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CONFIGURATION MANAGEMENT IN MANUFACTURING AND ASSEMBLY: CASE STUDY AND ENABLER DEVELOPMENT

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CONFIGURATION MANAGEMENT IN MANUFACTURING AND ASSEMBLY: CASE STUDY AND ENABLER DEVELOPMENT

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ABSTRACT

The overall goal of this research is to improve the product configuration change management process. The increase in the demand for highly customizable products has led to many manufacturers using mass customization to meet the constantly changing demands of a wide consumer base. However, effectively managing the configurations can be difficult, especially in large manufacturers or for complex products with a large number of possible configurations. This is largely due to a combination of the scope of the configuration management system and the difficulty in understanding how changes to one element of a configuration can propagate through the configuration system. To increase the engineer's ability to understand the configuration management system and how changes can affect it, an improved method is required.

Based on the results of a case study at a major automotive OEM, a configuration change management method is developed to address the aforementioned gap. In addition, a set of design enablers is deployed as part of the method. The major contribution of this work is the improved method for configuration change management and the use of graph visualization in exploring configuration changes. The use of graph visualizations for configuration management is validated through a user study, four implementation studies using ongoing configuration changes at the OEM, and user feedback and evaluation. The method is validated through application in three historical cases and user feedback. The results show that the method increases the capabilities of the engineer in exploring a proposed configuration change and identifying any potential errors.

DEDICATION

Dedicated to my wife because without her support, I would not have made it this far and to my parents for always encouraging me to strive for more.

ACKNOWLEDGEMENTS

I sincerely thank my advisor Dr. Joshua Summers. I cannot overstate how much his guidance has shaped me and my research during my time as a student. He has gone above and beyond in mentoring me as an engineer, a researcher, and as a person.

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As most of my research was funded through projects with BMW Spartanburg, I would like to them for their support and for providing the opportunity to work with them for the past two and a half years. I would also like to thank the personnel in the Launch and Change Control group for providing their time and expertise, without which the research would not have been as successful. I would especially like to thank Matt Wasatonic at BMW for countless hours of working with me and providing assistance in whatever capacity was required.

Last, but not least, I thank all of my CEDAR team members, both present and past, for supporting my research and assisting when called upon. The countless discussions of research, current events, and, most importantly, college football always provided an outlet when needed.

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CHAPTER ONE: INTRODUCTION

1.1 What is Configuration Management?

Configuration management is a method for capturing, verifying, and maintaining the information regarding how product variants can feasibly achieve customer requirements. The first aspect of this process is to understand the capabilities and interrelationships of the components within the product family. Product families, or "configurable products," are defined according to the following criteria [1,2]:

- Are adapted according to customer requirements [1]
- Consist of (almost) only pre-designed components [1,2]
- Have a pre-designed product structure [1]
- Are adapted by systematic product configuration [1,2]

It is important to note that a key element of these criteria is that the components that contribute to the product family are well specified, including the relationships between the components. In this way, the configuration management process is different from traditional design in that no new component types are created, nor are the interfaces between components modified in any way [3]. Therefore, a difficulty in configuration management is in accurately modeling this knowledge.

The second aspect of the configuration management process is to understand the individual needs of the customer and how the needs can be met through the selection and integration of specific components. As in the case of the product family domain knowledge, the customer requirements should all be well-specified when conducting configuration management. That is, before a new customer requirement should be added

as an option within a product family, a coordinating component for achieving that need must first be identified. This relationship is shown in Figure 1.1.

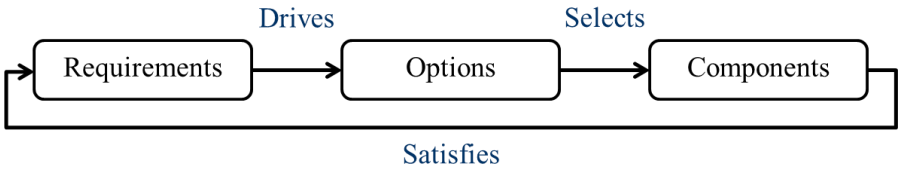

Figure 1.1: Configuration management entity relationships

While this may seem counterintuitive, the goal of configuration management is not to develop novel concepts, but rather to produce a new configuration of existing components that is adapted to the needs of the customer [1].

1.2 Why Configuration and Change Management?

Configuration management is essential to mass customization because without it the difficulty in managing the potential configurations can hinder the efficient manufacture of product [3–5]. When viewed from the perspective of assembly lines, the many different configurations can quickly lead to increases in the possibility of errors [3]. The high number of configurations available, specifically in the automotive industry, is shown in the model in Figure 1.2. These errors, depending on where they are identified in the product life-cycle, can be extremely costly. As a result, configuration management is necessary for successful manufacture of product families.

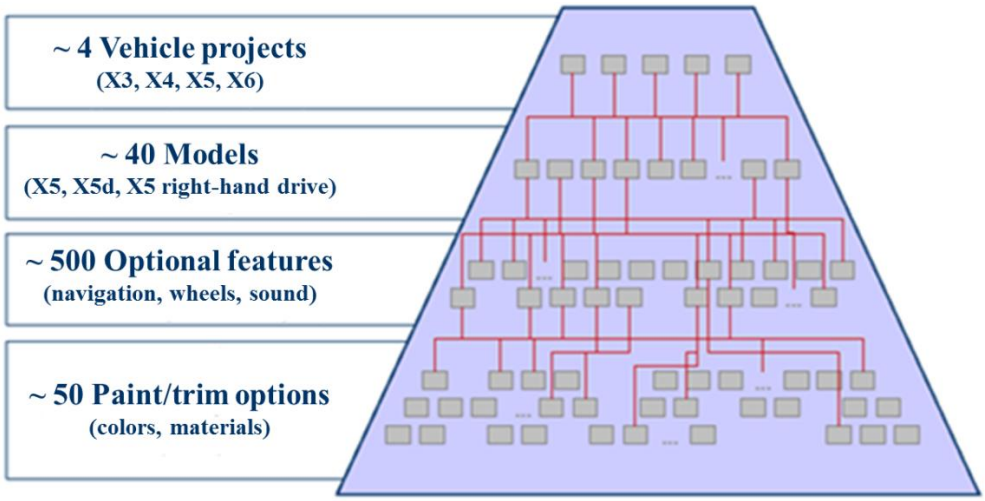

Figure 1.2: Model depicting possible configuration variants (adapted from [4]**)**

An additional benefit of configuration management is the ability to effectively conduct change management and product improvement [5]. While a central facet of configuration management is an understanding of how the components interrelate, when a change is required on a single component, one may identify how the specified change will affect the other components within any of the variants in that product family. This includes manufacturers that rely heavily on modifying existing products in the development of new designs, as is the case with the intra-organizational benefits of product configuration identified in a study of an aeronautics manufacturer [5]. As a current product is adapted to fit new customer requirements, it is easy to identify how the modifications will affect the other variants in a product family.

The implementation of configuration management also increases the amount of product control and organizational support of a manufacturer [4,5]. Others describe configuration management as a basic process within systems engineering that serves as the "backbone" of many of the core processes that enable efficient manufacture of a

configurable product [4]. Similar findings on the benefits of configuration management were identified in a case study based on interviews with employees in management positions within an aeronautics OEM [5]. The interviewees all stated that the use of configuration management practices increased the amount of control of the company over the product and the product variant development process.

1.3 Dissertation Outline

This section presents an overview of the dissertation, visually depicted in Figure 1.3. Chapter One provides an introduction to the research. This includes the motivation for the research and some background information on configuration management. Chapter Two presents the foundation for the research: a review of current change management practices (including a literature review and the development of a support tool for an existing change management support method) and a study on product component interaction. This preliminary research introduced the author to the principles of change management and developed the interest in change management, specifically with regard to change management in configurable products or products with multiple variants. Chapter Three presents the overall research plan for the dissertation. This includes the research objectives, their corresponding research sub-questions and the tasks that were executed to achieve the objectives.

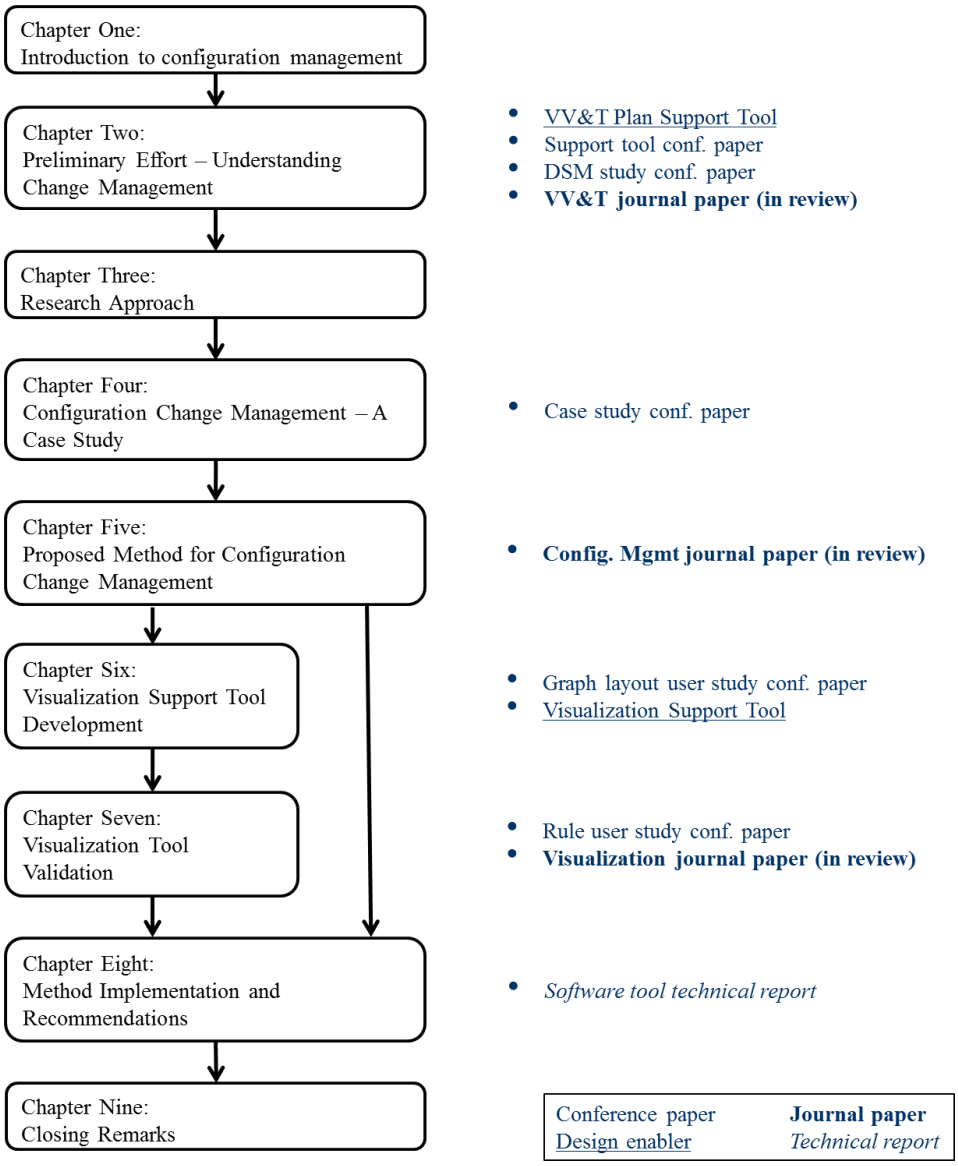

Figure 1.3: Dissertation overview

Chapter Four begins the process of answering the research questions through the presentation of an industrial case study on configuration management. The case study and accompanying literature review are intended to answer the question of how companies conduct configuration management (RO 1). Based on the findings of the case study, an improved method for configuration management, including design enabler support, is

presented in Chapter Five. The proposed method provides an integrated method that incorporates support tools from multiple domains (data visualization, algorithmic validation, and complexity analysis) to assist in the configuration management process.

