 20.

Table 20: Component ease of change rankings for both methods

Component	***Component-based ranking***	***Feature-based ranking***
Molded roof lining	3	2
Handles	2	1
Adaptor plates	1	3
Clips	4	4

As shown in Table 20, both methods produce the same ranking for the clips, but the rankings for the molded roof lining, handles, and adaptor plates do not coincide. The main reason for the inconsistency between the two methods is the ratio of the size of the molded roof lining and handles to the actual area that interfaces with other components. Both components are relatively large in comparison to the actual area of the component that is coupled with other parts. In the case of the molded roof lining, the size that is used to compute the manufacturing score is narrowed down to only include the area of the part that interacts with the other components in the assembly. However, this still represents an inflated number, as the only parts of the molded roof lining that actually directly interface with other components are the eight small holes through which the handles connect to the adaptor plates. Similarly, the only parts of the handle that interface with the rest of the assembly are the two small bosses on each end, which represent a small percentage of their overall size. Since the component-based method uses the overall size of the part to determine the manufacturing score, it does not take into account how much of the component is actually effected by change. In cases such as this, the feature-based method provides a better representation of the system because it only focuses on the parts of the components that are affected by change propagation.

4.1.4 Redesign of the BMW X5 Headliner Assembly

The proposed change prediction method is also used as a guide for the redesign of the BMW X5 headliner assembly. The focus of the redesign will be on improving the overall ease of change of the assembly. For this example, only the feature-based method is used as a guide and assessment for the redesign, as it offers a more detailed and accurate representation of the system. To evaluate the overall ease of change, the component ease of change values are summed for the entire assembly. The overall ease of change value is then used to assess the level of improvement offered by the redesign. The redesign will focus on lowering the connectivity within the assembly by decreasing the coupling between components, or if possible, entirely eliminating unnecessary components or features. The ease of change can also be lowered by decreasing the manufacturing cost of the components. This can be achieved by changing the process used to manufacture the parts, or by utilizing less costly features. For this redesign, however, improvements on the manufacturing of the parts are not considered. An exploded view of the handle grab assembly in the current BMW X5 headliner assembly is seen in Figure 16.

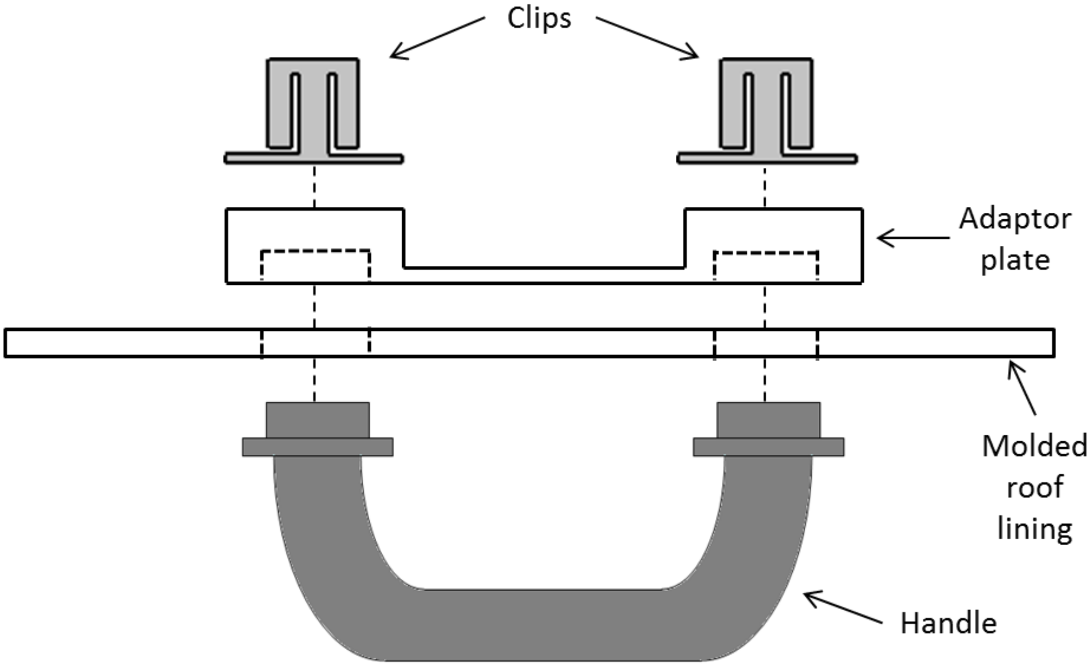


Figure 16: Exploded view of the BMW X5 handle grab assembly

The results of the original change assessment (see Table 19) identify the clips and adaptor plates as the being the most difficulty to change, and yields an overall score of 2464 for the difficulty of change of the entire assembly. The adaptor plate is first targeted for redesign because of its high level of connectivity and difficulty of change. When evaluating the function of the adaptor plates, it can be seen that they are primarily used as a connecting piece between the handles and clips. The adaptor plates are essentially a structural component that is used to connect the functional components in the assembly. Since they serve no functional importance, they can therefore be eliminated, and the handle bosses can be lengthened to attach to the clips. The clips were previously attached to the adaptor plates by three different features, a rectangular slot, two cylindrical bosses, and two smaller rectangular bosses (see Figure 17).

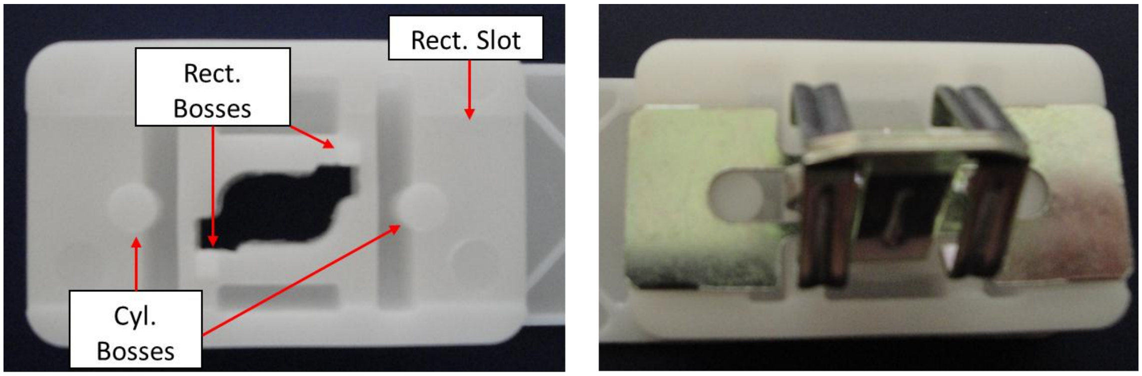


Figure 17: Adaptor plate and clip interface

The three different features used in the interface between the adaptor plates and clips are unnecessary and redundant. Therefore, the redesign uses just a rectangular slot to connect the handle bosses and clips, which means only the blanking of the clips will be affected by a change to the handle bosses. The schematic and DSM for the redesign are seen in Figure 18 and Table 21.

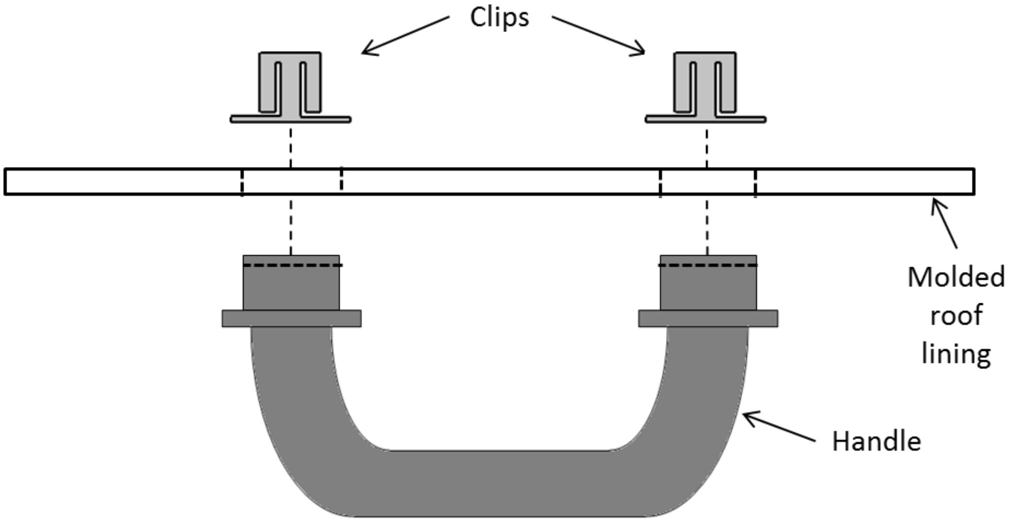


Figure 18: Exploded view of the redesigned handle grab assembly

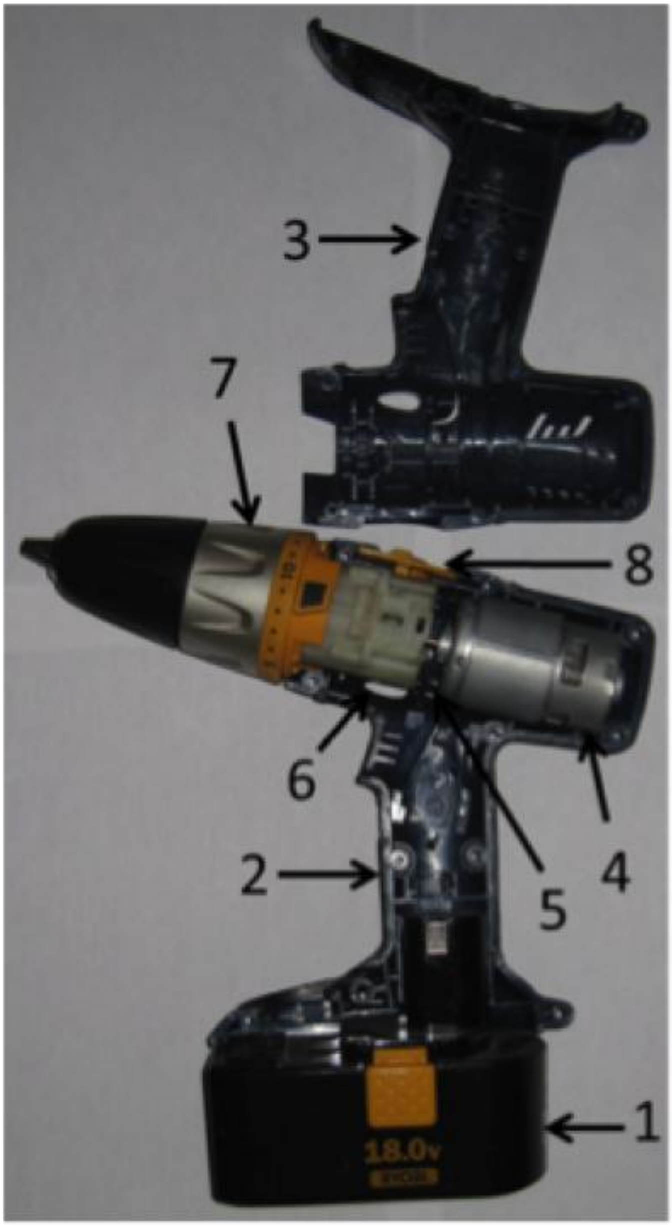
Table 21: DSM and component difficulty of change values for the redesigned BMW X5 headliner assembly

Component	Interfacing Features	# Features	Man. Hours	Total Hours	Comp. #	1	4.1	4.2	5.1	5.2	10	11	12	13	14	15	16	17	18.1	18.2	19.1	19.2	Feature change diff.	Comp. change diff.
Molded roof lining	holes	8	2	16.00	**1**	1	0.5	0	0.5	0	0	0	0	0	0	0	0	0	0.5	0	0.5	0	70.5	70.5
front handle (left)	rectangular boss	2	2.42	4.84	**4.1**	0.5	1	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	55.7	117.2
	rectangular slot	2	2.42	4.84	**4.2**	0	0.5	1	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	61.5	
front handle (right)	rectangular boss	2	2.42	4.84	**5.1**	0.5	0	0	1	0.5	0	0	0	0	0	0	0	0	0	0	0	0	55.7	117.2
	rectangular slot	2	2.42	4.84	**5.2**	0	0	0	0.5	1	0	0	0.5	0.5	0	0	0	0	0	0	0	0	61.5	
clip (front, left, 1)	change to blanking	1	40	40.00	**10**	0	0	0.5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	60.7	60.7
clip (front, left, 2)	change to blanking	1	40	40.00	**11**	0	0	0.5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	60.7	60.7
clip (front, right, 1)	change to blanking	1	40	40.00	**12**	0	0	0	0	0.5	0	0	1	0	0	0	0	0	0	0	0	0	60.7	60.7
clip (front, right, 2)	change to blanking	1	40	40.00	**13**	0	0	0	0	0.5	0	0	0	1	0	0	0	0	0	0	0	0	60.7	60.7
clip (back, left, 1)	change to blanking	1	40	40.00	**14**	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.5	0	0	60.7	60.7
clip (back, left, 2)	change to blanking	1	40	40.00	**15**	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.5	0	0	60.7	60.7
clip (back, right, 1)	change to blanking	1	40	40.00	**16**	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.5	60.7	60.7
clip (back, right, 2)	change to blanking	1	40	40.00	**17**	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.5	60.7	60.7
rear handle (left)	rectangular boss	2	2.42	4.84	**18.1**	0.5	0	0	0	0	0	0	0	0	0	0	0	0	1	0.5	0	0	55.7	117.2
	rectangular slot	2	2.42	4.84	**18.2**	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0.5	1	0	0	61.5	
rear handle (right)	rectangular boss	2	2.42	4.84	**19.1**	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.5	55.7	117.2
	rectangular slot	2	2.42	4.84	**19.2**	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0.5	1	61.5	

The results of the difficulty of change calculations show that the redesign has an overall change difficulty of 1025 and an average component change difficulty of 79. This compares to the overall change difficulty of 2464 and the average component change difficulty of 145 for the current design. Although the overall ease of change is greatly improved, there are some tradeoffs and drawbacks to the redesign. The positive aspects of the redesign are that it significantly lowers the change difficulty of the clips and eliminates the adaptor plates, which are also relatively difficult to change. The tradeoff is that this results in an increase in the change difficulty of the handles and molded roof lining. This shows that improving the ease of change of one area might result in making another area worse. When redesigning an assembly it may be necessary to weigh the tradeoffs and determine the overall benefit, or to only focus on improving certain sections of the assembly.