Chapter Six focuses on the development and implementation of a graph visualization support tool. The visualization support tool uses relationship information from the product rule databases to assist in understanding how proposed changes can propagate in unexpected ways. The validation of the graph visualization tool is presented in Chapter Seven. This consists of four implementation cases of ongoing configuration changes at the OEM and a user study to test the effectiveness of the proposed tool for configuration rule implementation. Chapter Eight consists of a validation of the entire configuration management support method through additional implementation cases and a user feedback interview with a change manager at the OEM. Finally, Chapter Nine concludes the dissertation and provides potential avenues for future research.

CHAPTER TWO: PRELIMINARY EFFORT – UNDERSTANDING CHANGE MANAGEMENT

The purpose of the research presented in this chapter is to understand current change management practice. This objective is achieved through the execution of three related tasks: a literature review of change management practices, the development of a change management support tool based on a verification, validation, and testing planning method, and a study on component interaction for change propagation. These three tasks will be discussed in the following sections, with the findings being summarized in 2.3.

2.1 Current Change Management Practice

In order to develop a better understanding of current configuration change management, a literature review is conducted and a computational support tool is developed to increase the usability and adoptability of an existing change management method. These are discussed in Sections 2.1.1 and 2.1.2, respectively.

2.1.1 Literature Review of Change Management Practice

There has been a large amount of research conducted on ways to mitigate the effects and/or occurrences of engineering change [6–9]. The research can be categorized according to the following types of mitigation: tools for documentation, tools for decision-making, and engineering change coping strategies [7].

2.1.1.1 Documentation Tools

The first type of tool involves those used for assistance in documentation and managing the work flow of the engineering change process. Such tools are recognized as

necessary to effectively and efficiently execute engineering changes [6,10]. Engineering change management systems that are primarily paper-based are typically inefficient in that the information is largely centralized. As the number of engineering changes of a product increases, the situation is compounded [6]. The high degree of centralization limits the ability for all personnel within a company to have access to the changes and understand how they can affect different operations within the company [11]. Therefore, having the ability to document and manage change can greatly improve the efficiency of the change management process by ensuring that all parties are kept current on a change's status.

As a result, there has been a focus on computer-based systems for documenting the instances of engineering change over the life of an engineering change. Huang and Mak [12] use the following classification method for computer-based tools:

- Dedicated engineering change management systems: They include databases of engineering change activities and can generate engineering change forms.
- Computer aided configuration management systems: These systems are software-based engineering change management systems and allow the user to address product structuring and versioning.
- Product data management (PDM) or product life-cycle management (PLM) systems: These systems incorporate all of the above functionalities and also are able to encompass all stages of the product life-cycle, such as product planning. Often, the scope of these systems requires that they be developed externally by software design companies.

The increase in the use of computer networking in company infrastructures has led to an increase in academic research into computer-based change management systems [12,13]. One example, a stand-alone, web-based system for managing the engineering

change process, has been developed at the University of Hong Kong's Department of Industrial and Manufacturing Systems Engineering [13]. The proposed engineering change management (ECM) system seeks to remove the limitations due to time and geography typically found in paper-based systems by using a distributed web-based system. The major limitation of the system is that it only supports basic ECM functions and activities. Additionally, no case study regarding implementation or validation of the tool is provided. Reddi [11,14] presents a framework for engineering change management based on Service Oriented Architecture that allows for an agile engineering change management process to be used in a collaborative environment. The primary limitation of this work is that the tool was not validated with industry data, but rather with previous research. Additionally, the tool requires an extensive amount of user expertise in order to estimate the values for parameters used in the process.

Despite the prevalence of commercially available engineering change management software packages, it has been found that few companies have moved to integrate these systems [15]. Some possible reasons behind this are [12]:

- Companies do not realize the systems are available
- Available systems do not meet the needs of the user
- Available systems are not worth the difficulty to implement
- The systems require too much data input to be time-effective
- The technology does not fulfil its functions as promised

In a study of three Swedish engineering companies [16], it was found that none of the companies used the benefits of computer-based support of change management to their full potential. However, it is understood that at the time of the report that all of the

companies were investing in these computer-based systems. The biggest determining factor was whether it was more efficient to develop their own software or to revise commercially available software for use within the company. In a similar review of two British companies [6], the companies felt that adapting a commercially available system would be more expensive and time-consuming than developing their own. Thus, cost of adoption and development appear to be major hurdles in adoption.

The following conclusions are made regarding the current research on documentation tools for configuration management:

- Many of the tools discussed have not been implemented in an industry setting to validate their usefulness
- Difficulty in adopting an existing ECM system leads companies to develop their own support tools instead
- Many of the tools require a large amount of user input in order to fulfill the required functions

2.1.1.2 Decision-Making Tools

A major emphasis of research on engineering change has been on tools to aid in the decision-making of the engineering change process. While solid modelling, Failure Mode and Effects Analysis (FMEA), and Value Analysis are examples of enablers that can be used in engineering change mitigation, the focus of this section is on methods and research prototype systems.

Ollinger and Stahovich [17] propose a tool called "RedesignIT," a computer program that employs model-based reasoning to create and evaluate proposals for redesign plans. The program uses the relevant physical parameter of the design and the relationships

between the parameters to build the model. The benefit to this tool is that it proposes modifications to the proposals to mitigate negative effects of the proposed change. However, it only provides the parameters that should be modified and does not propose how the quantities should be altered.

Laurenti and Rozenfeld [18] present a modified version of FMEA that specifically covers the analysis of modifications to a system. The method, Failure Mode and Effect Analysis of Modifications (FMEAM), was developed based on an integration of FMEA and Design Review Based on Failure Mode (DRBFM). It incorporates a multi-disciplinary work group to review engineering changes and the possible failure rates that may be associated with them. At this point, there has been no validation of the feasibility or utility of the proposed method.

The Change Prediction Model [19] is a tool for predicting how change will propagate through a design. This method uses Design Structure Matrices (DSMs) to build a product model. The product model consists of the relationships between components that increase either the likelihood or impact of engineering change propagation. By determining the possible propagation pathways, it is then possible to use the product model to create DSMs representing the predicted likelihood and risk of a change. From these DSMs it is possible to predict the possible impact of a change. This model is shown in Figure 2.1.

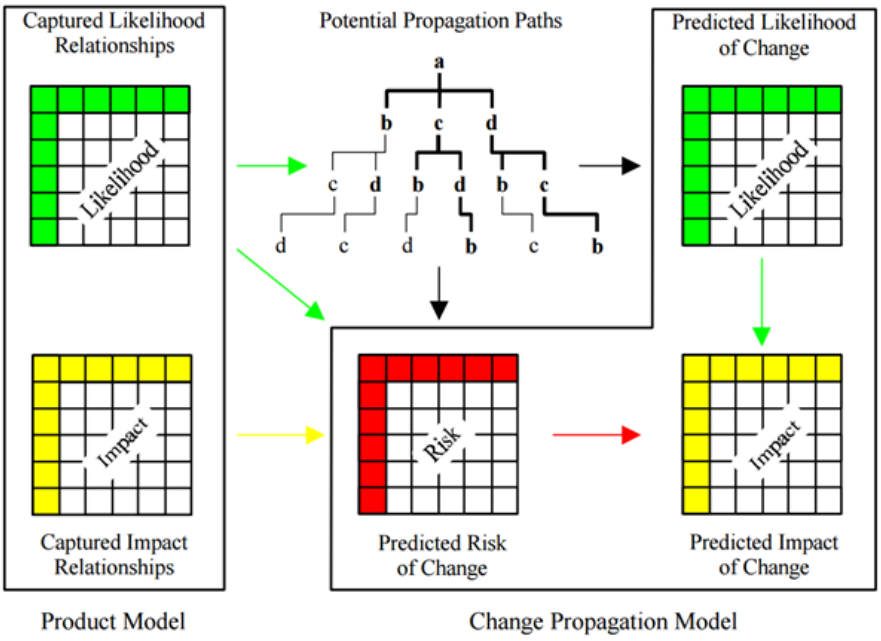

Figure 2.1: Change Propagation Model (CPM) [19]

This method has also been used in additional research and has been applied in several case studies [20–22]. A similar method has been proposed that uses DSMs to determine the second-order relationships between requirements [23]. From these secondary relationships, they were able to successfully predict how product requirements would change as a result of an initial requirement change. By modelling the predicted change early in the design process, during requirements development, it is possible to minimize the associated costs resulting from an engineering change. The method was shown to be successful in predicting the resulting changes in two industrial case studies, but more validation is needed to explore its effectiveness. Another potential negative of this method is that it requires an initial change in order to be effective.

Change Favorable Representation (C-FAR) [24] is a method that uses product information to assist in the representation, propagation and evaluation of changes. C-FAR

decomposes a product into its basic entities and then represents these entities as vectors, with the attributes of the entity as components of the vector. The approach then uses matrices to create relationships between entity vectors, with the individual components of the matrix being referred to as linkage values. The linkage values represent the relationship between two attributes (one from each entity) and can be used to determine how change in one attribute or entity can affect other entities/attributes. The method has been used with numerous industrial case studies, but because of the high processing power required, it is only feasible when used with fairly simple products.