4.2 Ryobi Hand-held Drill

A Ryobi hand-held drill requires improvements for subsequent generations that necessitate the redesign of key components. The proposed change prediction method is used to identify which component(s) offers the greatest ease of change, and thus should be targeted for redesign. The Ryobi drill assembly is shown below in Figure 19.



(1)	Battery	(5)	Motor Connector
(2)	Right Cover	(6)	Gear Housing
(3)	Left Cover	(7)	Chuck
(4)	Motor	(8)	Switch

Figure 19: Ryobi drill assembly

4.2.1 Component-based Method

The resulting design structure matrix with the component difficulty of change calculations for the Ryobi drill assembly is seen below in Table 22. The body of the DSM is populated with the coupling index calculations for each component versus every other component in the assembly. It should be noted, that in the case of the motor the assigned manufacturing hours are not based directly on DFM principles because the motor is an outsourced subassembly. For this reason, any changes to the motor would be very costly, and thus a relatively high value of 80 hours is assigned.

Table 22: DSM for the Ryobi drill assembly

Comp.	**Man. Process**	**Man. Hours**	**Comp. ID**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Comp. diff. of change**
Battery	injection molding	49.2	**1**	1	0.5	0.5	0	0	0	0	0	124.9
Right cover	injection molding	48.8	**2**	0.5	1	1	0.5	0.5	0.5	0.5	0.5	176.0
Left cover	injection molding	48.8	**3**	0.5	1	1	0.5	0.5	0.5	0.5	0.5	176.0
Motor	outsourced subassembly	80.0	**4**	0	0.5	0.5	1	0.75	0	0	0	153.8
Motor connector	injection molding	7.1	**5**	0	0.5	0.5	0.75	1	0.75	0	0	139.1
Gear housing	injection molding	7.1	**6**	0	0.5	0.5	0	0.75	1	0.75	0	125.4
Chuck	injection molding	7.1	**7**	0	0.5	0.5	0	0	0.75	1	0	99.1
Switch	injection molding	6.3	**8**	0	0.5	0.5	0	0	0	0	1	92.7

The results of the component difficulty of change calculations show that the right and left covers present the greatest difficulty of change, while the chuck, switch, and battery offer the greatest ease of change. The covers prove to be difficult to change because of a high level of connectivity. As seen in Table 22, the covers are directly coupled to all the other components in the assembly. Furthermore, the covers are also relatively hard to change in terms of manufacturing, and a change to one cover will result in a direct, corresponding change to the other. The battery, chuck, and switch all prove relatively easy to change mostly because they are not directly coupled to the motor and have an overall low level of connectivity. This is somewhat expected, because the motor is purposefully assigned a relatively high manufacturing score of 80 hours to prioritize it as a component to avoid changing. In the case of the chuck and switch, low manufacturing scores are also a factor in their relative ease of change.

4.2.2 Feature-based Method

The Ryobi drill assembly is further broken down into the interfacing features for each component. The resulting component and manufacturing information, coupling index DSM, and change difficulty for the Ryobi drill assembly are included in Table 23, Figure 20, and Table 24.

Table 23: Component, interface, and manufacturing hours information for Ryobi drill

Component	Interface Features	# Features	Man. Hours	Total Hours	Feature ID
Battery	clip boss (left)	1	2.42	2.42	1.1
	clip boss (right)	1	2.42	2.42	1.2
	top boss	1	2.42	2.42	1.3
	base boss	1	2.42	2.42	1.4
Right Cover	holes	11	0.76	8.36	2.1
	radial ribs (motor)	4	2.42	9.68	2.2
	radial ribs (gear housing)	1	2.42	2.42	2.3
	radial ribs (chuck)	3	2.42	7.26	2.4
	battery slot	1	1.82	1.82	2.5
	base	1	2.42	2.42	2.6
	clip boss	1	2.42	2.42	2.7
	alignment slots	13	2.42	31.46	2.8
	switch slot	1	1.82	1.82	2.9
Left Cover	hole bosses	11	1.26	13.86	3.1
	radial ribs (motor)	4	2.42	9.68	3.2
	radial ribs (gear housing)	1	2.42	2.42	3.3
	radial ribs (chuck)	3	2.42	7.26	3.4
	battery slot	1	1.82	1.82	3.5
	base	1	2.42	2.42	3.6
	clip boss	1	2.42	2.42	3.7
	alignment bosses	13	2.42	31.46	3.8
	switch slot	1	1.82	1.82	3.9
Motor	Outside diameter	1	40	40	4
Motor Connector	tabs	2	2.42	4.84	5.1
	outside diameter	1	0.31	0.31	5.2
Gear Housing	slots	2	1.82	3.64	6.1
	outside diameter	1	0.31	0.31	6.2
	inside diameter	1	0.31	0.31	6.3
	outside diameter of end ring	1	0.31	0.31	6.4
	holes	4	0.31	1.24	6.5
Chuck	inside diameter	1	0.31	0.31	7.1
	outside diameter	1	0.31	0.31	7.2
	holes	4	0.31	1.24	7.3
	right tab	1	2.42	2.42	7.4
	left tab	1	2.42	2.42	7.5
Switch	boss	1	2.42	2.42	8

Feature ID	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4	5.1	5.2	6.1	6.2	6.3	6.4	6.5	7.1	7.2	7.3	7.4	7.5	8
1.1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.2	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.3	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.4	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.1	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.2	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.3	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.17	0.00	0.00
2.5	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.6	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.7	0.00	0.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
3.1	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.17	0.00
3.5	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.6	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.7	0.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
4	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	1.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.2	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00
6.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00
7.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	1.00	0.00	0.00	0.00	0.00	0.00
7.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
7.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00
7.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
7.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Figure 20: Coupling index between component features represented in DSM for Ryobi drill

The body of the DSM contains the coupling index calculations (see Figure 20), and the two rightmost columns contain the feature difficulty of change and the overall component difficulty of change (see Table 24). It should again be noted, that in the case of the motor the assigned manufacturing hours are not based directly on DFM principles because the motor is an outsourced subassembly. For this reason, any changes to the motor would be very costly, and thus a relatively high value of 40 hours is assigned.

The results of the calculations identify the two covers and the motor as the components that should be avoided during re-design. In the case of the covers, it is largely because of a high degree of connectivity, while in the case of the motor it is due to the high costs associated with any manufacturing changes. The results also identify the switch as being the component that offers the greatest ease of change. However, in terms of the objective of identifying a component for redesign in subsequent generations, the switch offers little room for improvement. The results show that the battery has the second lowest difficulty of change, and thus should be the component selected for re-design. The reason for the battery's relatively low score is because of a low level of connectivity and because it is not coupled to the motor while most of the other components, to some degree, are.

The method does not clearly identify any features that offer the greatest ease of change because of very similar manufacturing and coupling scores. It does, however, identify the features coupled to the motor as having the highest difficulty of change. This shows the importance of also including manufacturing costs in the difficulty of change calculations, as just modeling connectivity would not have prioritized the motor as a component to steer clear of when making changes. The highest order of coupling in the system is found to be fifth order.

Table 24: Feature and component difficulty of change calculation

Component	Interfaced Features	Feature change difficulty	Component change difficulty
Battery	clip boss (left)	4.44	17.15
	clip boss (right)	4.44	
	top boss	4.24	
	base boss	4.03	
Right Cover	holes	22.22	112.53
	radial ribs (motor)	17.19	
	radial ribs (gear housing)	2.67	
	radial ribs (chuck)	8.35	
	battery slot	3.49	
	base	3.50	
	clip boss	4.44	
	alignment slots	47.19	
	switch slot	3.49	
Left Cover	hole bosses	22.22	112.53
	radial ribs (motor)	17.19	
	radial ribs (gear housing)	2.67	
	radial ribs (chuck)	8.35	
	battery slot	3.49	
	base	3.50	
	clip boss	4.44	
	alignment bosses	47.19	
	switch slot	3.49	
Motor	Outside diameter	49.91	49.91
Motor Connector	tabs	6.05	31.36
	outside diameter	25.31	
Gear Housing	slots	6.06	24.62
	outside diameter	2.73	
	inside diameter	12.89	
	outside diameter of end ring	0.47	
	holes	2.48	
Chuck	inside diameter	0.47	23.71
	outside diameter	7.97	
	holes	2.48	
	right tab	6.40	
	left tab	6.40	
Switch	boss	4.24	4.24

4.2.3 Comparison of the Component and Feature Based Methods

To further evaluate the results from the component and feature based methods, the overall ease of change rankings for the components of the Ryobi drill assembly are presented in Table 25.

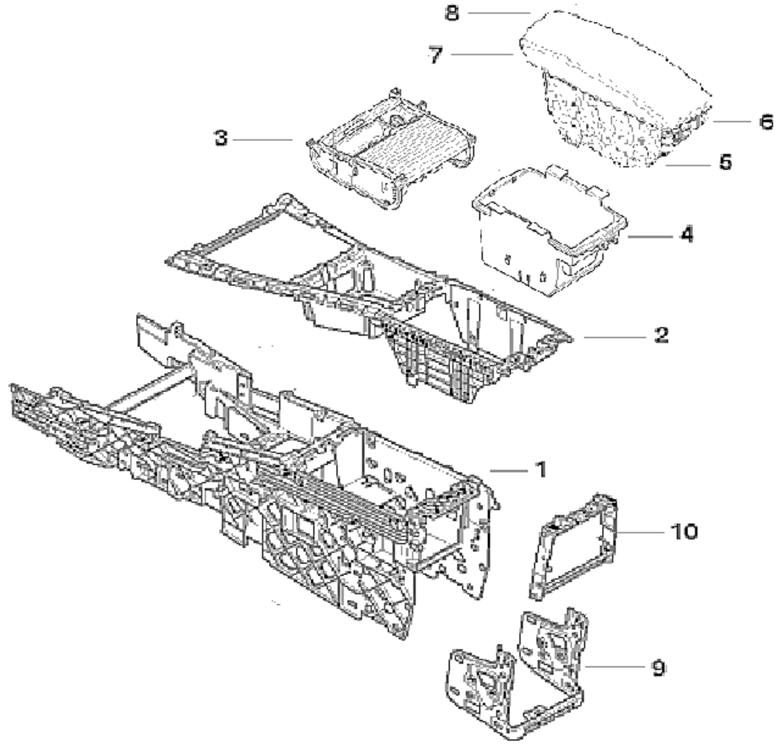
Table 25: Component ease of change rankings for both methods

Component	*Component-based ranking*	*Feature-based ranking*
Battery	3	2
Right Cover	7	7
Left Cover	7	7
Motor	6	6
Motor Connector	5	5
Gear Housing	4	4
Chuck	2	3
Switch	1	1

As shown in Table 25, the two methods produce the same overall trend with the covers, motor, and motor connector being the most difficult to change, and the switch, chuck, battery, and gear housing being the easiest to change. The biggest discrepancy between the two methods is the relative score of the battery. The feature-based method identifies it as a component that should be selected for change, but the component-based method produces a lower ranking and relative score, identifying other components that should be changed first. This discrepancy can largely be attributed to the way change is assessed in each method. The component-based method bases the manufacturing difficulty of change on the size of the components. This means that a relatively large component like the battery is assumed to be more difficult to change. The feature-based method, however, is based on the type of interfaced features, and more importantly, the number of interfaced features per component. The majority of the time, the two ways of assessing manufacturing difficulty of change will lead to similar results because, in general, a larger component will have more interfacing features. In the case of the battery, however, this is not shown to be completely true because only the top part of the battery is connected to other components, thus leading to less interfacing features than smaller components like the gear housing and chuck.

4.3 BMW X5 Center Console Assembly

A BMW X5 center console assembly is analyzed using the proposed change prediction method to identify which component(s) offer the greatest ease of change. For simplification, only the key components that offer an opportunity for change are included in the analysis. The BMW X5 center console assembly is seen below in Figure 21.



(1)	Lower mount	(6)	Right tray side piece
(2)	Upper mount	(7)	Left tray flap
(3)	Cup holder tray	(8)	Right tray flap
(4)	Back tray	(9)	Large bracket
(5)	Left tray side piece	(10)	Small bracket

Figure 21: Schematic of the BMW X5 center console assembly (from www.realoem.com)

The center console assembly differs from the previous two examples, in that it does not allow for a clear decomposition from the component level to the feature level. The components do not have distinguishable interfacing features, but instead interface on a higher level, with entire sides of components interfacing with corresponding surfaces on other components. Therefore, the center console assembly is only analyzed using the component-based method. The DSM with the component difficulty of change values for the BMW X5 center console assembly is seen below in Table 26.

Table 26: DSM with component difficulty of change values for the BMW X5 center console assembly (component-based method)

	Man. Process	**Man. Hours**	**Comp. ID**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Comp. change diff.**
Lower Mount	injection molding	1131.8	**1**	1	0.5	0.5	0.17	0	0	0	0	0.33	0.5	1882.9
Upper Mount	injection molding	804.4	**2**	0.5	1	0.5	0.17	0.5	0.5	0	0	0	0	1752.4
Cup Holder Tray	injection molding	230.9	**3**	0.5	0.5	1	0	0	0	0	0	0	0	1346.2
Back Tray	injection molding	249.7	**4**	0.17	0.17	0	1	0.5	0.5	0.17	0.17	0	0	849.5
Left Tray Side Piece	injection molding	127.6	**5**	0	0.5	0	0.5	1	0	0.17	0	0	0	1082.3
Right Tray Side Piece	injection molding	127.6	**6**	0	0.5	0	0.5	0	1	0	0.17	0	0	1082.3
Left Tray Flap	injection molding	101.0	**7**	0	0	0	0.17	0.17	0	1	0	0	0	282.3
Right Tray Flap	injection molding	101.0	**8**	0	0	0	0.17	0	0.17	0	1	0	0	282.3
Bracket (large)	stamping	192.5	**9**	0.33	0	0	0	0	0	0	0	1	0.5	835.7
Bracket (small)	die casting	111.0	**10**	0.5	0	0	0	0	0	0	0	0.5	1	1088.9

The results of the component difficulty of change calculations show that the upper and lower mounts are the most difficult to change, while the left and right tray flaps offer the greatest ease of change. The upper and lower mounts are identified as being difficult to change, because they have high levels of connectivity and significantly higher manufacturing scores. The high manufacturing scores are due to the size of the mounts relative to the other components. As seen in Figure 21, the mounts are considerably larger than the other components. The left and right tray flaps, on the other hand, exhibit much lower difficulty of change scores than the other components in the assembly. This is mostly due to the fact that they are the only components in the assembly that are not directly coupled to either the upper or lower mount. Since the mounts have such high manufacturing scores, the level of coupling between the mounts and the other components account for the majority of the separation in the difficulty of change scores.

CHAPTER FIVE

DISCUSSION OF THE PROPOSED CHANGE PREDICTION METHOD

The proposed change prediction method is demonstrated on three different industry examples, and in one of the examples the method is also used as a guide for a redesign. In this section, the insights from the three examples are discussed in general. A summary of the overall results from the three industry examples is seen in Table 27.

Table 27: Difficulty of change results from BMW X5 headliner and center console assemblies and the Ryobi handheld drill assembly

	Component	*Component-based method*		*Feature-based method*	
		Score	**Ranking**	**Score**	**Ranking**
BMW X5 Headliner Assembly	Molded roof lining	177.5	**3**	28.9	**2**
	Handles	176.4	**2**	19.3	**1**
	Adaptor Plates	171.5	**1**	136.1	**3**
	Clips	209.8	**4**	227.8	**4**
Ryobi Handheld Drill Assembly	Battery	124.9	**3**	17.2	**2**
	Right/Left Cover	176.0	**7**	112.5	**7**
	Motor	153.8	**6**	49.9	**6**
	Motor Connector	139.1	**5**	31.4	**5**
	Gear Housing	125.4	**4**	24.6	**4**
	Chuck	99.1	**2**	23.7	**3**
	Switch	92.7	**1**	4.2	**1**
BMW X5 Center Console Assembly	Lower Mount	1882.9	**8**		
	Upper Mount	1752.4	**7**		
	Cup Holder Tray	1346.2	**6**		
	Back Tray	849.5	**3**		
	Left/Right Tray Side Piece	1082.3	**4**		
	Left/Right Tray Flap	282.3	**1**		
	Bracket (large)	835.7	**2**		
	Bracket (small)	1088.9	**5**		

When comparing the results of the component and feature based methods, the same general trends and rankings are, for the most part, produced. The rankings for the headliner assembly somewhat differ, but the scores for the component-based method are close enough that the discrepancy could just be attributed to the uncertainty in the manufacturing and coupling scores. Conceptually, the feature-based method should produce a better and more accurate representation of the change propagation, because it is the more detailed approach and only focuses on the areas that are affected by change (Hypothesis 3). This can be seen in the differences in the results of the two methods for the headliner assembly. The component-based scores for the molded roof lining and handles are somewhat inflated, because the manufacturing scores are based on the assumption that a change will affect the whole component. In reality, the handles would not be greatly affected by change propagation because only the interfaces on each end of the handles would have to be changed. Similarly, the only feature of the molded roof lining that interfaces with the rest of the assembly are eight holes, which represent a small percentage of the overall size of the component. Therefore, the component-based method will only produce entirely accurate results if there is a trend between the size of a component and the size/number of interfaces. The component-based method may provide a sufficient analysis in some cases, such as with the drill assembly, but the feature-based method is shown to produce more accurate and detailed results. The one drawback of the feature-based method, as compared to the component-based method, is that it is more time consuming and requires more knowledge of the system. This means that it may not be able to be completed during the earlier stages of detailed design, until all the features are finalized. The overall difficulty of change scores for both methods for the three industry examples are seen below in Figure 22.

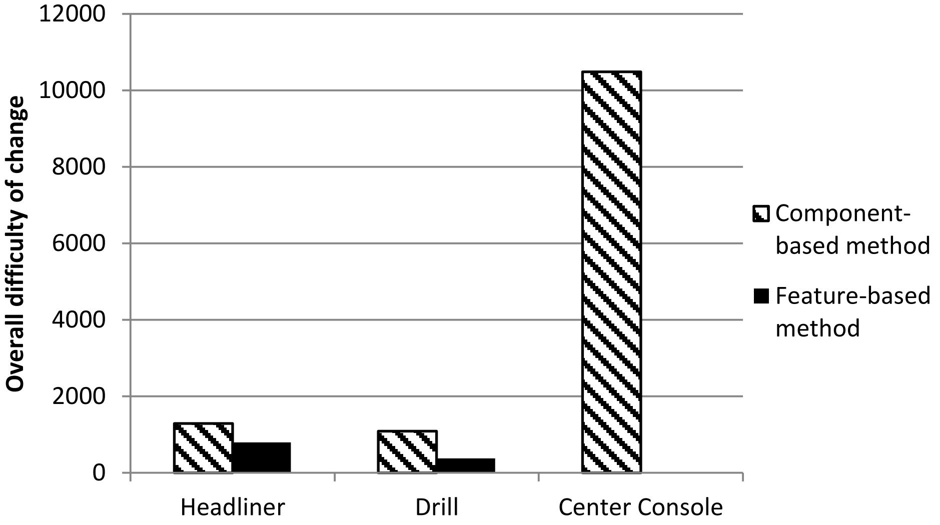


Figure 22: Overall difficulty of change scores for the component and feature based methods for all three industry examples

As shown in Figure 22, the overall difficulty of change produced by component-based method is significantly greater than that produced by the feature-based method. This difference in scale is expected, as the two methods base the manufacturing costs on different DFM assessments that are not comparable. Therefore, the results from the two methods cannot be directly compared, but must instead be assessed based on their relative rankings.

To gain a better understanding of the proposed change prediction method, the resulting difficulty of change scores from the three industry examples are analyzed to identify the important determining factors. The effect of the number of features per component on the resulting difficulty of change score is seen in Figure 23.

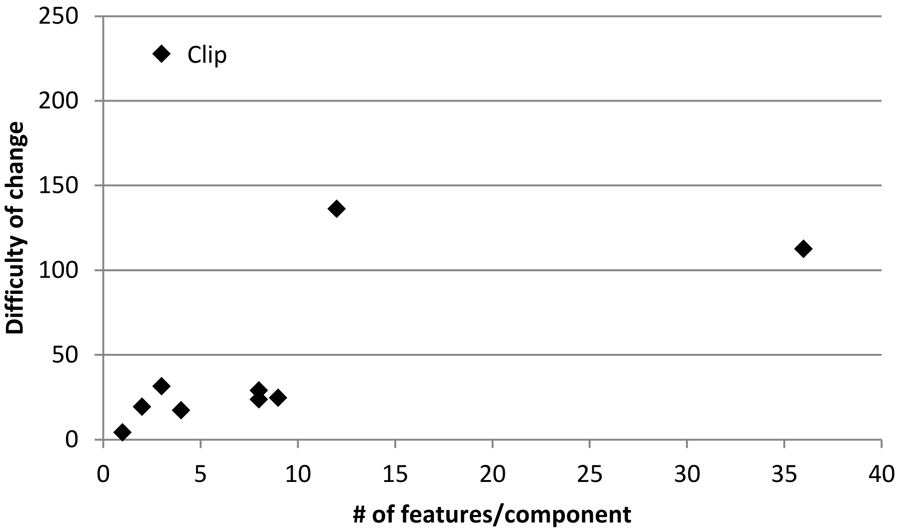


Figure 23: Difficulty of change versus the number of features per component

The data shows that a positive correlation exists between the number of interfacing features on a component and the resulting difficulty of change score. The outlier in the upper left of the graph is the data point for the clips. It falls outside the general trend because it is a stamped component, while the rest are injection molded. If more stamped components had been included in the analysis, it can be inferred that a similar correlation would have formed, but with higher difficulty of change scores.

The effect of the initiating component's manufacturing cost on the resulting difficulty of change is shown in Figure 24 for the component-based method and Figure 25 for the feature-based method. These manufacturing costs are based on relative estimates that are used for comparison purposes in the method, and do not represent the actual cost of the components. The component manufacturing costs for the component-based method derive from the tooling time estimates that are based solely on the size of each component. The component manufacturing costs for the feature-based method are based on the total tooling hours required for the interfacing features of each component.

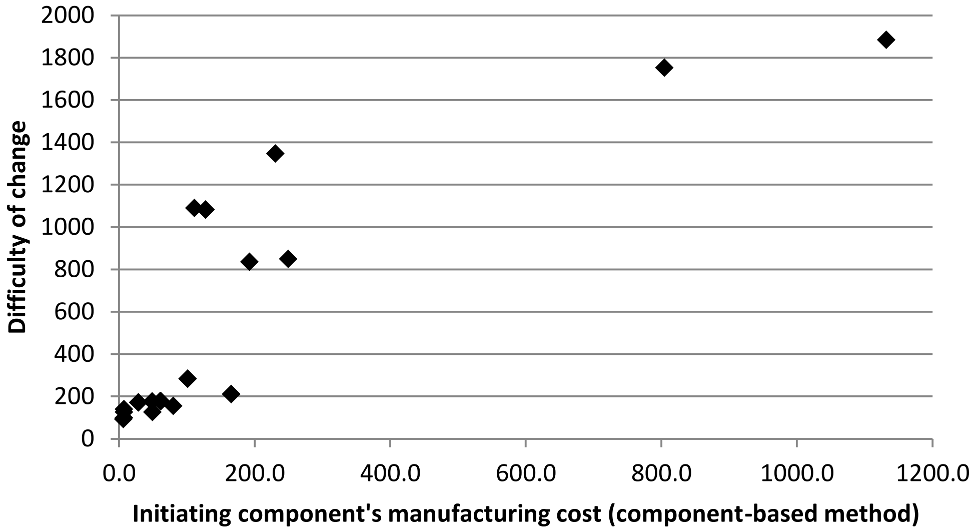


Figure 24: Initiating component's difficulty of change versus manufacturing cost for the component-based method

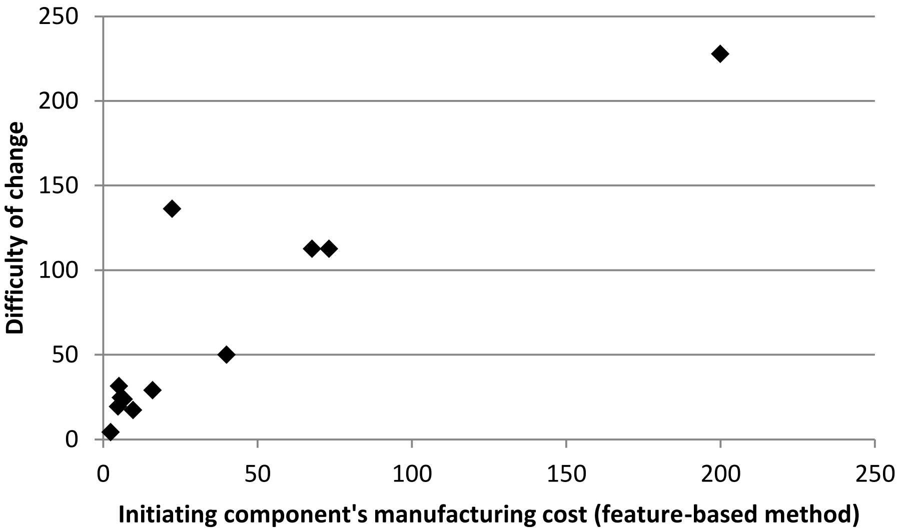


Figure 25: Initiating component's difficulty of change versus manufacturing cost for the feature-based method

For both methods, a positive trend is shown to exist between the initiating components' manufacturing costs and the resulting difficulty of change values. This indicates that the initiating component's manufacturing cost is a fairly good predictor of its difficulty of change, and thus that on average the coupled components have less of an effect. The spread of the data does not form a completely consistent trend, however, which means that while the initiating components' manufacturing costs are probably the largest factor, the coupled components still have an effect. In Figure 26, the average component difficulty of change, normalized per unit projected area, for each manufacturing process is compared for both methods.