The following conclusions are made regarding the current research on decision tools for configuration management:

- Many of the tools discussed have not been implemented in an industry setting to validate their usefulness
- Difficulty in adopting an existing ECM system leads companies to develop their own support tools instead
- Many of the tools require a large amount of user input in order to fulfill the required functions

2.1.1.3 Engineering Change Mitigation Strategies

While other researchers [25,26] have also proposed strategies for mitigating the effects of engineering change, Fricke, et al. [15] provides a comprehensive list of strategies:

1. Prevention: Reduce the number of emergent changes of a product. This is often the majority of changes that occur for a given design [9,27]. It is understood that this can be extremely difficult to execute effectively.
2. Front-loading: Early detection of engineering changes within the product- life-cycle. This is in line with the "Rule of Ten" discussed earlier in the paper. The use of

concurrent engineering encourages early identification of changes that must be made to a product. However, due to the ever-changing nature of the market, implementing this to its fullest extent may prevent the company from changing to meet the latest needs of the customer, possibly leading to an eventual loss of market share and profitability.

3. Effectiveness: Conducting analysis on the benefit of executing an engineering change against the cost of implementation. As previously mentioned, not all engineering changes are meaningful and/or mandatory. Therefore, it is necessary that design engineers understand the difference between meaningful and meaningless changes.
4. Efficiency: Implementing engineering changes as efficiently as possible by optimally using available resources (time, costs, etc.). To facilitate this effort, engineering changes must be communicated to all contributing parties as quickly as possible. In some instances, this may be assisted by being flexible with the engineering change process. Loch and Terweisch promoted this idea by proposing methods to remove some of the bottlenecks in the process [28].
5. Learning and reviewing: Conducting a review of the engineering change process for each implemented change. Despite the fact that every change is a chance to improve upon a company's engineering change management process, few companies regularly execute reviews following a change. The United States Army has recognized the importance of after-action reviews to continuously improve upon previous operations, mandating that reviews be conducted at all levels.

Additional research has been done that supplements the above strategies. Tavcar and Duhovnik [26] have developed a questionnaire to assist in the review process that assess the quality of a company's engineering change management process. The questionnaire assesses the process based on a variety of information, including: resources expended in implementation, duration of the engineering change, change tracking, frequency of

decision points, and the accuracy and precision of implementing the change in both production and documentation. In their review of current engineering change practices, Jarratt, et al. [8] believe that a fundamental shift away from "ab initio" design advocated by many systematic design methods, such as the approach proposed by Pahl and Beitz [29], would lead to increased effort in change research.

2.1.2 Development of a Change Management Support Tool

A recurring theme in review of existing change management practices is that despite the prevalence of available methods for managing change, the difficulty in adopting the proposed methods has resulted in many companies not implementing them. To better understand how existing methods can be adapted to better increase adoptability, a computational support tool was developed from an existing validation, verification and testing (VV&T) planning method [30]. The VV&T method was selected due to its inclusion of variant propagation pathways, which is an aspect that is unique to the method and is of interest to the researcher. The purpose of this task is to determine how the methods proposed in academia can be supported to increase their usability by industry and therefore increase the level of adoption

2.1.2.1 Overview of Method

The purpose of the change management support tool is to assist a change engineer in executing the validation, verification, and testing (VV&T) planning method discussed in [30]. The support tool follows the steps outlined in the 7-Step VV&T planning [31]:

- Step 1: Identify requirements – identify the requirements for the system at one level above the sub-system that contains the changed component
- Step 2: Conduct system analysis – determine the other components that are likely to be affected by the changed component
- Step 3: Identify assembly configurations – identify the potential assembly configurations for the affected components, including different variants and suppliers for each component
- Step 4: Filter assembly configurations – determine whether any assembly configurations can be removed from the VV&T method
- Step 5: Develop design validation plan (DVP) matrix – create the matrix for the VV&T plan, including administrative data, such as responsibilities and timelines for the validation of each requirement
- Step 6: Develop test strategy – determine the baseline for each test to be run
- Step 7: Conduct trade-off analysis – identify areas where tests can be combined and prioritize the validation of specific requirements

2.1.2.2 Tool Requirements

Case studies of applying the method at International Truck and Reliable Sprinkler led to requirements for the support tool. In addition to the primary requirement (the tool should easily guide the engineer through the process) other requirements were identified to mitigate some of the other issues that have been identified when using the 7-step planning method. One major issue is the large amount of data that must be carried between the steps, leading to the possibility for human input errors. Additionally, the tool should

assist in the documentation of the change management process. The resulting design problem is as follows: Develop a computational support tool to guide a change engineer through the 7-step VV&T process while minimizing the opportunity for error and assisting in documenting the change process without the requirement for additional input.

As previously mentioned, one requirement of the tool was its adoptability. One reason that support tools developed in academia are not used heavily in industry is the resistance to new software or interfaces [1]. In order to ensure easy distribution and use of the computational support tool, it was developed in Microsoft Excel using the Visual Basic for Applications programming language. This allowed for simplified implementation while maximizing the functionality of the tool for prototyping purposes.

To determine the appropriate level of automation, each step was analysed to determine what information and reasoning needed to be supported and what would be conducted manually. For example, in the first step (Identify Requirements), it is possible to have the tool import a requirements list from an external source, such as a requirements document generated and used by the company. However, because the source document was of unknown origin, the information for this step is manually entered. On the other hand, the creation of the Design Validation Plan (DVP) matrix is almost completely automated. The only manual input required for this document is the administrative data, such as team members and testing responsibility (Table 2.7). Another factor that prevented automation of a step was the need for experiential knowledge in understanding the specifics of the engineering change in question. This is shown in the filtering of assembly configurations (Step 5). Determining which assembly configurations can be neglected is

dependent on the system in question. As such, it would be difficult to automate the identification of which configurations could be eliminated.

Following the best practices for software engineering approaches, the module for each step was created on an individual basis and then these modules were linked together [32–34]. The tool consists of a series of spreadsheets that are able to be edited by the user. Once pertinent data for a given step has been entered, an associated macro may be run to facilitate the completion of that step in the process. The steps below follow the VV&T plan development for an example change to the brake drum in an automotive braking system.

2.1.2.3 Step 1 – Identify Requirements

The first step in the VV&T planning method is the identification of requirements at the level of the component of interest and one system level above the component being changed. An example of the requirement data table is shown in Table 2.1. It should be noted that sections highlighted in yellow are those intended for data entry. This step also stores the requirements for future use in the process. Note that these are not requirements on the brake drum, but rather on the encapsulating braking system.

Table 2.1: Example requirements table

#	Requirement
R1	Stopping distance <60ft
R2	Stopping dist <75ft after down hill test
R3	Brake lining life >40000 miles

2.1.2.4 Step 2 – Conduct System Analysis

The next step in the process is a system analysis to identify any components that may be affected by the component being changed. This interaction can include geometric, behavioural, variant, and organization propagation pathways. In this step, the engineer manually enters the design structure matrix (DSM) for the system containing the change component. Additionally, the external components that interact with the system of interest are included. The DSM is developed by identifying the relationships between components in the system. In this example, only physical, geometric relationships are considered. However, as discussed in the VV&T planning method [31], other possibilities exist for relationships, such as organizational pathways. It is important to note that building the DSM is a possible source of human error. A section of an example DSM entered by the engineer is shown in Table 2.2 (a). The intersections with "1" represent interactions between the specified components. The same section of the DSM is shown in Table 2.2(b) and includes higher order interactions. The complete DSMs are found in 9.2Appendix A:. Any cells containing "2" or higher represent higher order interactions and will be discussed below. For instance, the brake drum directly interfaces with the brake lining. Because the brake lining also directly interfaces with the foundation brake, a second order interaction occurs between the foundation brake and the brake drum.

Table 2.2: Section of an example design structure matrix (DSM) (a) initial and (b) extended

	Component Name		Internal						
			A	B	C	D	E	F	G
Internal	Foundation Brake	A			1	1	1		
	Brake Drum	B					1		
	Slack Adjuster	C	1			1			
	Brake Chamber	D	1		1				
	Brake Lining	E	1	1					
	Air Tanks	F							1
	E Valve	G						1	

	Component Name		Internal						
			A	B	C	D	E	F	G
Internal	Foundation Brake	A		2	1	1	1		
	Brake Drum	B	2				1		
	Slack Adjuster	C	1			1	2		
	Brake Chamber	D	1		1		2	2	
	Brake Lining	E	1	1	2	2			
	Air Tanks	F				2			1
	E Valve	G						1	

The support tool also requires the entry of the number of components, the change component, and the desired order of interaction. The desired order of interaction is required because research has shown that interactions at the second order are often useful in identifying/predicting change propagation [27]. Once all relevant data has been entered, the support tool populates the rest of the DSM with any higher order interactions (the second order of interaction was desired in the example in Table 2.2) and a list of all of the components affected by the change component is created. Based on the DSM from the example in Table 2.2, the following list was created, as shown in Table 2.3. Thes components will then be used in the next step.

Table 2.3: List of affected components for brake drum

Interacting Components	Order
Brake Lining	1
Hub	1
Tie and Wheel Trim	1
Foundation Brake	2

2.1.2.5 Step 3 – Identify Assembly Configurations

The third step in the process is the identification of possible assembly configurations. Each component affected by the engineering change (from list in Table 2.3) may have multiple variants and multiple suppliers. Therefore, when considering a VV&T plan, it is necessary to determine all of the combinations that may need to be tested. Testing all of the possible component combinations would be equivalent to a full-factorial design of experiments, and while thorough, this may or may not be feasible. To support this, the tool populates a list of components, while the engineer enters information regarding the suppliers and variants possible for each component. Once the data is entered, each element-supplier-variant (E-S-V) combination is given a unique identifier and the total number of E-S-Vs for each component is tallied. This is shown in Table 2.4. For example, the hub has two different variants from two different suppliers, while the brake lining has the same variants from different suppliers.

Table 2.4: E-S-V combination identification

Affected Elements	Supplier (S#)	Variants (V#)	E-S-V Identifier	Combination selection? (Y or N)	Selection reasoning	Number of E-S-V combinations
Brake Lining	S1	V1	1.S1.V1	Y		2
	S2	V1	1.S2.V1	Y		
Hub	S3	V3	2.S3.V3	Y		2
	S4	V4	2.S4.V4	Y		
Tire and Wheel Trim	S5	V5	3.S5.V5	Y	Variant 6 is not used in this platform	1
	S5	V6	3.S5.V6	N		

The tool also allows the engineer to remove any combinations from being evaluated and provides an area for comments regarding the reasoning behind the removal. For the example in Table 2.4, E-S-V 3.S5.V6 is not used because that specific variant of the tire and wheel trim is not used in the platform being tested. It is important to note that the removal of specific E-S-V combinations from the list of possible configurations is manually executed by the engineer. The support tool also provides a list of all of the combination vectors (possible combinations of different E-S-V combinations) for further evaluation. The results from this are shown in Table 2.5. The list of combinations then undergoes additional filtering in the following step.