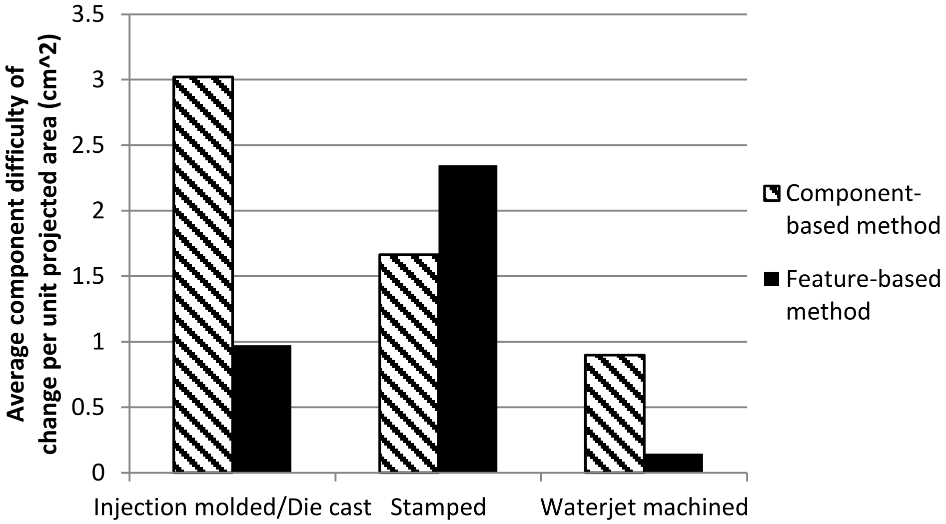


Figure 26: Average component difficulty of change (normalized per unit projected area) for each manufacturing process

As seen in Figure 26, changing an injection molded part on a component level is relatively difficult, while changing the individual features of an injection molded part is relatively easy. For a stamped part the opposite is shown to be true, as it is relatively easier to change a stamped part on the component level than the feature level.

Conceptually this makes sense, because a change to a stamped feature requires the redesign of a whole station, while a change to an injection molded feature requires just that specific area to be re-machined. On an overall component level, the size of a part does not have as much of an effect on the cost of stamping as it does injection molding. Waterjet machined components are shown to be the least difficult to change, which is expected because it is a relatively cheap and easy to change process. Normally waterjet machined components would be easier to change, but the molded roof lining is supported by a corresponding aluminum mold during cutting, which adds to the change difficulty.

The effect of a component's total level of coupling on the resulting difficulty of change score is seen in Figure 27 for the component-based method and Figure 29 for the feature-based method. A graph including just the drill and headliner assemblies is shown in Figure 28 for the component-based method.

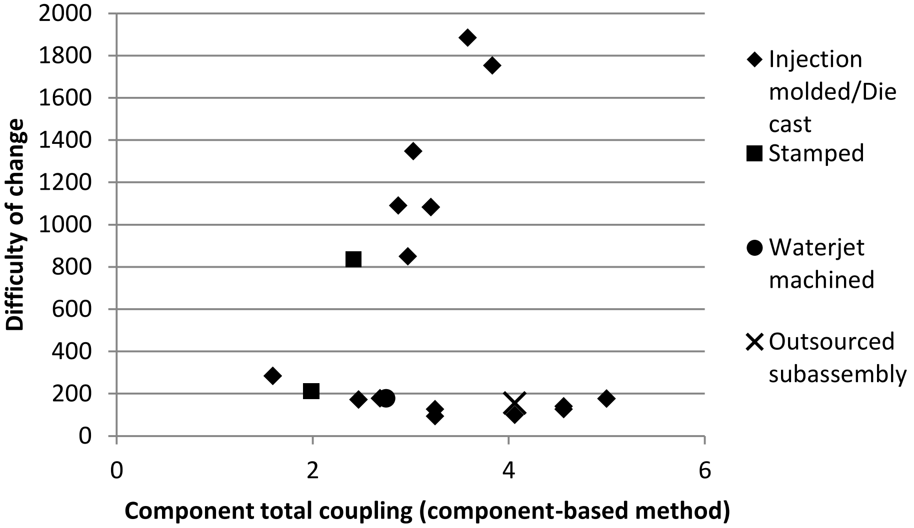


Figure 27: Component difficulty of change versus total level of coupling for the component-based method

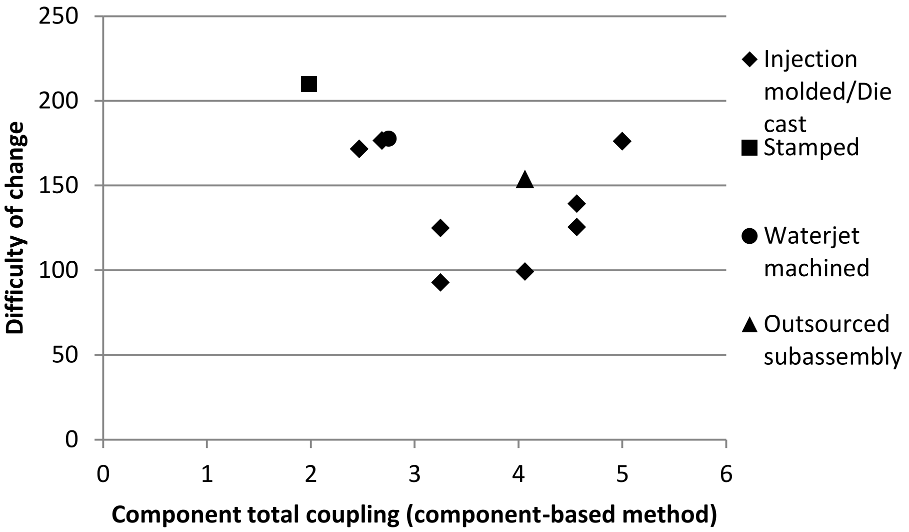


Figure 28: Component difficulty of change versus total level of coupling for the component-based method (drill and headliner assemblies only)

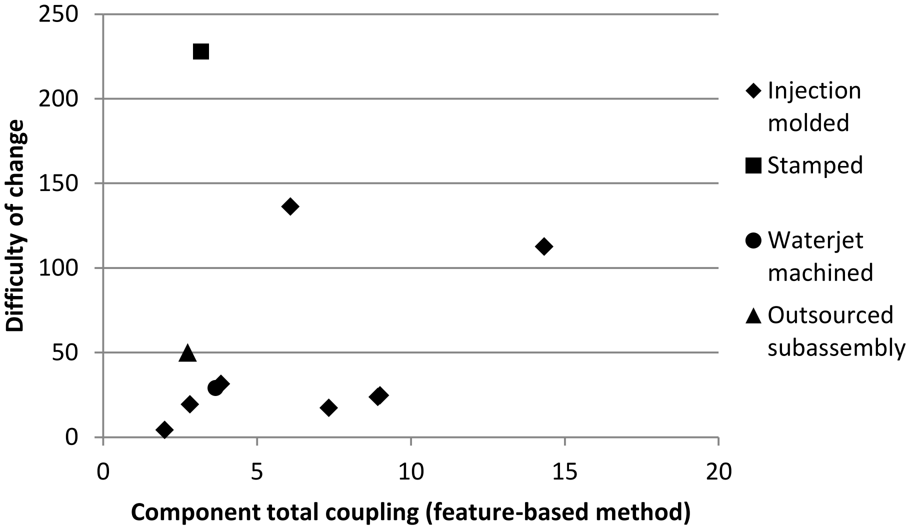


Figure 29: Component difficulty of change versus the total level of coupling for the feature-based method

In Figure 27, there does not appear to be an overall trend, but a positive trend can be seen for just the center console components. The center console components are the points with the higher difficulty of change values that form an upward trend. A plot of just the drill and headliner (Figure 28), confirms that the two assemblies are the cause for a lack of an overall trend. The reason that only the center console components form a trend is probably because they have higher and more separated manufacturing scores. The degree of coupling becomes more significant when it is multiplied by large manufacturing scores such as those of the upper and lower mounts. In Figure 29, no real trend is evident, but it can be seen that increasing the level of coupling does have an effect on some of the component difficulty of change scores. Overall, the total level of coupling does have an effect on the difficulty of change, but it is not as good of a predictor as the initiating component's manufacturing score.

The effect of a component's level of direct coupling on the resulting difficulty of change score is seen in Figure 30 and Figure 31 for the component-based method and Figure 32 for the feature-based method.

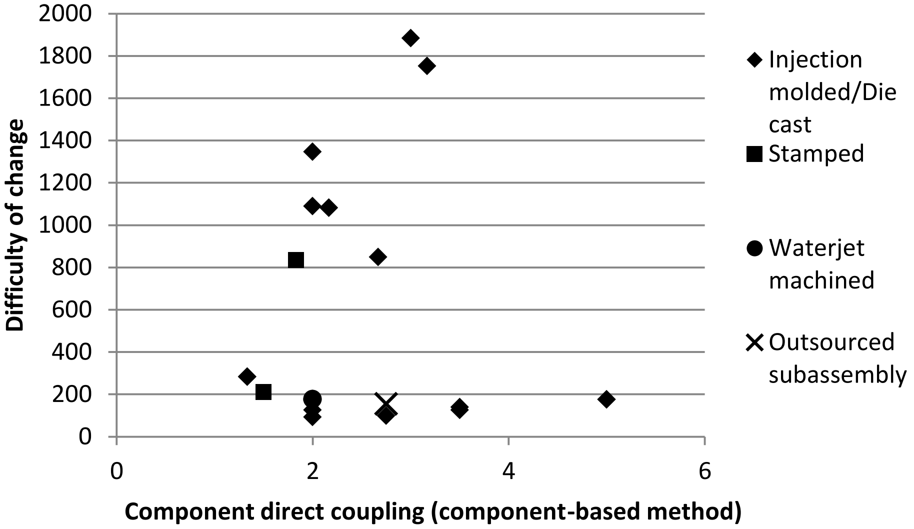


Figure 30: Component difficulty of change versus the level of direct coupling for the component-based method

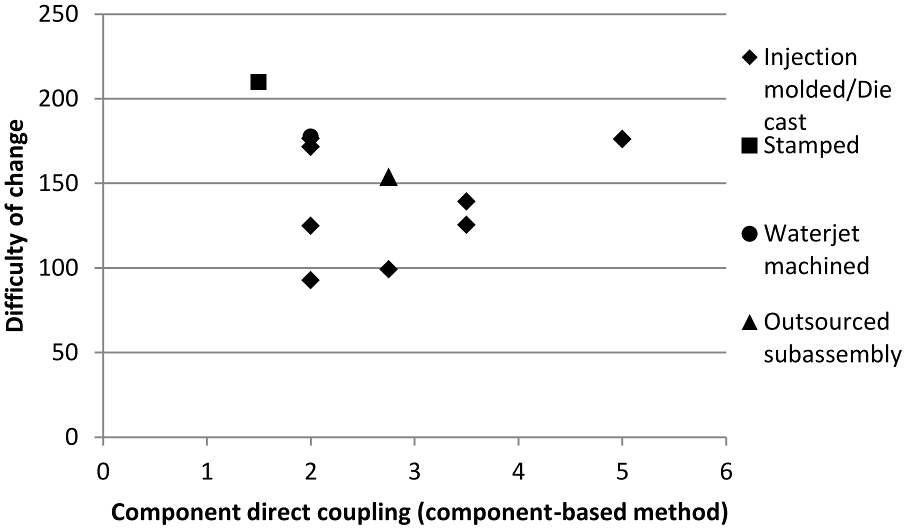


Figure 31: Component difficulty of change versus the level of direct coupling for the component-based method (drill and headliner assemblies only)

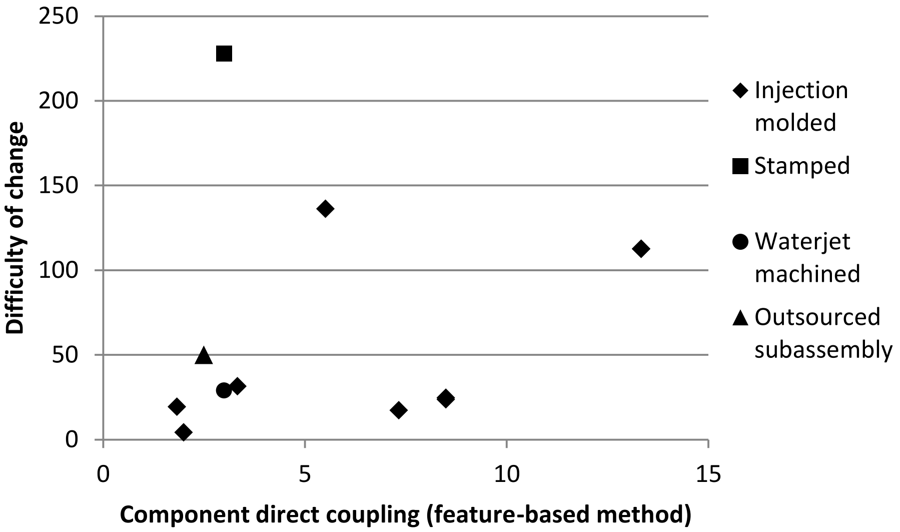


Figure 32: Component difficulty of change versus the level of direct coupling for the feature-based method

A comparison of the graphs for the total and direct coupling levels shows that, for the most part, the point spread remains consistent for both measures. This indicates that the directly coupled components/features have a much greater effect on the resulting difficulty of change than the indirectly coupled components/features. This is expected, as the probability of change propagating from one component to the next decreases as the order of coupling increases. A closer comparison of the component-based graphs also shows that although the same general trend still exists, the difference between the graphs for the total and direct levels of coupling is larger than that of the feature-based graphs. This indicates that indirect coupling has more of an effect in the component-based method than the feature-based method. Conceptually, this makes since because the feature-based method offers a more detailed representation that focuses in on the interfaces between features instead of components. In general, a change is less likely to propagate from one of a component's features to the others, because on a feature level the effect of a change is localized to the individual interfacings features instead of the whole component.

In Table 27, another trend that can be seen across the three industry examples is that the structural components in all the assemblies are identified as being the most difficult to change. In the center console assembly the upper and lower mounts are the most difficult to change, while in the Ryobi drill assembly the two covers are the most difficult to change. In the headliner assembly the adaptor plates can be considered the structural components, and they also have the highest difficulty of change. These results tend to support the established industry standard of having set structural components and only changing the visual components that the user interacts with. This suggests that significant time should be spent during the initial design of a product on the structural components so that they can remain set during subsequent generations or re-designs. In order to lower the probability that change will propagate to the structural components, design effort must be spent on either creating set, uniform interfaces or lowering the coupling at the interfaces. The Ryobi drill design is different than the other two designs, in that its structural components (right/left covers) are also visual components that will change generation to generation. From an ease of change perspective this is not optimal, and without taking size constraints into account, a better design would be to have a structural backbone inside the drill that all the components attach to. This would significantly lower the cover's level of coupling, thus making them easier to change. This idea goes against the objective of a one-to-one mapping between the physical architecture and functions of a product that Suh stresses, and instead suggests adding non-functional, structural components to a design. One area in industry where this is especially prevalent is with mass customization products. In order to make a mass customization product economically viable, the numerous changes that are offered have to be cost effective and have as little impact as possible. An example of this can be seen in the BMW X5 center console, which has dozens of different setups that are available to the customer. The structural components (upper and lower mounts) that are difficult to change are set, while all the easier to change visual components are switched out. Essentially, the center console is much like a chassis type design. The upper and lower mount fit together to form the large structural component or chassis that all the smaller, interchangeable components connect to. The interfaces are then kept as constant as possible to lessen change propagation.

The manufacturing costs and coupling calculations that are used in the change prediction method are approximations that do not always provide accurate representations, and to some degree, are affected by human interpretation. This makes it necessary to evaluate the effect of uncertainty in the manufacturing cost and coupling on the final results. To assess the sensitivity of the difficulty of change results, the coupling is first held constant while an uncertainty of +/- 10% is applied to all the manufacturing costs. The resulting uncertainty for the component-based method is seen in Figure 33, Figure 34, and Figure 35 for the headliner, Ryobi drill, and center console assemblies. The uncertainty for the feature-based method is seen in Figure 36 and Figure 37 for the headliner and Ryobi drill assemblies.

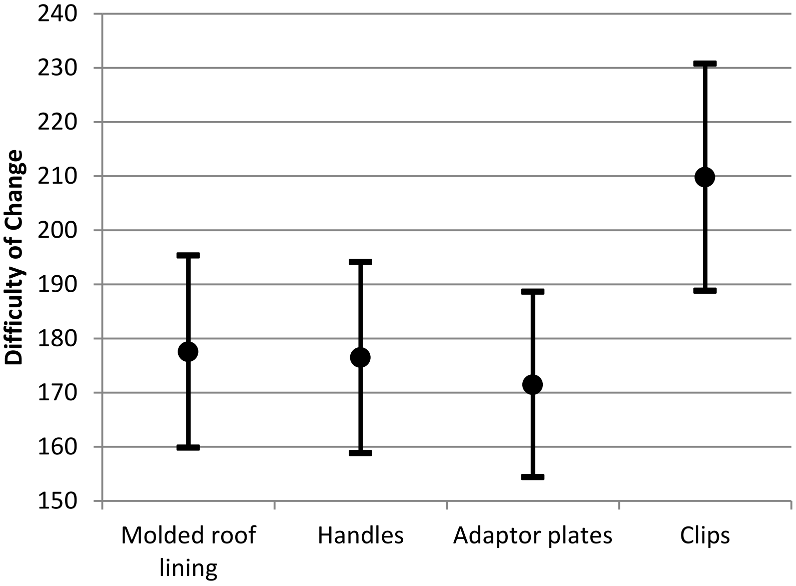


Figure 33: Uncertainty of the component difficulty of change values for the headliner assembly due to a +/- 10% uncertainty in manufacturing costs (component-based method)

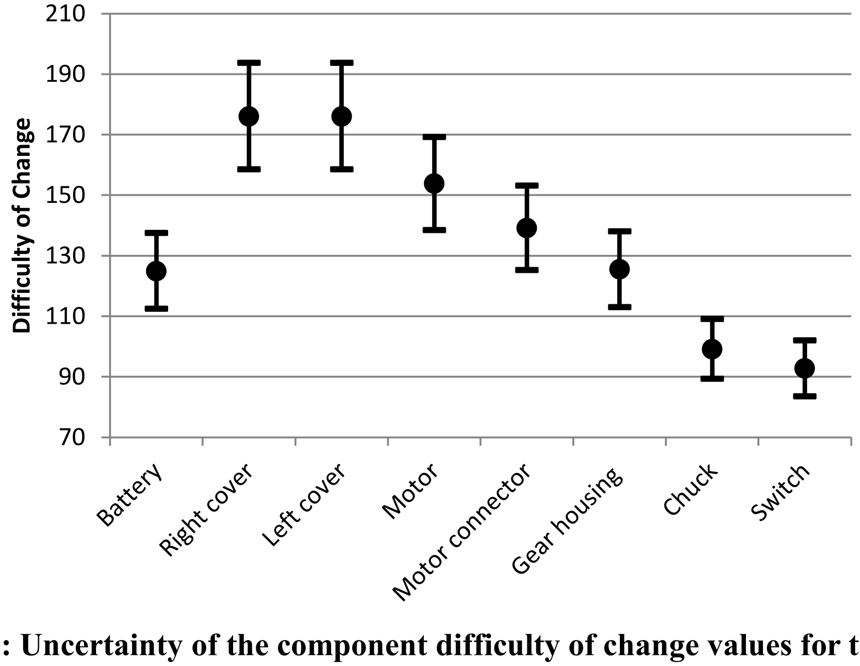


Figure 34: Uncertainty of the component difficulty of change values for the Ryobi drill assembly due to a +/- 10% uncertainty in the manufacturing costs (component-based method)

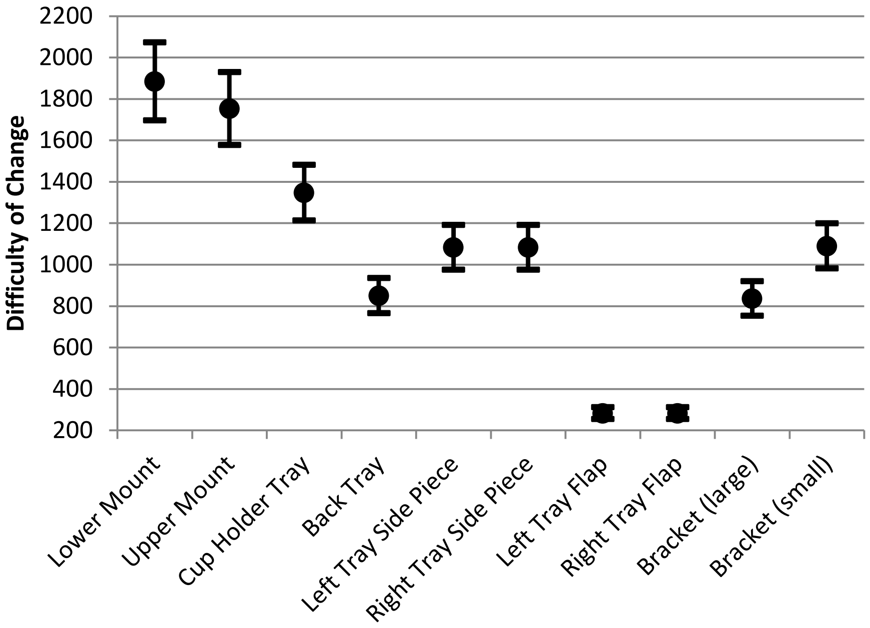


Figure 35: Uncertainty of the component difficulty of change values for the center console assembly due to a +/- 10% uncertainty in manufacturing costs (component-based method)

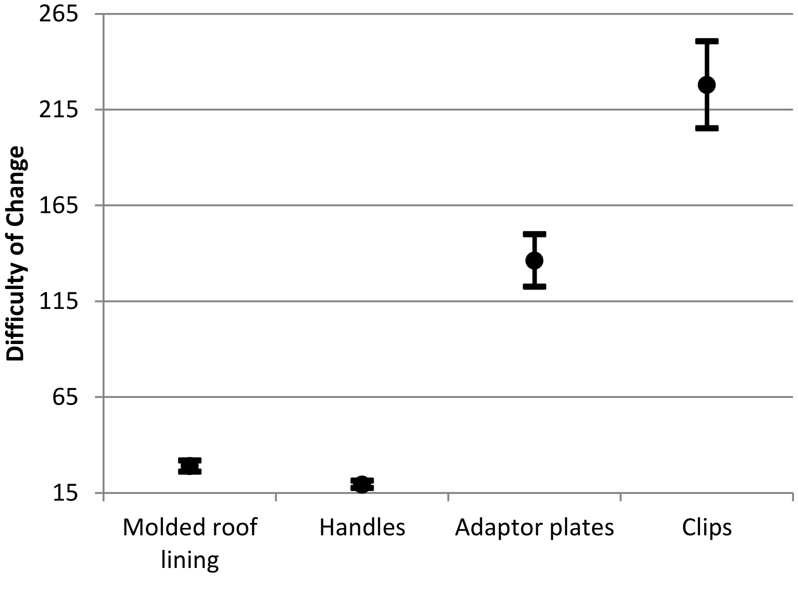


Figure 36: Uncertainty of the component difficulty of change values for the headliner assembly due to a +/- 10% uncertainty in manufacturing costs (feature-based method)