Table 2.5: Combination vectors

Total Combination Vectors	4				
Vector	E-S-V Identifiers				
C1	1.S1.V1	2.S3.V3	3.S5.V5		
C2	1.S1.V1	2.S4.V4	3.S5.V5		
C3	1.S2.V1	2.S3.V3	3.S5.V5		
C4	1.S2.V1	2.S4.V4	3.S5.V5		

2.1.2.6 Step 4 – Filter Assembly Configurations

The fourth step involves the filtering of assembly configurations identified in Step 3. Conducting a full analysis for each assembly combination can be time-consuming and costly. Therefore, it is beneficial to identify any combinations that may be ignored. One reason a particular subset of configurations could be ignored is that one variant might perform better in all requirements than the alternate variant. An example of this would be two different wheel variants, one of which provides a significantly larger amount of airflow, thereby minimizing the amount of heat build-up and increasing the performance. In this instance, the higher airflow, performance wheel would be ignored. As such, it is reasonable to assume that combinations featuring the first variant would perform better than combinations featuring the second variant. Therefore, the better performing combinations may be ignored in future analysis. Essentially, it is desirable to test the worst-case scenario.

This aspect of the VV&T planning method remains manual because the analysis required to identify which combinations may be neglected is highly specific to the system requirements. In this instance, the support tool provides an interface for documenting the decisions made and the reasoning behind the decisions. The interface provided to the user is shown in Table 2.6.

Table 2.6: Filtering of assembly combinations interface

Vector	E-S-V Identifiers				Keep Vector? (Y/N)	Reasoning
~~C1~~	~~1.S1.V1~~	~~2.S3.V3~~	~~3.S5.V5~~		N	
C2	1.S1.V1	2.S4.V4	3.S5.V5		Y	
~~C3~~	~~1.S2.V1~~	~~2.S3.V3~~	~~3.S5.V5~~		N	
C4	1.S2.V1	2.S4.V4	3.S5.V5		Y	

As shown in the example in Table 2.6, two of the combinations were neglected. As a result, the associated cells were highlighted and marked through for ease of visualization. The remaining combinations are stored for use in future analysis.

2.1.2.7 Step 5 – Develop Design Validation Plan (DVP) Matrix

The next step in the VV&T planning method is to construct the Design Validation Plan (DVP) matrix. The DVP matrix consists of all of the administrative data as well as all of the requirements, associated tests, and any additional information regarding how the testing will be executed. An example DVP matrix is shown in Table 2.7. At present, much of the administrative data must be entered manually, while 70% of the testing data is populated by the tool. In Table 2.7, R1 is the requirement for a stopping distance of less than 60 feet. The method to validate is a vehicle test as per FMVSS 121, with stopping distance being the test measurable. The combinations vectors to be tested are C2 and C4.

Table 2.7: Example DVP matrix

DVP #						Date					
DVP Ver #						System					
Program #						Team					
Requirements doc #						Physical test engineer		Supplier		Marketing	
						Virtual test engineer		Manufacturing			
						Development engineer		Service			
Req. Index	Requirement	Test	Combination vectors	V & V method	Test measureable	Acceptance criteria	Need for legal certification	Responsibility	Start date	End date	Remarks
R1	Stopping distance <60ft	As per FMVSS 121	C4, C2,	Vehicle test	Distance in ft.	As per FMVSS 121	Y	A	07/10	08/10	
R2	Stopping dist <75ft after down hill test	As per FMVSS 121	C4, C2,	Vehicle test	Distance in ft.	As per FMVSS 121	Y	A	07/10	08/10	
R3	Brake lining life >40000 miles	Fit lining in field vehicle	C4, C2,	Field Demonst ration	Lining wear in in.	Average life >40000 miles	N	B	07/10	10/10	

In order to assist in the creation of the DVP matrix, additional data must be entered elsewhere. The support tool uses a test database to store all information regarding the tests that must be executed to evaluate the system.

Additionally, two separate matrices are required to aid the creation of the DVP matrix. The matrices identify the relationships between the requirements and the system components and between the requirements and the tests. Examples of these matrices are shown in Table 2.8 and Table 2.9. The purpose of the two matrices is to relate the system components and possible tests to the design requirements. Having this information allows the engineer to focus on the aspects of the VV&T plan that are most relevant. Entering the relationship information into the matrices is another potential source for human error as the requirements to component information is likely to be determined based on experiential knowledge. In the example, the brake lining life requirement relates only to the field vehicle test as the other test only considers the performance during a single braking event.

Table 2.8: Requirements to tests relationships matrix

	Requirements x Tests		Tests		
			As per FMVSS 121	Fit lining in field vehicle	
			T1	T2	
Requirements	Stopping distance <60ft	R1	Y		
	Stopping dist <75ft after down hill test	R2	Y		
	Brake lining life >40000 miles	R3		Y	

When relating the requirements to the components, the example shows that the brake lining life requirement only relates to the brake lining and is not affected by the hub or the tire and wheel trim.

Table 2.9: Requirements to components relationship matrix

	Requirements x Components		Components							
			Brake Chamber	Brake Lining	Axle	Hub	Tie and Wheel Trim	Engine	Instrument Panel	Frame
			C4	C5	C12	C13	C14	C15	C16	C17
Requirements	Stopping distance <60ft	R1				Y	Y			
	Stopping dist <75ft after down hill test	R2				Y	Y			
	Brake lining life >40000 miles	R3		Y						

All of the components, tests and requirements are automatically retrieved from elsewhere in the support tool in order to reduce user data entry. Only the relationship data is required to be manually entered during this stage of the process.

2.1.2.8 Step 6 – Develop Test Strategy

The sixth step in the VV&T planning method is to develop a baseline test strategy to evaluate the requirements. The purpose of this step is to identify the acceptance criteria for any tests that must be conducted, oftentimes based on the performance values for the existing design. Once again, this step is highly specific to the system being evaluated and requires the data to be entered manually. The support tool assists in this step by providing

a table consisting of all of the tests identified in the DVP matrix with cells for each of the information requirements. An example of the interface is shown in Table 2.10.

Table 2.10: Baseline test strategy

#	Test	Baseline Combination	Baseline Test Description	Acceptance Criteria for the modified design
T1	As per FMVSS 121	C3	With existing vehicle, identify stopping distance	New system should be on par with existing vehicle
T2	Fit lining in field vehicle			

2.1.2.9 Step 7 – Conduct Trade-Off Analysis

The final step in the process is to conduct a trade-off analysis for the tests and requirements to be conducted based on the DVP matrix. It is not always feasible to conduct every test or to test every requirement due to cost or lead time restrictions. Therefore, it is essential to prioritize which tests to conduct given certain parameters. The VV&T planning method used in the development of this tool focuses on the requirements to be tested, as opposed to the tests available to be run. The method uses the Verification Complexity Index (VCI) to determine the complexity of verifying an individual requirement [1]. While other methods for developing a testing plan exist, the VCI is chosen in the VV&T planning method because it focuses on the requirements as opposed to the tests. The VCI is calculated using the following equation:

$$VCI = req_{severity} * \sum (num_{tests} * PI) \quad (1)$$

In order to facilitate this, the support tool provides the requirements and tests from the DVP matrix. The user enters the severity of each requirement, the cost and lead times for each test, and the number of tests to verify each requirement as described in the VV&T

method. The tool calculates the VCI for each requirement and ranks them. An example of the trade-off analysis matrix is shown in Table 2.11.

Table 2.11: Example of a test-analysis matrix

Requirement	Severity (1/3/9)	Tests (# iterations req'd)										Verification complexity index	Ranking
		T1	T2										
R1	9	1	3									2268	1
R2	9		3									2187	2
R3	3	1										27	3
Cost/Test (1/3/9)		3	9										
Lead time/Test (1/3/9)		3	9										
Performance indicator		9	81										

In the example shown in Table 2.11, a severity is entered for each requirement. The severity is based on how necessary each requirement is. For instance, 9 would be a legal requirement, whereas 1 would be less important. The tests are then populated on the table, with the number of iterations of the test that are required to verify each requirement being below the test identifier. Also in the same column are the cost and lead time per test, where a high number indicates a relatively high cost or lead time. This indicates the relative cost/time to the company for the tests. The scale can be adjusted to conform to company-specific definitions. The performance indicator for each test is the cost multiplied by the lead time. At this point, the VCI can be calculated according to Equation 1 and the requirements are ranked accordingly.

Requirement 1 (R1) has the highest VCI in Table 2.11, which implies that the change engineers should focus on that requirement to consider for trade-off and

prioritization. The tool also allows the user to visualize how specific tests can possibly verify multiple requirements.

2.1.2.10 Conclusions

The VV&T planning method the research in this section is based on [31] has been shown to effectively mitigate change propagation resulting from an in-production engineering change. However, the large amount of data entry involved and the planning method's reliance on an engineer's experience can hinder the application of the method in complex engineering systems.

The computational support tool described in this section successfully addresses these issues. The support tool was shown to correctly guide an engineer through the implementation of the VV&T planning method for a historic example of an engineering change in an automotive brake assembly. The support tool also minimized the opportunities for human error by carrying data over between the process steps. When manually conducting the planning method for the described example, the user would have to enter and keep track of 193 data points. With the implementation of the tool, the user was required to manually input data in 129 locations. Therefore there was a 33% reduction in the number of opportunities for human error. It should be noted that this is a fairly simple system and the results would increase as the system becomes more complex. Additionally, the support tool conducts all calculations and any analysis required for evaluating change propagation beyond just the first order of interaction.

Without any additional input required from the user, the support tool provided documentation to show how the prescribed VV&T planning method was implemented.

The documentation includes the requirements list, a list of the affected components, the DVP matrix, the baseline test strategy, and the trade-off analysis. Additionally, the support tool provides space to specify why individual decisions were made regarding the design of the VV&T plan

Additional research needs to be conducted in order to improve the trade-off analysis functionality of the computational support tool. Currently, the trade-off analysis is conducted based solely on the Verification Complexity Index (VCI), which focuses on the importance of verifying individual requirements, combined with the costs and lead times for the associated tests. However, depending on the scope and characteristics of the engineering change being made, different companies will have different goals in executing the trade-off analysis. For instance, in certain situations, a requirement associated with an engineering change may have legal ramifications and needs to be implemented immediately. As a result, the company would likely focus on tests that focus on the legal requirement and can be conducted with minimal lead time. Therefore additional trade-off metrics need to be determined that can allow companies to determine which criteria are most important and guide the testing plan in that direction.

Another area of future research is to consider the level of change propagation when managing the effects of engineering change. As previously discussed, the support tool allows for the consideration of change propagation beyond the first order. However, it is not clear to what level the change propagation should be considered. Further research into this area is discussed in the following section.

2.2 Study on Product Component Interaction

During the development of the change management support tool, the question was asked about how deep one must traverse the relation graph to ensure complete exploration. In order to answer this question, a study was conducted on product component and option interaction using design structure matrices.

2.2.1 Background

Before executing the study, a review of design structure matrices, their use in change management and understanding change propagation, and the use of complexity metrics for understand product architecture was conducted.

2.2.1.1 Design structure matrices

Design structure matrices (DSM) are commonly used to better understand and analyse product architectures [35]. DSMs can be used to model product architecture, organizational structure, information flow, and design parameter relationships [35]. Others extend the research by providing a review of the benefits of applying DSMs in understanding product architecture, while acknowledging that a major limitation of DSMs is that they are only applicable in a single domain [36]. The domain mapping matrix (DMM) maps the interactions between DSMs from different domains [37]. Similarly, DSMs are used to characterize complex systems by decomposing them down into clusters or "building blocks" [38]. DSMs have also been used to explore how software architectures can be managed [39], introducing architectural metrics, derived from the software architecture DSMs, that can be used in development.

As DSMs become more prominent in engineering design, the number of proposed applications in which DSMs can be implemented has increased [40]. An early example of using DSMs to predict some aspect of product development resulted in a proposed method to predict the time required for product development [41]. This time prediction model uses the amount of dependencies between product development tasks to determine how required changes to specific tasks will affect the other tasks. Other applications include product configuration [42], modelling engineering design activities [43], and product modularity [32].

2.2.1.2 Change propagation

As DSMs provide an effective method for both viewing and analysing the interactions between components [21], they are commonly used to better understand change propagation within a product or system. Based on a study on engineering changes and how the interactions between product components could be used to better understand change propagation through the product, a DSM-based engineering change management tool was created to assist in product development [44]. DSMs have been used to understand change propagation in a complex system by decomposing the system into interacting subsystems [20]. The change requests over the system's life-cycle was related to one another by considering the decomposed subsystems from which they originated.

DSMs have also been used to predict change propagation. Based on the use of DSMs in understanding change propagation, the Change Prediction Method (CPM) software tool was developed to assist in visualizing the possible change propagation pathways from a single component prior to the execution of an engineering change [19].

Since its development, the CPM tool has been implemented in case studies, demonstrating the effectiveness of using DSMs to predict change propagation in a system [45,46]. While the CPM tool focuses on change propagation in the product development process, the DSMs primarily consist of product components with the change indices being subjectively assigned.

Additional research on predicting requirements change has been conducted using DSMs linking product requirements [23]. A historical based approach was used with many different relationship sets to determine which combinations yielded the best predictors. A significant conclusion from this research is the fact that using higher order DSMs, specifically at the second order of interaction, is necessary to best predict future changes to requirements. Thus, the question at hand is whether second or higher order interactions are critical in other DSM applications for understanding and, eventually, predicting change. To better answer this question, one may consider how product complexity could play a role in increasing change propagation within a system or product.

2.2.1.3 Product complexity

When considering product structural or connectivity complexity, 29 different graph theory metrics have been used for evaluating a product or system to predict assembly time from component assemblies [47]. However, when focusing on how complexity can influence change propagation within a product, the researchers focused on the complexity metrics that primarily looked at the interactions between the components. This mirrors the concept of complexity as coupling that is proposed in [48], with an initial algorithm based on decomposability proposed to determine connectivity complexity. Using this algorithm,

a simple experiment was conducted using the proposed metric to evaluate multiple existing products represented in different model types [49]. The experiment showed the importance of coupling when considering complexity in a product's architecture. Similarly, the connective complexity in a system was used to model and understand design tasks [50]. Using connectivity metrics, the researchers were able to identify patterns and infer additional relationships within the system.

2.2.2 Approach

The approach used in this portion of the research consists of two phases. The first phase is the development of the DSMs from models of existing products. The second phase consists of the analysis of the products based on how the individual components or elements interact beyond the first order of interaction. The analysis is done based on both assembly models and also on product configuration (option) graphs.

2.2.2.1 Product architecture

In the development of the product assembly-based DSMs for this study, previous models are used to address issues of research objectivity and bias. The DSMs allow one to draw comparisons between the physical attributes of the product and the data on how the product's components interacted. This was especially beneficial in looking for patterns between different products that exhibit similar interaction behaviours. Previous work was done to create connectivity graphs of all of the physical interactions between components within a product based on the analysis of a 3-D CAD model [47]. Figure 2.2 shows an example of a 3-D CAD model and the corresponding connectivity graph. In the work

presented here, the types of relationships between components (elements) are not studied, rather only the adjacency topology of the system architecture is investigated. Specifically, the relationships in Figure 2.2(b) are capturing when parts are touching.

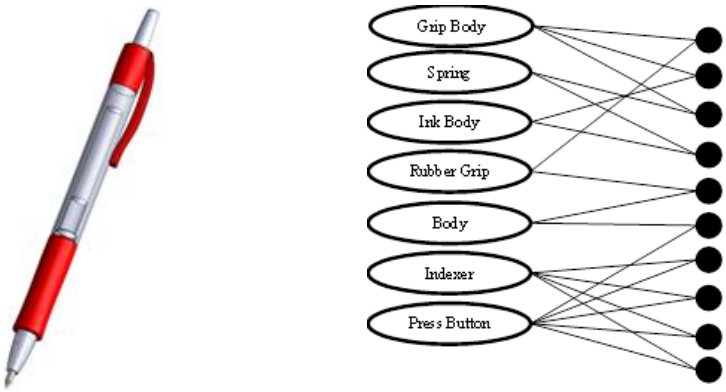

Figure 2.2: 3-D CAD model for a pen (a) and the resulting connectivity graph (b)

Using the connectivity graphs, it was possible to construct a DSM for each of the products being analysed. It is important to note that these DSMs created from the connectivity graphs only include physical interactions identified in the associated 3-D CAD models. An example of the resulting DSM is shown in Figure 2.3(a). The second phase begins with the identification of component interactions beyond the first order. The DSMs are then populated with the higher order interactions. A higher order interaction is an interaction between two components through other components. For example, in Figure 2.2(b), a second order interaction exists between the body and the grip body through the rubber grip. An example of a completed DSM with higher order interactions is shown in Figure 2.3(b). The cells in the DSM indicate the shortest path length between the components, or the minimum order of interaction between components.

Component Name		A	B	C	D	E	F	G
Grip Body	A		1		1	1		
Rubber Grip	B	1					1	
Press Button	C						1	1
Spring	D	1				1		
Ink Body	E	1			1			
Body	F		1	1				
Indexer	G			1				

Component Name		A	B	C	D	E	F	G
Grip Body	A		1	3	1	1	2	4
Rubber Grip	B	1		2	2	2	1	3
Press Button	C	3	2		4	4	1	1
Spring	D	1	2	4		1	3	5
Ink Body	E	1	2	4	1		3	5
Body	F	2	1	1	3	3		2
Indexer	G	4	3	1	5	5	2	

Figure 2.3: Initial (a) and full populated (b) product design structure matrices for a pen

The final step is to calculate the population density of the DSMs at each order of interaction. The population density refers to the percentage of existing interactions compared to the total number of possible interactions. The population density includes any interactions that take place up to and including a given order. In the example of the pen (Figure 2.3(b)), the population density for the 1st order would be 33.33% (14 interactions out of a possible 42). Then, for the 2nd order, the population density is 57.14% (24 interactions out of 42 possible interactions). The complete graph for the population densities for all orders of interaction is shown in Figure 2.4.

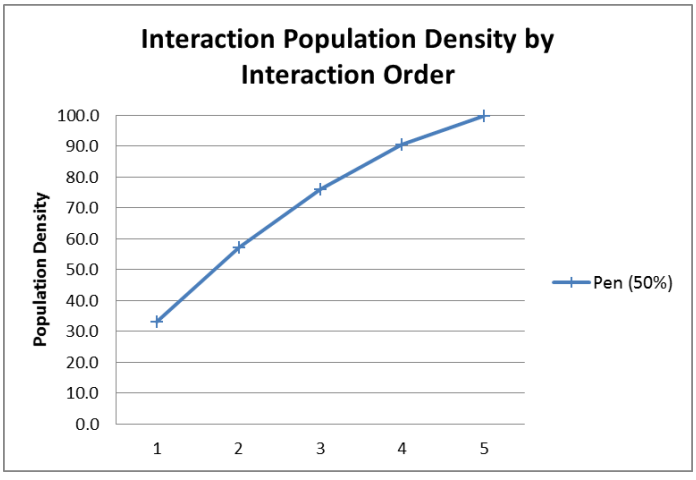

Figure 2.4: Graph of population densities for a pen

Another statistic used to analyse the data is the average shortest path length applied against the entire graph. The shortest path length for a given component is the minimum number of steps required to reach every other component in the system. Therefore, the average shortest path length for the DSM is the average for all of the relations in the system. In the example shown in Figure 2.2, the maximum shortest path length for "press button" to reach each of the other components is 4. By averaging the path lengths in the example, the average maximum shortest path length is 4.143 (average of all values in its row).

2.2.2.2 Product configuration

In addition to considering propagation in products, product configuration data was also evaluated. The purpose of this aspect of the research is to determine how DSMs for product configuration are similar to DSMs for product architecture. This is of interest in that it is important to understand change propagation in configuration management, especially when using rule-based configuration management [51]. An example DSM for product configuration is shown in Figure 2.5(a) considering 14 options. These are related through option rules. This DSM represents the options found in a single change request.

Option Name		A	B	C	D	E	F	G	H	I	J	K	L	M	N
161	A														
167	B													1	
169	C								1	1					
1CB	D								1						
2VB	E													1	
6UF	F													1	
823	G									1					
842	H			1	1										
843	I			1				1			1				
858	J									1					
8EB	K													1	
8S9	L													1	
991	M		1			1	1					1	1		1
9AE	N													1	

Option Name		A	B	C	D	E	F	G	H	I	J	K	L	M	N
161	A														
167	B					2	2					2	2	1	2
169	C				2			2	1	1	2				
1CB	D			2				4	1	3	4				
2VB	E		2				2					2	2	1	2
6UF	F		2			2						2	2	1	2
823	G			2	4				3	1	2				
842	H			1	1			3		2	3				
843	I			1	3			1	2		1				
858	J			2	4			2	3	1					
8EB	K		2			2	2						2	1	2
8S9	L		2			2	2					2		1	2
991	M		1			1	1					1	1		1
9AE	N		2			2	2					2	2	1	

Figure 2.5: Initial (a) and fully populated (b) product configuration DSMs for a product change

In Figure 2.5(a), the elements of the DSM are product options that might be selected independently or within packages by a customer. They relate to other options by a series of rules that might be either engineering based or marketing focused. In the DSM, the connections, through the rules, are shown by 1st order interactions in the DSM. For example, in Figure 2.5(a), Option 167 is directly related to Option 991 through a configuration rule. Using the same method discussed previously, a higher order DSM is created. Figure 2.5(b) shows the resulting higher order DSM based on the DSM in Figure 2.5(a). When analysing product configurations, two levels of DSMs are used: a full configuration ruleset, consisting of approximately 600 components connected by 1400 rules; and a series of configuration DSMs created by considering the affected components from historical changes implemented at an automotive OEM. The DSMs are created by starting with the options affected by the change. The rest of the DSM is populated using the 1st and 2nd order interactions stemming from the initial change components. In the example shown in Figure 2.5, the graph is not fully populated due to clustering in the ruleset. For example, option 161 is not connected to any other options, while options 169, 1CB, 823, 842, 843, and 858 for a cluster and do not interact with any options outside of the cluster. Once the higher order DSM is created, the same analysis is conducted as with the product architecture DSMs. The purpose behind this is to use the conclusions drawn from analysing product architecture and apply it to product configuration.