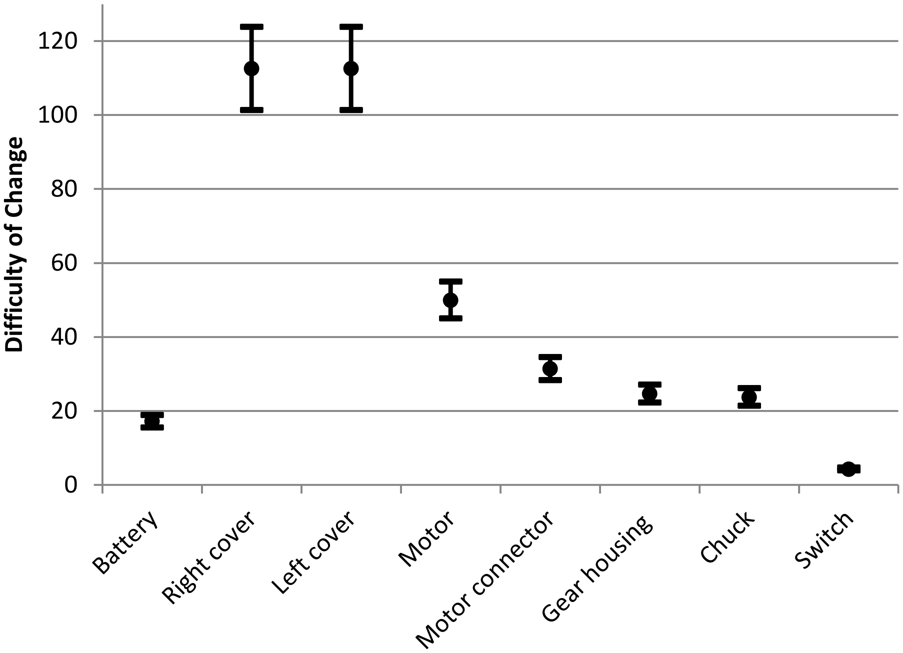


Figure 37: Uncertainty of the component difficulty of change values for the Ryobi drill assembly due to a +/- 10% uncertainty in manufacturing costs (feature-based method)

The analysis shows that an uncertainty of +/- 10% for the manufacturing costs has a substantial effect on the overall results for the component-based method. The uncertainty causes overlap in many of results, which means that the rankings cannot be assigned with a high level of confidence. The uncertainty analysis of the feature-based method, on the other hand, shows very little sensitivity to changes in the manufacturing costs. The overall rankings are unaffected, and thus can be held with confidence.

The sensitivity to changes in the total level of coupling is then evaluated by holding the manufacturing cost constant. The uncertainty in the coupling index values derives from the level of constraint values, which are an approximation and depend on interpretation. Values of 1 and 0 for the level of constraint are assumed to hold zero uncertainty, as they represent either full dimensional constraint or no dimensional constraint. All different levels of constraint in-between those two values are assigned a 0.5 for half dimensional constraint, so inherently there is uncertainty in the value. An uncertainty of +/- 20% is applied to all the 0.5 values for level of constraint. The resulting uncertainty in the difficulty of change scores for the component-based method are seen in Figure 38, Figure 39, and Figure 40 for the headliner, Ryobi drill, and center console assemblies. The uncertainty in the difficulty of change scores for the feature-based method are seen in Figure 41 and Figure 42 for the headliner and Ryobi drill assemblies.

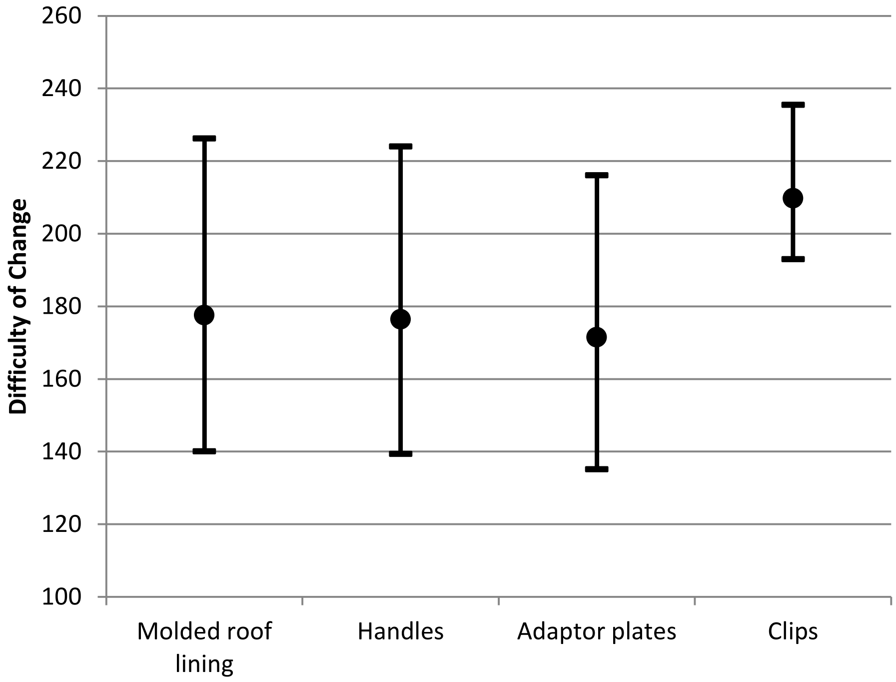


Figure 38: Uncertainty of the component difficulty of change values for the headliner assembly due to a +/- 20% uncertainty in the coupling index (component-based method)

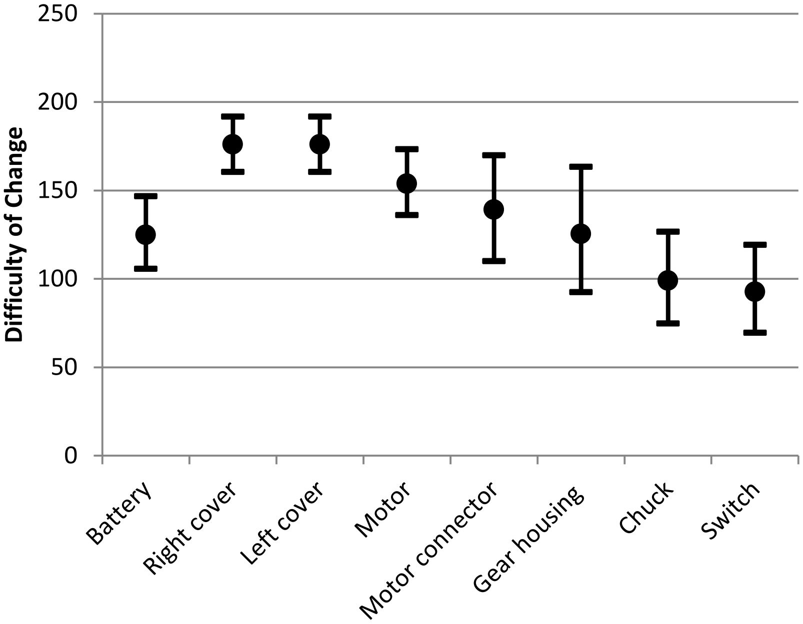


Figure 39: Uncertainty of the component difficulty of change values for the Ryobi drill assembly due to a +/- 20% uncertainty in the coupling index (component-based method)

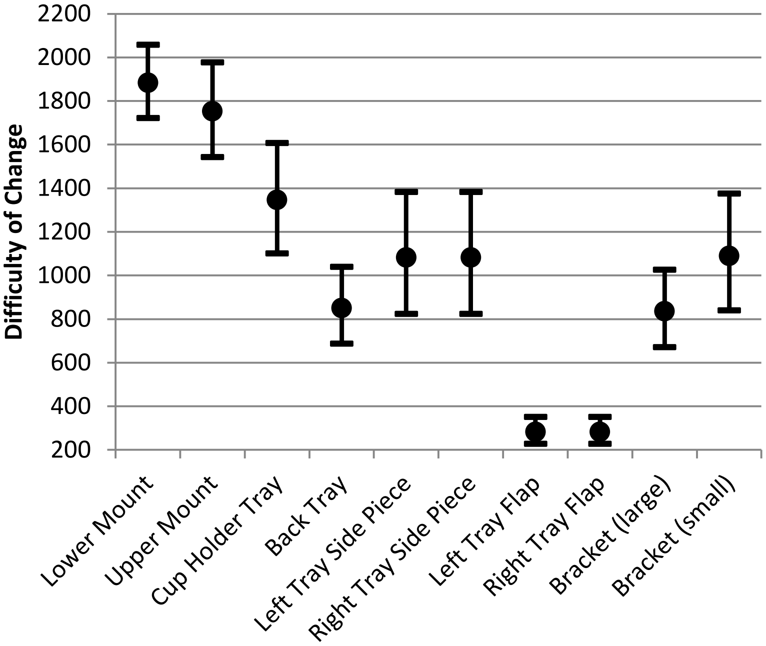


Figure 40: Uncertainty of the component difficulty of change values for the center console assembly due to a +/- 20% uncertainty in the coupling index (component-based method)

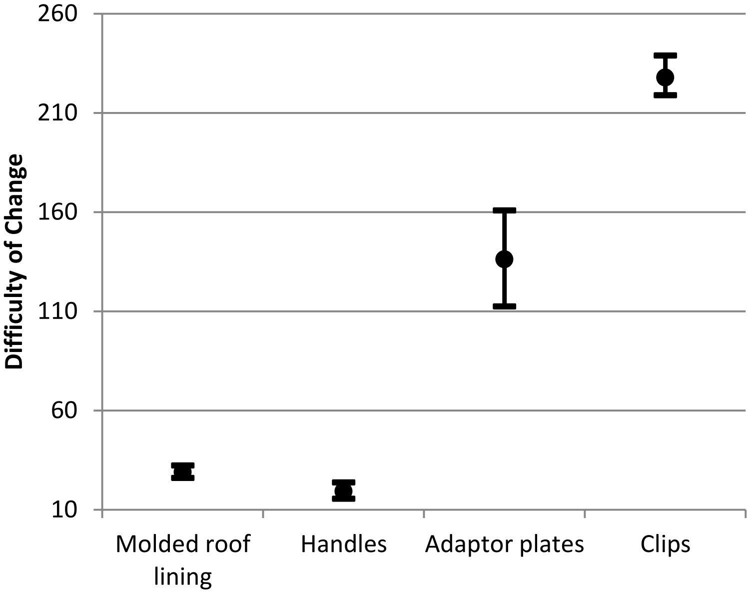


Figure 41: Uncertainty of the component difficulty of change values for the headliner assembly due to a +/- 20% uncertainty in the coupling index (feature-based method)

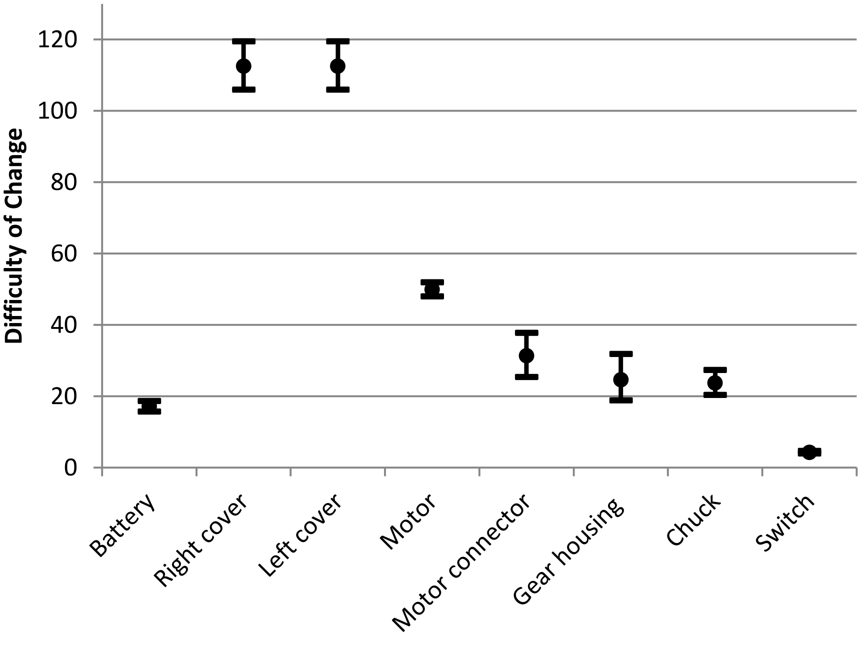


Figure 42: Uncertainty of the component difficulty of change values for the Ryobi drill assembly due to a +/- 20% uncertainty in the coupling index (feature-based method)

The results of the uncertainty analysis again show that the component-based method is very sensitive to any uncertainty in the coupling index calculations. The overlap between many of the components is significant enough that the exact rankings cannot be held in confidence. The method is still accurate enough, however, to identify the general difficulty of change groupings that the components fall into. The feature-based method, on the other hand, is again shown to be relatively insensitive to any uncertainty in the coupling index calculations. For the most part, the rankings are still definable, and the method produces more of a separation between the scores, which adds to the confidence level. Overall, the uncertainty analysis identifies the feature-based method as being more accurate and reliable, because it is shown to be less sensitive to uncertainty and it produces more definition in the results.