2.2.3 Results

The results were compiled for component saturation rates and higher order component interaction levels.

2.2.3.1 Component saturation

When applied to thirteen products [47], the given approach yielded the results shown in Table 2.12. In the table, the number of components, the betweenness density, and the population density for each product based on the order of interaction are illustrated.

Table 2.12: Component interaction saturation for product architecture

Product Architecture											
Product	Row Density	# of Comp	Saturation	Betweenness Density	Population Density by Order of Interaction						
					1	2	3	4	5	6	7
Boothroyd Piston	67%	7	2	0.314	47.6	100.0	100.0	100.0	100.0	100.0	100.0
Mouse	82%	12	3	0.186	25.8	86.4	100.0	100.0	100.0	100.0	100.0
Stapler	87%	16	4	0.245	27.5	83.3	99.2	100.0	100.0	100.0	100.0
Pencil Compass	45%	12	4	0.431	27.3	66.7	92.4	100.0	100.0	100.0	100.0
Solar Yard Light	64%	15	5	0.454	19.1	57.1	88.6	99.1	100.0	100.0	100.0
Drill	70%	28	5	0.259	14.0	61.9	92.1	99.2	100.0	100.0	100.0
Hole Punch	39%	27	4	0.658	9.1	34.8	74.4	100.0	100.0	100.0	100.0
Vise	44%	19	5	0.546	15.2	42.1	80.1	97.7	100.0	100.0	100.0
Chopper	38%	41	6	0.577	8.4	35.5	73.9	93.9	99.3	100.0	100.0
Blender	33%	43	6	0.620	7.8	32.6	70.2	92.3	99.0	100.0	100.0
Pen	50%	7	5	0.857	33.3	57.1	76.2	90.5	100.0	100.0	100.0
Maglight	38%	14	7	1.471	17.6	39.6	58.2	74.7	87.9	95.6	100.0
Brake subsystem	40%	11	7	Unknown	20.0	43.6	63.6	81.8	92.7	98.2	100.0

Betweenness density is a measure of the average betweenness value for all of the components with a given product. Betweenness is a useful metric for evaluating complexity in that it provides a measure of the importance of a specified component [52]. It is equal to the number of shortest paths from all vertices to all others that pass through that node. Also shown in Table 2.12 are the orders of interaction for complete saturation of the DSM and the row density for each product. The row density shows the highest percent of interactions present for a single component of the product. For example, in the pen, there are seven components, resulting in six possible interactions between a single component and the other components. The most interconnected component, the grip body,

interacts with three components out of the possible six. Therefore, the pen has a 50% row density. The row density was considered as it may help to explain why some of the saturation rates behave as they do.

Using visual inspection, one can separate the resulting graphs into groupings of products that exhibit similar curves. Figure 2.6 shows the first grouping, consisting of the stapler and the computer mouse. These curves exhibit quick saturations (3rd order) with a steep initial slope. The second grouping is depicted in Figure 2.7 and consists of the pencil compass, solar yard light, and the electric drill. The curves of this group exhibit slightly slower saturations (4th order) and resemble a parabola. Figure 2.8 contains the third grouping, consisting of the 3-hole punch, an electric food chopper/processor, a pony vise, and an electric blender. These curves exhibit medium saturation order (4th/5th orders) and have a slight "s-curve" as the order of interaction is increased. The final grouping is shown in Figure 2.9 and consists of the pen, a Maglite flashlight, and the brake subsystem modelled in the motivating project. The curves of this group exhibit slow saturations (5th-7th orders) and are parabolic in shape. Trendlines that represented all of the points for each product within the grouping were created using cubic polynomials. The resulting R^2 values are as follows: Group 1 – 0.9797; Group 2 – 0.9895; Group 3 – 0.9791; Group 4 – 0.9559. The R^2 value for the trendline from all of the product curves together is 0.8663. The complete graphs showing the trendlines can be found in 9.2Appendix B:. It should be noted that all of the trendlines were created using third order polynomials. The noticeable increase in R^2 values when the product curves are combined indicates that the groupings are correct.

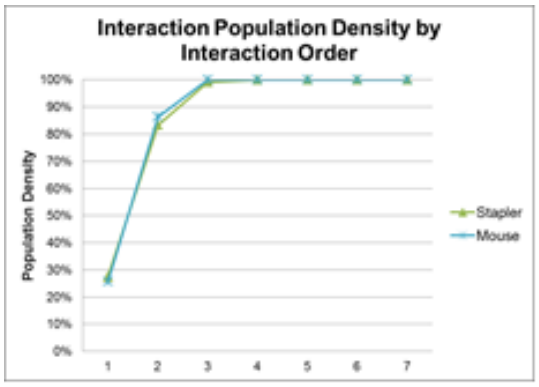

Figure 2.6: Product group 1 saturation graph

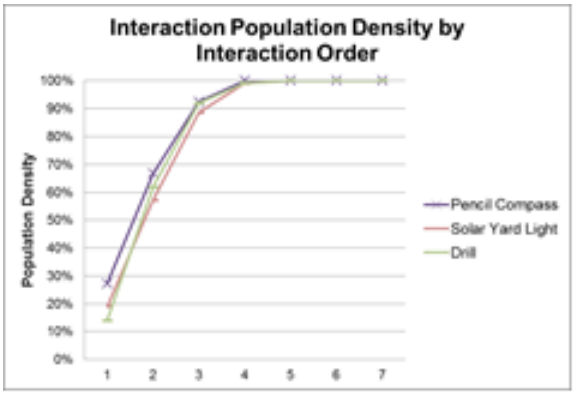

Figure 2.7: Product group 2 saturation graph

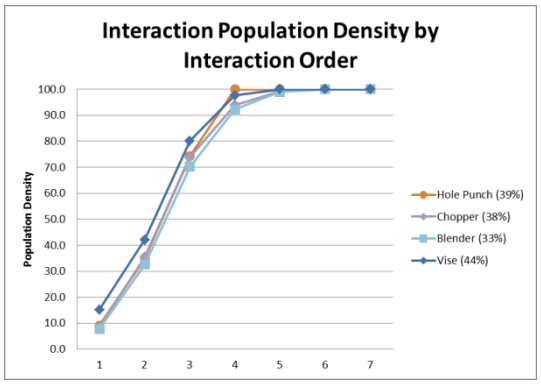

Figure 2.8: Product group 3 saturation graph

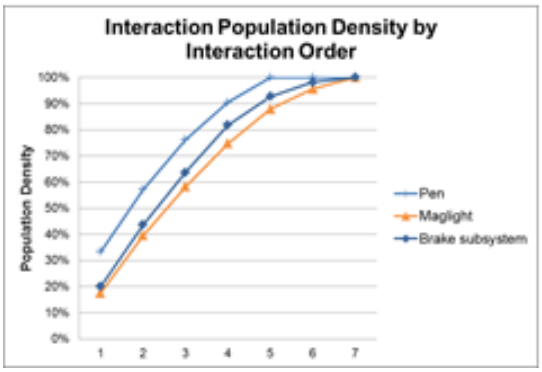

Figure 2.9: Product group 4 saturation graph

Similar results were created for four product configuration change DSMs from the automotive OEM. The results are shown in Table 2.13. The resulting graphs for the product configuration changes are shown in Figure 2.10. When a trendline is created for the product configuration change curves, the R^2 value is 0.2175. Much of this is due to two of the curves not reaching 100% saturation.

Table 2.13: Component interaction saturation for product configuration

Product Configuration														
Product	Row Density	# of Comp	Saturation	Population Density by Order of Interaction										
				1	2	3	4	5	6	7	8	9	10	11
Change 1	35%	38	7	8.3	32.6	50.9	61.5	73.7	92.9	100.0	100.0	100.0	100.0	100.0
Change 2	80%	26	N/A	21.5	71.1	78.8	78.8	78.8	78.8	78.8	78.8	78.8	78.8	78.8
Change 3	46%	14	N/A	12.1	34.1	37.4	39.6	39.6	39.6	39.6	39.6	39.6	39.6	39.6
Change 4	50%	17	5	19.9	52.9	86.8	98.5	100.0	100.0	100.0	100	100	100	100
Complete Ruleset	6%	395	N/A	0.63	2.24	4.63	7.26	10.35	13.29	15.12	15.92	16.14	16.17	16.17

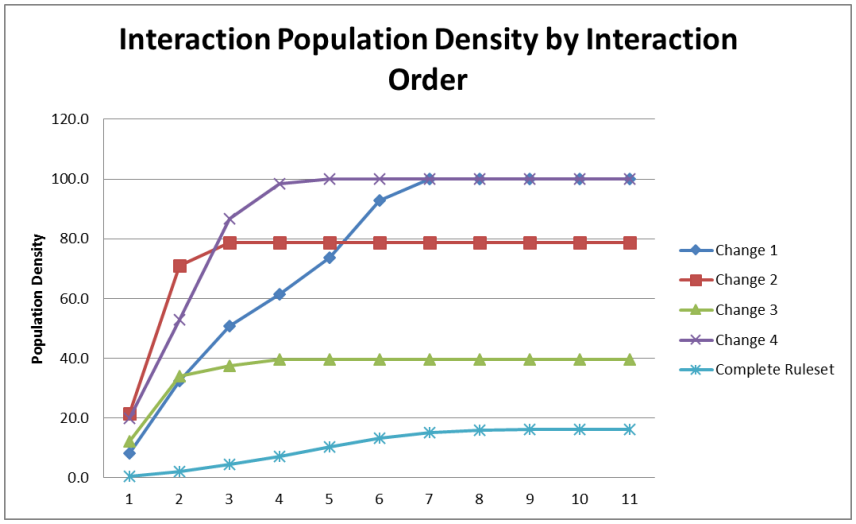

Figure 2.10: Product configuration saturation graph

When the product configuration subsets are considered alongside the products, three of the changes (1, 2, 4) fit within three of the product groups. The resulting graphs are shown in Figure 2.11, Figure 2.12, and Figure 2.13. It should be noted that Change 3 and the complete ruleset were not able to be matched to a specific group due to the low maximum population density. When considering product configurations, it is common that there will be clusters of product options that do not interact in any way with other clusters. It the case of the complete ruleset, this was much more severe, with only 16.17% of the possible interactions existing at maximum saturation (reached in the 10^{th} order). When trendlines for the three groups are created, the following R^2 values are achieved: Group 1

– 0.8533; Group 3 – 0.9197; Group 4 – 0.9408. The complete graphs can be found in 9.2Appendix B:.

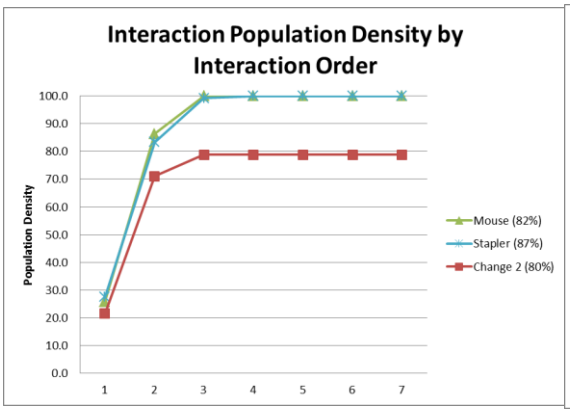

Figure 2.11: Group 1 saturation graph

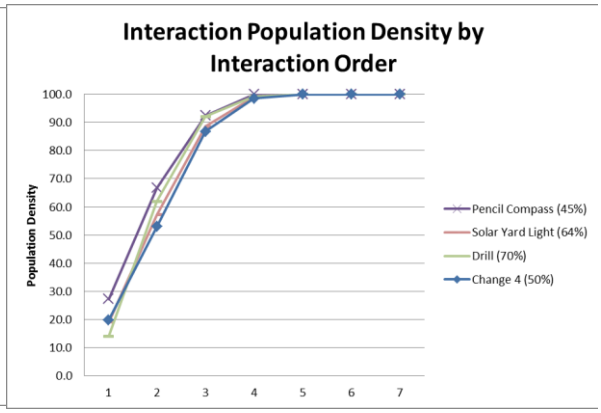

Figure 2.12: Group 2 saturation graph

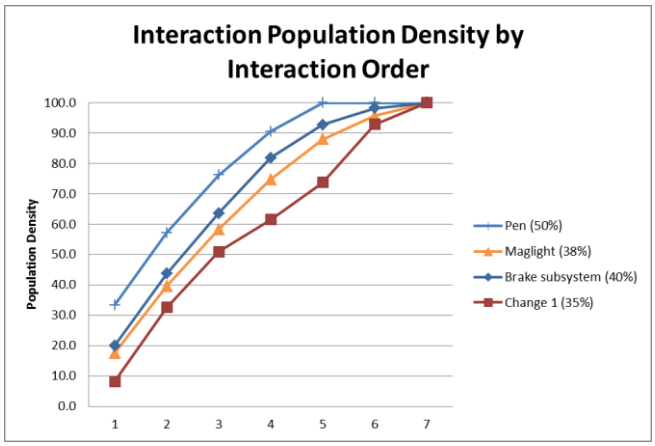

Figure 2.13: Group 3 saturation graph

2.2.3.2 Higher order component interaction

The average shortest path length is also considered as a method for better understanding component interaction within a system. By applying the outlined approach to the product DSMs, the following results table was created and is shown in Table 2.14.

Table 2.14: Product architecture component interaction

Product Architecture				
Product	Row Dens.	Saturation	Avg Path	Comp
Boothroyd Piston	67%	2	2.00	7
Mouse	82%	3	2.58	12
Stapler	87%	4	3.50	12
Pencil Compass	45%	4	2.94	16
Solar Yard Light	64%	4	3.64	27
Drill	70%	5	4.14	7
Hole Punch	39%	5	4.00	15
Vise	44%	5	3.89	28
Chopper	38%	5	4.05	19
Blender	33%	6	4.71	41
Pen	50%	6	4.98	43
Maglight	38%	7	5.86	14
Brake subsystem	40%	7	5.45	11

In addition, the same approach was used to analyse the product configuration DSMs. The resulting data is shown in Table 2.15.

Table 2.15: Product configuration component interaction

Product Configuration				
Product	Row Dens.	Saturation	Avg Path	Comp
Change 1	35%	7 (100%)	6.16	38
Change 2	80%	3 (78.8%)	2.42	26
Change 3	46%	4 (39.6%)	2.36	14
Change 4	50%	5 (100%)	4.00	17
Complete Ruleset	6%	11 (16.17%)	3.26	395

Visual inspection of both the product architecture and product configuration datasets show that the average shortest path length and the order for complete saturation are closely related. A larger sample population would be required for a more robust correlation analysis. However, it is clear from the results that the relationships between average shortest path length and complete saturation of the DSM are similar for both

product architecture and product configuration. Therefore, one can be used as a substitute for the other.

2.2.4 Analysis

When the betweenness values are compared to the saturation curves for the four product groupings, a correlation is suggested; as the betweenness density decreases, the slope of the saturation curve increases, or the individual components more quickly interact with all of the other components through higher order interactions. It can also be noted that the betweenness density values for those products within a group are similar when compared to the values for the other products (for example, all of the products in group 3 have values between 0.54 and 0.66). This shows that as the slope of the saturation curve increases, the interconnectivity (betweenness) of the product increases.

Because of the familiarity with the products involved, it was possible to identify additional relationships regarding the product groupings with respect to the product architecture. It was noted that the products in group 4 exhibited a stacked-linear assembly structure [53], which likely corresponds to a decreased saturation rate as components only directly interact with neighbouring components along the body of the product. On the opposite end of the spectrum, those products in group 1 all exhibit chassis product architectures similar to the spokes of a wheel [53], where a single body or frame component interacts with a large percentage of the other components in the product. This would correspond with a rapid saturation rate as any given component would quickly interact with the other components through higher order interactions as soon as it interacts with the

central frame/body component. Additionally, the high amount of interactions for a single component is also shown in the row density statistic provided.

Average shortest path length is another metric often used when considering the complexity of a system as it correlates to the level of interconnectedness of the components in the system [47,50,54]. In the analysis of component interaction a clear relationship is identified between the average shortest path length and the order of interaction at which the DSM is fully saturated. This shows that as the level of interconnectivity of the system increases, the DSM saturation rate also increases.

When comparing the metrics for product architecture and product configuration, it is clear that the metrics for analysing product complexity can also be applied to evaluating the complexity of a product configuration subset or even the entire product configuration ruleset. This analysis is based on the similarities that were identified between the different types of DSMs and the fact that the saturation graphs for the product configuration subsets were able to be matched closely with the graphs depicting product architecture.

2.3 Conclusions

The research objective that is covered in this chapter is to increase understanding of existing industry practices for conducting change management. This objective was accomplished through three related sub-questions, discussed below.

The first sub-question is: What is the state-of-the-art for engineering change management? In order to answer this question, a literature review of change management practice was conducted. The literature review consisted of an analysis of engineering change and change propagation, followed by a discussion of existing change management

tools and methods, including their usefulness and shortcomings. In the literature review, it was identified that numerous tools and methods exist for engineering change management. However, it was also noted that much of the research conducted in academia is not put into practice in industry. The primary reasons for this include costs and difficulty of adopting the methods or tools proposed by researchers.

The answers to the first sub-question directly tie into the second question: How can the existing change management practices be improved to further enhance usability and efficiency? To answer this question, a computational support tool was developed and evaluated based on an existing change management planning method. The planning method selected for adoption into a tool was chosen due to its focus on variant change propagation, something that was not seen in the other change management support methods. The resulting support tool was developed with an emphasis on increasing adoptability and minimizing costs, while also increasing change management capabilities. The support tool was evaluated using a case example and showed a significant decrease in the potential for human entry error, as well as an ability to automatically document the steps and decisions taken in the change management process.

During the development of the change management support tool, the question was asked regarding the depth required to sufficiently evaluate the effects of change propagation. The led to the final sub-question for this research objective: When considering change propagation, what order of interaction is required to verify affected components? In order to answer this question, a study was conducted on component interaction. In the study, design structure matrices (DSMs) were created based on product

assembly models and option configuration rulesets. The DSMs were then evaluated based on how quickly the components interacted with all of the other components through higher order interactions. Through the study, it was found that the second or third order is recommended when considering change propagation, though this is dependent on the system and the change in question. Additionally, it was identified that interaction saturation rates could be a useful metric when evaluating or describing the complexity in a system.

2.4 Dissertation Roadmap

The motivation for this dissertation was an interest in product configuration, with an emphasis on configuration change and configuration management practices. Chapter Two presented the research in current change management practice that led to the author's interest in dynamic configuration management. Since this chapter has provided the foundation for the remainder of the research, the next chapter (Chapter Three) builds on this by presenting the research objectives of the dissertation. The progress of this dissertation is shown in Figure 2.14 in which the completed portion is highlighted in green.