The change difficulty calculations in the proposed change prediction method base the coupling between two components on the propagation path of highest probability. The path of highest probability represents one way to model the propagation of change between components; another commonly used model is a total path representation. A total path representation models all the propagation paths between the root component and the other components in an assembly. To assess the effect of the propagation path representation on the final change difficulty values, Table 28 shows a comparison of the results produced using highest probability and total path representations for the Ryobi drill assembly.

Table 28: Comparison of change difficulty results for highest probability and total path representations for the Ryobi drill assembly

Components	***Component-based method***				***Feature-based method***			
	Path of highest probability		**Total path**		**Path of highest probability**		**Total path**	
	Score	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**
Battery	124.9	**3**	336.6	**2**	17.2	**2**	17.2	**2**
Right/Left Cover	176.0	**7**	406.0	**5**	112.5	**7**	115.7	**7**
Motor	153.8	**6**	365.9	**4**	49.9	**6**	50.0	**6**
Motor Connector	139.1	**5**	433.4	**7**	31.4	**5**	34.9	**5**
Gear Housing	125.4	**4**	431.3	**6**	24.6	**4**	27.6	**4**
Chuck	99.1	**2**	358.7	**3**	23.7	**3**	25.0	**3**
Switch	92.7	**1**	319.4	**1**	4.2	**1**	4.2	**1**

The results of the comparison show that the type of path representation has little effect on the results of the feature-based method. As discussed earlier, this is largely due to the fact that in the feature-based method the effects of change are localized to the individual interfacing features, so the occurrence of indirect coupling is much lower. This causes the propagation trees to be considerably smaller and more manageable, which is why the results from the total and highest probability path representations are so close. One other reason is that the manufacturing scores are, on average, lower for the feature-based assessment. This lessens the effect of any additional propagation paths that are not modeled in the highest probability path representation.

The magnitudes of the results for the component-based method vary greatly between the two representations, but the same overall trend still exists. The large difference in the values shows how much bigger and more cumbersome the propagation trees are for the component-based method. The component-based method contains far more indirect coupling and propagation paths, which leads to more redundant coupling in the difficulty of change calculations. However, since the same overall trend still exists, the type of path representation is again shown to have little effect on the end results.

CHAPTER SIX

CONCLUSIONS AND FUTURE WORK

6.1 Answering the Research Questions

As outlined in the first chapter of this thesis, the principle objective of this research is ***to develop a change prediction method to better model the change propagation within a system, and assess the difficulty and cost of initiating changes***. Specifically, the focal point of this research is to develop a change prediction method that is based on objective measures of component/system coupling and manufacturing change costs. To accomplish this principle objective, four research questions are formulated and outlined in Chapter 1. These research questions are recalled here as follows.

> **Research Question 1a:** What factors affect change propagation and impact, and how can they be incorporated into a simple and effective method of predicting change?
>
> **Research Question 1b:** What form of modeling will be most efficient in incorporating the determining factors?
>
> **Research Question 2:** Can the proposed method be used as a tool during the initial design of a product to optimize its overall ease of change?
>
> **Research Question 3:** What are the benefits and costs of modeling a product at the feature level over the component level?

Research question 1a addresses the need to identify the determining factors in change propagation and impact. In section 2.1, research literature concludes that the connectivity within a system, or more specifically the level of coupling between components, is a good predictor of how change will propagate through a system. A coupling index (CI) (detailed in section 3.3) is developed to assess the level of direct coupling between components/features, and is based on the level of dimensional constraint of the parameters. The indirect coupling within a system is modeled by multiplying the coupling index values together to produce a decreased probability for higher orders of coupling. To evaluate the level of effort that is required for each individual change that occurs as a result of change propagation, current change management strategies (detailed in section 2.3) include a measure of the cost or impact of a change to a component. However, the measures that are currently utilized in change prediction methods are dependent on speculation or previous historical change data. A more objective measure of the cost of a change is provided by integrating design for manufacturing (DFM) information into the model. This is detailed in section 3.2. Results from the three industry examples show the manufacturing cost associated with changes as a significant factor in determining the overall difficulty of change. In fact, Figures 24 and 25 show that the relative manufacturing cost of changing the initiating component is a good predictor of its overall difficulty of change. Furthermore, Figure 26, along with the results in Table 27, show that the process used to manufacture a component has a significant impact on its resulting overall difficulty of change.

Research question 1b addresses the need for a model that will represent the connectivity and manufacturing estimates in an effective and efficient way. Section 2.2 details the different change propagation representations, and their respective strengths and weaknesses. A design structure matrix (DSM) is shown to offer a good model for change prediction because it is a concise means of data representation, and it is easy to interpret and populate. A DSM is also easily integrated into software, which allows for efficient calculations and the ability to analyze more complex systems.

The proposed change prediction method is primarily used as a tool during the redesign of a product, but extending its application to the initial design of product would add to its value during concept development. This need is addressed in research question 2. Section 4.1.4 details the redesign of the BMW X5 headliner assembly, and demonstrates that method can also be a valuable tool during the design of a new product. While it does not provide a precise guide for the design of a product, it does offer recommendations for the features, interfaces, and manufacturing types that will result in a lower overall difficulty of change. This allows engineers to assess initial design plans and make strategic decisions on which areas could be improved to offer greater change flexibility. In the redesign of the BMW X5 headliner, the method is able to identify the components and features that offer room for improvement, and the result is that the overall and average change difficulty are cut in half.

Traditionally a system's connectivity is modeled on the component or subsystem level. The proposed change prediction method also analyzes a system on the feature level, by modeling the relationships between the interfacing features. Research question 3 addresses the benefits and costs of this more detailed analysis, as opposed to the traditional component level analysis. The results of the three industry examples, as presented in Table 27, show that the feature-based method provides a better representation of change, and thus produces more accurate results than the component-based method. The component-based method assumes that a change will affect the whole component and thus all of its coupled components. This can lead to inflated difficulty of change values, because often times a change will only affect a component locally at its interfaces. This is why in some instances the feature-based method produces more accurate results. Other advantages of the feature-based method are that it produces more definition between the results, and is less sensitive to uncertainty in the manufacturing and coupling estimates. This creates more confidence in the accuracy of the results, and allows for an easier selection of which component(s) to change. Figures 33 through 42 show that the feature-based method, for the most part, maintains the same relative rankings when an uncertainty of +/- 10% for the manufacturing scores and +/- 20% for the coupling values is introduced. On the other hand, the component-based method shows significant overlapping in the rankings. The final advantage of the feature-based method is that it is also insensitive to the path representation that is used. Table 28 shows that the feature-based method produces the exact same rankings for both a total and highest probability path representation. The component-based method produces the same general rankings, but several component rankings are switched. While the benefits are substantial, they do come at a cost. The feature-based method is more time consuming than the component-based method due to the additional information and detail that is required. Also, it requires more knowledge of the system that may not be available during the earlier stages of detailed design until all the features are finalized.

Overall, the proposed change prediction method produces realistic results, and is able to reliably identify the component(s) that offer the greatest ease of change. The method is based on objective measures of component/system coupling and manufacturing change costs, which allows for a wide-ranging applicability and improves consistency. Furthermore, the method proves to be a valuable tool that can be used during the initial design of a product to assess and improve its overall ease of change.

6.2 Method Validation

The proposed method is a prescriptive model for evaluating manufacturing change, and thus cannot be validated solely through empirical means. Therefore, confidence in the validity and usefulness of the method must be built through both quantitative and qualitative measures [54, 55]. The first step in building confidence in the validity of a method is accepting the validity of the individual constructs that constitute the method. This can be achieved by basing a method on reliable resources that are widely accepted, and provide insight into the intended purpose of the method [54]. The proposed method draws from well-established literature on change propagation and management. The method is broken down into four steps that are based on inputs from valid resources. Steps 1 and 3 produce a model of a system's connectivity that is consistent with accepted literature on system decomposition, DSMs, and coupling measures. Step 2 uses design for manufacturing (DFM) assessments that are the result of extensive industry studies as a basis for evaluating an individual component/feature's cost of change. Step 4 draws from the results of the previous steps to produce the final change difficulty values. Because each step is based on a valid input, it is likely that the anticipated outputs will occur [54]. As a result, confidence can be built in the method's internal consistency.

The method must also be shown to fulfill the prescribed requirements for its intended purpose. In Chapter 1, the identified requirements for an effective change prediction method are detailed. For the proposed method to be valid, it must adequately address all the requirements. A list of the requirements, and a discussion of how the method addresses them, is provided in Table 29.

Table 29: Evaluation of the proposed method against the prescribed requirements

Requirements	How the Method Addresses the Requirements
Evaluate the level of coupling between components to assess the probability of change propagating from one component to another	A coupling index (CI) is developed to assess the level of physical constraint between components/features.
Assess the manufacturing costs associated with changes	DFM information is incorporated to provide a relative assessment of a component/feature's cost of change.
Model the connectivity within a system, including the direct and indirect coupling, and the resulting propagation paths	A DSM populated with CI values is used to model the direct links in a system. The direct CI values are multiplied together to model the indirect coupling and full extent of the propagation paths.
Identify the sub-systems that should and should not be targeted for change	Change difficulty calculations provide a relative assessment of the sub-systems that should and should not be targeted for change.
Evaluate the relative design effort required for redesigns	A comparison of the change difficulty values provides a relative assessment of the required design effort.
Be computationally practical	The computations are minimized by using tabulated data and a highest probability path representation.
Be easily integrated into software	A matrix-based model is used to allow for integration into any computational software.
Identify areas and means for improving the overall ease of change of a system	The method is able to identify features, interfaces, and manufacturing types that will lower a product's overall ease of change

The next step in building confidence in the validity of the method is accepting the appropriateness of the example problems with respect to the intended application of the method [54]. The proposed method is demonstrated on three industry examples: BMW X5 headliner and center console assemblies, and a Ryobi drill assembly. These examples are mass produced systems, so standard manufacturing and assembly processes are used. Each system has undergone change and refinement, with cost being a key consideration. The examples represent different types of systems and thus demonstrate the wide-ranging applicability of the method. The center console is a customizable system that contains a wide array of components in terms of both size and complexity. The Ryobi drill is a self-contained, generational product. The headliner is a subsystem with numerous recurring components, and different manufacturing processes.

The final step in demonstrating the method’s usefulness is to assess the validity of the results produced in the three industry examples. Although the results from the method cannot be empirically validated, confidence in their validity can be built through logic and intuition [55]. Conceptually, the results from the method consistently align with the logical outcome based on the change difficulty factors identified in literature. The larger, structural components that exhibit a high degree of connectivity are shown to be the most difficult to change, while the smaller, accessory components are shown to be the easiest to change. Furthermore, the results are consistent with manufacturing standards, as stamped components are generally found to be more difficult to change. Finally, the results from the method for the headliner example are in line with changes made by an automotive OEM to address assembly problems.

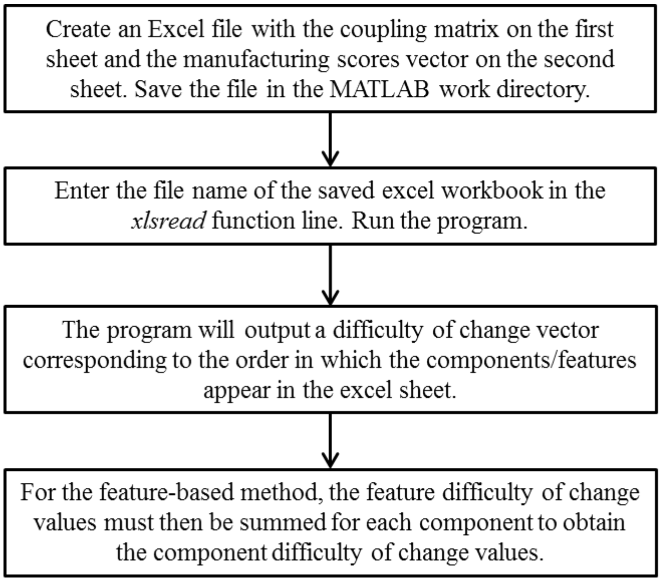
6.3 Future Work

The research that is presented in this thesis is a starting point for the proposed change prediction method, as several avenues for future work still exist. Further accuracy and value can be obtained by including other means of manufacturing in the scheme, and modeling larger, more complex systems to judge whether the method retains its effectiveness. The clustering of changes should be studied, as it may provide a way to simplify the analysis of complex systems. The effects on the scheme of the inclusion of a components' functional importance should also be considered. The initial results of this research indicate that a component's manufacturing cost of change could be a predictor of its overall difficulty of change. Through the analysis of more products, the strength of this trend can be assessed, and possibly lead to a simpler means of predicting change difficulty. One final avenue of future work is to further research and test the applicability of the method during the design of new products. Could the method be used to establish the physical architecture of a product? Could the information required to populate the method be directly extracted from a CAD model? This would allow for different physical configurations of a product to be rapidly evaluated during early design stages, and through further development, could allow for a product's ease of change to be optimized based on inputted parameters.

APPENDIX A

COMPUTER PROGRAM MANUAL

A MATLAB (version R2009a) program is used to calculate the resulting difficulty of change values from the coupling matrix and manufacturing scores. A flow chart of the procedure that should be followed to run the program is shown below in Figure A1. The code for the program is shown following the flow chart.



Create an Excel file with the coupling matrix on the first sheet and the manufacturing scores vector on the second sheet. Save the file in the MATLAB work directory.

Enter the file name of the saved excel workbook in the *xlsread* function line. Run the program.

The program will output a difficulty of change vector corresponding to the order in which the components/features appear in the excel sheet.

For the feature-based method, the feature difficulty of change values must then be summed for each component to obtain the component difficulty of change values.

Figure A1: Flow chart

The commented code for the MATLAB program:

```
clear
%read in the manufacturing scores vector from sheet two in the Excel
file
[num1] = xlsread('drillmatrix.xlsx',2);
l=length(num1);
effort=0;
a=1;
z=0;pos=0;
coupling=zeros(1,l);
%loops through and calculates the difficulty of change for each
%feature/component
```

```
for i=1:l
    %read in the coupling dsm from sheet 1 in the excel file
    [num] = xlsread('drillmatrix.xlsx',1);
    %creates a matrix of zeroes and enters the vector for 1st order
    %coupling in the first row
    matrix=zeros(l);
    matrix(1,:)=num(i,:);
    num(:,i)=0;
    %enters the vectors for 2nd order coupling in the matrix and saves
    %their positions
    for j=1:l
        if num(i,j)>0
            a=a+1;
            num(j,j)=0;
            matrix(a,:)=num(j,:)*num(i,j);
            num(j,:)=num(j,:)*num(i,j);
            pos(1,a-1)=j;
        end
    end
    %enters the vectors for 3rd and above order coupling in the matrix
    %until the propagation path ends
    while pos>0
        pos1=pos;
        pos=0;
    for k=pos1
        for b=1:l
            if num(k,b)>0
                a=a+1;
                z=z+1;
                 num(b,b)=0;
                matrix(a,:)=num(b,:)*num(k,b);
                num(b,:)=num(b,:)*num(k,b);
                pos(1,z)=b;
            end
        end
    end
    z=0;
    end
    z=0;pos=0;
    %Calculates the difficulty of change by multiplying the max
    %coupling for each component/feature by the manufacturing scores
    %vector
    for x=1:l
        coupling(1,x)=max(matrix(:,x));
    end
    effort=coupling*num1';

    %For a total path representation, substitute the preceding for loop
    %with the following for loop:
    %     o=length(matrix);
    %     for x=1:o
    %         coupling=matrix(x,:)*num1';
    %         effort=effort+coupling;
```

```
    %     end

    a=1;
    %creates a vector of the difficulty of change values for all the
    %features/components
    total_effort(i,1)=effort;
    effort=0;
    coupling=zeros(1,l);
end
disp(total_effort)
```

REFERENCES

[1] M. Giffen et al., "Change Propagation Analysis in Complex Technical Systems," *Journal of Mechanical Design*, vol. 131, pp. 1-14, 2009.

[2] C. Earl, C. Eckert, and P.J. Clarkson, "Design Change and Complexity," in *2nd Workshop on Complexity in Design and Engineering*, Glasgow, 2005, pp. 24-33.

[3] P. Pikosz and J. Malmqvist, "A Comparitve Study of Engineering Change Management in Three Swedish Engineering Companies," in *Proceedings of the DETC98 ASME Design Engineering Technical Conference*, 1998, pp. 78-85.

[4] P. J. Clarkson, C. Simmons, and C. Eckert, "Predicting Change Propagation in Complex Design," *Journal of Mechanical Design*, vol. 126, pp. 788-797, September 2004.

[5] A. Riviere, *Aircraft Components Impact Analysis: State of the Art*.: VIVACE Consortium, 2004.

[6] T. R. Browning, "Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions," *IEEE Transactions on Engineering Management*, vol. 48, no. 3, pp. 292-306, 2001.

[7] S. D. Eppinger, D. E. Whitney, R. P. Smith, and D. A. Gebala, "A Model-based Method for Organizing Tasks in Product Development," *Research in Engineering Design*, vol. 6, no. 1, pp. 1-13, 1994.

[8] T. Jarratt, R. Keller, S. Nair, C.M. Eckert, and P.J. Clarkson, "Visualization Techniques for Product Change and Product Modelling in Complex Design," *Lecture Notes in Computer Science*, vol. 2980, pp. 1-21, 2004.

[9] M. Ghoniem, J. D. Fekete, and P. Castagliola, "A Comparison of the Readability of Graphs Using Node-Link and Matrix-Based Representaions," *IEEE Symposium on Information Visualization*, pp. 17-24, 2004.

[10] J. Lamping and R. Rao, "Laying Out and Visualizing Large Trees Using a Hyperboloc Space," *Proceedings of UIST*, pp. 13-14, 1994.

[11] R. Keller, T. Eger, C.M. Eckert, and P.J. Clarkson, "Visualising Change Propagation," *International Conference on Engineering Design*, pp. 1-12, August 2005.

[12] T. Jarratt, C. Eckert, and P. J. Clarkson, "Development of a Product Model to Support Engineering Change Management," in *Tools and Methods of Competitive Engineering Conference*, Lausanne, Switzerland, 2004.

[13] H. A. Bashir and V. Thomson, "An Analogy-based Model for Estimating Design Effort," *Design Studies*, vol. 22, pp. 157-167, 2001.

[14] H. A. Bashir and V. Thomson, "Models for Estimating Design Effort and Time," *Design Studies*, vol. 22, no. 2, pp. 141-155, 2001.

[15] H. A. Bashir and V. Thomson, "Estimating Design Effort for GE Hydro Project," *Computers and Industrial Engineering*, vol. 46, no. 2, pp. 195-204, 2004.

[16] H. A. Bashir and V. Thomson, "Estimating Design Complexity," *Journal of Engineering Design*, vol. 10, no. 3, pp. 247-257, 1999.

[17] M. Giffin, "Change Propagation in Large Technical Systems," SM thesis, System Design and Management Program, MIT, Cambridge, MA, 2007.

[18] C. Eckert, R. Keller, C. Earl, and P. J. Clarkson, "Supporting Change Processes in Design: Complexity, Prediction and Reliability," *Reliability Engineering and System Safety*, vol. 91, no. 12, pp. 1521-1534, 2006.

[19] F. Ameri and J. Summers, "Engineering Design Ccomplexity: an Investigation of Methods and Measures," *Research in Engineering Design*, vol. 19, pp. 161-179, 2008.

[20] J. Summers and J. Shah, "Mechanical Engineering Design Complexity Metrics: Size, Coupling, and Solvability," *Journal of Mechanical Design*, vol. 132, no. 2, 2010.

[21] H. Simon, *The Sciences of the Artificial*. Boston, USA: MIT Press, 1996.

[22] K. M. M. Holtta and K. N. Otto, "Incorporating Design Effort Complexity Measures in Product Architectural Design and Assessment," *Design Studies*, vol. 26, no. 5, pp. 463-485, 2005.

[23] D. Braha and O. Maimon, "The Measurement of a Design Structural and Functional Complexity," *IEEE Transactions on Systems, Man, and Cybernetics (Part A - Systems and Humans)*, vol. 28, no. 4, pp. 527-535, 1998.

[24] G. Palmer, B. Morkos, and J. Summers, "Investigation of Design Tools as Complexity Management Techniques," in *ASME International Design Engineering Technical Conferences*, Montreal, Canada, 2010.

[25] N. P. Suh, *The Principles of Design*. New York, USA: Oxford University Press, 1990.

[26] N. Suh, *Axiomatic Design: Advances and Applications*. New York: Oxford Press, 2001.

[27] B. El-Haik and K. Yang, "The Components of Complexity in Engineering Design," *IIE Transactions*, vol. 31, no. 10, pp. 925-934, 1999.

[28] K. Ulrich, "The Role of Product Architecture in the Manufacturing Firm," *Research Policy*, vol. 24, pp. 419-440, 1995.

[29] M. Martin and K. Ishii, "Design for Variety: Developing Standardized and Modularized Product Platform Architectures," *Research in Engineering Design*, vol. 13, pp. 213-235, 2002.

[30] M Martin, *Design for Variety: Methodology for Developing Product Platform Architectures.*: PhD Thesis, Stanford University, 1999.

[31] C. Eckert, P. J. Clarkson, and W. Zanker, "Change and Customisation in Complex Engineering Domains," *Research in Engineering Design*, vol. 15, pp. 1-21, 2004.

[32] D. V. Steward, "The Design Structure System: A Method for Managing the Design of Complex Systems," *IEEE Transactions on Engineering Management*, vol. 28, pp. 71-74, 1981.

[33] A Yassine, "An Introduction to Modeling and Analyzing Complex Product Development Processes Using the Design Structure Matrix (DSM) Method," University of Illinois at Urbana-Champaign, 2004.

[34] R. Keller, C. Eckert, and J. Clarkson, "Viewpoints and Views in Engineering Change Management," in *2nd Workshop on Complexity in Design and Engineering*, 2005, pp. 188-192.

[35] R. Keller, T. Flanagan, C. Eckert, and P. J. Clarkson, "Two Sides of the Story: Visualising Products and Processes in Engineering Design," in *Information Visualization*, London, England, 2006, pp. 362-367.

[36] J. Malmqvist, "A Classification of Matrix-based Methods for Product Modeling," in *International Design Conference*, Dubrovnik, Croatia, 2002.

[37] J. Mathieson and J. Summers, "Complexity Metrics for Directional Node-Link System Representations: Theory and Applications," in *ASME International Design Engineering Technical Conferences*, Montreal, Canada, 2010.

[38] B. Morkos and J. Summers, "Requirement Change Propagation Prediction Approach: Results from an Industry Study," in *ASME International Design Engineering Technical Conferences*, Montreal, Canada, 2010.

[39] M. D. Guenov and S. G. Barker, "Application of Axiomatic Design and Design Structure Matrix to the Decomposition of Engineering Systems," *Systems Engineering*, vol. 8, no. 1, pp. 29-40, 2005.

[40] T. R. Browning and S. D. Eppinger, "Modeling Impacts of Process Architecture on Cost and Schedule Risk in Product Development," *IEEE Transactions on Engineering Management*, vol. 49, no. 4, pp. 428-442, 2002.

[41] T. L. Flanagan, C. Eckert, J. Smith, T. Eger, and P. J. Clarkson, "A Functional Analysis of Change Propagation," in *International Conference on Engineering Design*, Stockholm, Sweden, 2003.

[42] C. Eckert, J. Clarkson, and C. Earl, "Predictability of Change in Engineering: A Complexity View," *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2005.

[43] J. Coppendale, "Manage Risk in Product and Process Development and Avoid Unpleasant Surprises," *Engineering Management Journal* , vol. 5, no. 1, pp. 35-38, 1995.

[44] A. Rutka, M. Guenov, Y. Lemmens, C. Schmidt-Schaffer, and A. Riviere, "Methods for Engineering Change Propagation Analysis," in *25th International Congress of the Aeronautical Sciences*, Hamburg, Germany, 2006.

[45] T. Jarratt, P. J. Clarkson, G. Parks, and C. Eckert, "Use of Monte Carlo Methods in the Prediction of Change Propagation," in *Engineering Design Conference*, London, 2002.

[46] T. Eger, C. Eckert, and P. J. Clarkson, "Towards a Change Process Planning Tool," in *International Conference on Engineering Design*, Stockholm, Sweden, 2003.

[47] H. A. Bashir and V. Thomson, "Metrics for Design Projects: a Review," *Design Studies*, vol. 20, no. 3, pp. 263-277, 1999.

[48] E. S. Suh, O. L. de Weck, and D. Chang, "Flexible Product Platforms: Framework and Case Study," *Research in Engineering Design*, vol. 18, no. 2, pp. 67-89, 2007.

[49] G. Boothroyd, P. Dewhurst, and W. Knight, *Product Design for Manufacture and Assembly.*: CRC Press, 2001.

[50] L. Sors, L. Bardocz, and L. Radnoti, *Plastic Molds and Dies*. New York: Van Nostrand Reinhold, 1981.

[51] C. Poli, *Design for Manufacturing: A Structured Approach*. Amherst, MA: Butterworth-Heinemann, 2001.

[52] (2011) Waterjets. [Online]. http://www.waterjets.org

[53] R. Gottipolu and K. Ghosh, "A Simplified and Efficient Representation for Evaluation and Selection of Assembly Sequences," *Computers in Industry*, vol. 50, pp. 251-264, 2003.

[54] K. Pedersen, J. Emblemsvag, R. Bailey, J. Allen, and F. Mistree, "Validating Design Methods and Research: The Validation Square," in *ASME Design Engineering Technical Conferences*, Baltimore, Maryland, 2000.

[55] A. Olewnik and K. Lewis, "On Validating Engineering Design Decision Tools," *Concurrent Engineering: Research and Applications*, vol. 13, no. 2, pp. 111-122, 2005.