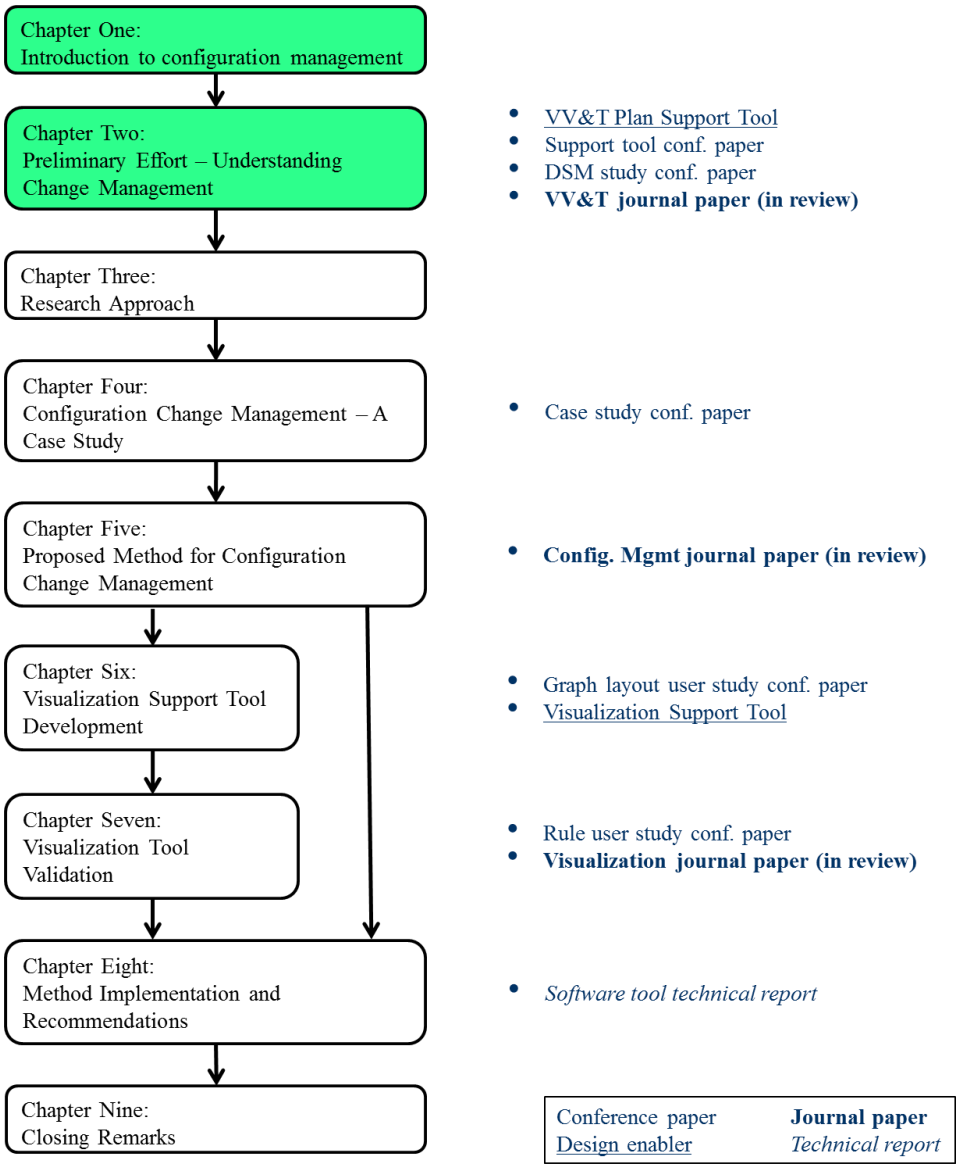

Figure 2.14: Dissertation roadmap

CHAPTER THREE: RESEARCH APPROACH

Once again, the goal of this research is to understand how configuration change management is conducted in industry in order to increase the capabilities of the configuration change management process through method development. An overview of the research path followed is shown in Figure 3.1.

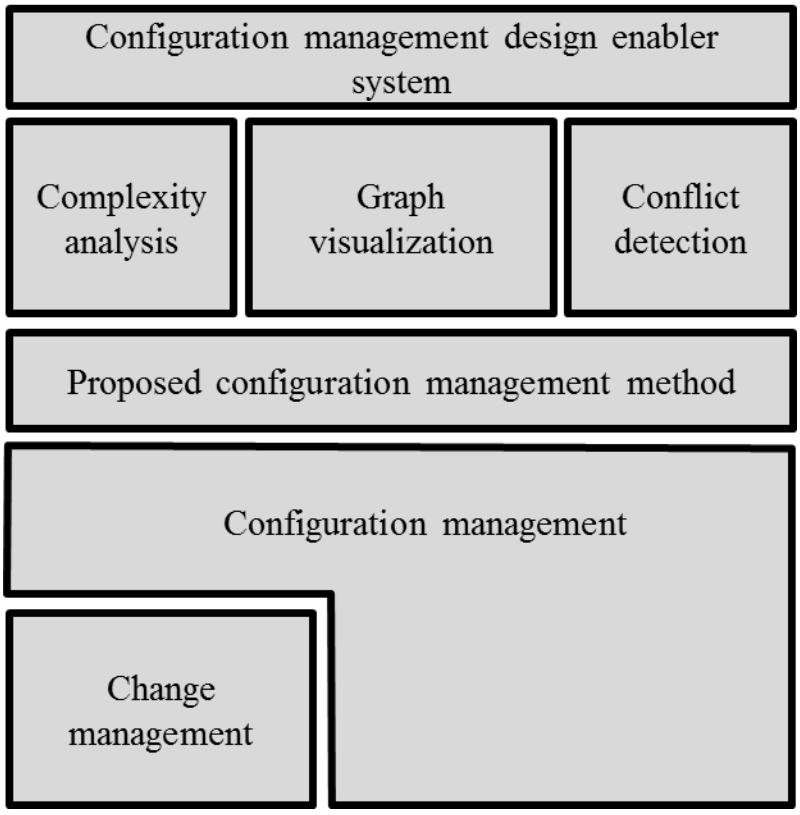

Figure 3.1: Research plan overview

In order to address this goal, the research is divided into three separate, but related, objectives. The first objective consists of the preliminary work that led to the proposed research: understanding existing industry practice for change management (Chapter Two). This includes a review of current literature regarding engineering change management

methods and strategies. An existing method for identifying possible change propagation pathways is selected and used to develop an engineering change management support tool [55]. This method was selected in part because of its focus on understanding change propagation through variant pathways. During the development of the support tool, a question asked was about how far into a change propagation pathway is necessary to identify affected components for verification. This led to a study into how design structure matrices (DSMs) can be used to understand component and configuration option interaction and interconnectedness [56]. As shown in Figure 3.1, the lessons learned from the preliminary research were applied to product configuration to assist in understanding and improving configuration change management.

The second research objective is to understand how a major automotive OEM conducts configuration management (Chapter Four). The purpose of the second objective is to develop a better understanding of product configuration management. The approach taken to develop this understanding was through case study analysis at a major automotive OEM to identify how the company conducts configuration management. A review of the literature on configuration management in other industries and in academia provides insight to determine if the processes identified in the case study are in line with the state-of-the-art and relevant best practices [51]. As shown in Figure 3.1, the knowledge gained from this objective is used to develop an improved configuration change management method.

The third objective includes the development of an improved method for conducting product configuration change management (Chapter Five). To accomplish this,

a visualization support tool was developed to assist in understanding the potential implications of configuration changes and to increase the user's ability to explore a proposed change (Chapter Six). Additionally, the use of complexity metrics and a satisfiability engine are explored in support of the method. During the development of the visualization support tool, a user study was conducted to investigate the relationship between specific graph parameters and the user's ability to read and interpret the graph [57]. To validate the effectiveness of the visualization method, a second user study was employed (Chapter Seven). Further, the visualization tool was used in four ongoing configuration changes at the automotive OEM. Additional validation is presented for the overall configuration change management method through three select cases where the benefit of the method was evaluated (Chapter Eight).

3.1 Research Questions and Tasks

Nine specific tasks were defined to answer these research questions. Table 3.1 illustrates the research objectives and their related tasks. These tasks are detailed further in the following sections.

Table 3.1: Research Questions and Tasks

Research Objectives	Research Sub-questions	Tasks
RO 1- Understanding existing industry practice for change management	RQ 1.1 What is the state-of-the-art for engineering change management?	Task 1A: Review of change management practice Task 1B: Support tool development Task 1C: Component interaction study
	RQ 1.2 How can the existing change management practices be improved to further enhance usability and efficiency?	
	RQ 1.3 When considering change propagation, what order of interaction is required to verify affected components?	

RO 2- Understand how an OEM conducts configuration change management	RQ 2.1 What is the state-of-the-art for configuration management?	Task 2A: Review of current configuration management practices Task 2B: Case study with automotive OEM
	RQ 2.2 How does a major automotive OEM conduct configuration change management?	
RO 3 – Development of an improved method for configuration change management	RQ 3.1 How can data visualization be used to increase the ability to understand component relationships in a system?	Task 3A: Review of visualization techniques Task 3B: Graph layout user study Task 3C: Rule implementation user study Task 3D: Implementation
	RQ 3.2 Does the implementation of a graph visualization design enabler assist in identifying errors and understanding the relationships in a proposed configuration change?	
	RQ 3.3 Does the proposed method assist in identifying errors and understanding the relationships in the possible product configurations?	

3.1.1 RO 1: Understanding existing industry practice for change management

The preliminary portion of this research began with a review of existing change management practice. This is shown in the first research sub-question for the objective:

RQ 1.1: What is the state-of-the-art for change management practice?

The question is answered through a literature review of engineering change and change propagation and the existing change management support tools to manage the changes (Task 1A). The purpose of this task is to gain a better understanding for change management in industry and identify areas where the existing practices can be supplemented to increase their effectiveness and/or usability. During the review of existing support tools it is identified that a significant gap exists between change management methods proposed by academia and the methods in use by industry [15].

This led to the development of the second sub-question:

RQ 1.2: How can the existing change management practices be improved to further enhance usability and efficiency?

To answer this research question, an existing change management support method was selected and developed into a computational support tool to assist in its implementation (Task 1B). The VV&T method was selected due to its inclusion of variant propagation pathways, which is an aspect that is unique to the method and is of interest to the researcher [30]. The purpose of this task is to determine how the methods proposed in academia can be supported to increase their usability by industry and therefore increase the level of adoption. During the development of the change management support tool, the question was asked about how deep one must traverse the relation graph to ensure complete exploration.

This led to the creation of the third sub-question:

RQ 1.3: When considering change propagation, what order of interaction is required to verify affected components?

To answer this research question, a study is conducted on component interactions using design structure matrices (Task 1C). In the study, component interactions (option rules and touching parts) were used to identify how a change could potentially propagate through a system at higher orders of interaction. The purpose of this task is to gain a better understanding of component interaction in product architecture and configuration rulesets and determine whether similar patterns exist between them.

3.1.2 RO 2: Understand how an OEM conducts configuration change management

In addition to regularly changing their products to remain current, many companies also use multiple possible configurations to reach the needs of individual customers [58]. In the last decade, there has been a widespread shift in manufacturing from mass production to mass customization, such as making multiple configurations from a single product platform, which enables companies to maintain the efficient production practices associated with mass production, while targeting specific customers [58,59]. Due to the increased use of product configuration as a means towards mass customization, a large amount of research has been conducted to develop tools for possible use in configuration management [3,60–68]. However, research has shown that there is a significant gap between the latest methods and tools developed in academia and what is being used in industry [1]. If companies are not using the proposed methods, then it is necessary to understand why the companies are not using those methods and what practices they are using instead.

The first step in achieving this objective is to build a knowledge base regarding configuration management practices in industry. This led to the research sub-question:

RQ 2.1: What is the state-of-the-art for configuration management?

This question is answered through a literature review of configuration management and the existing configuration change management methods (Task 2A). The purpose of this task is to gain a better understanding of configuration management in industry and aid in identifying the specific practices in use at the OEM during the case study. While the literature review provides a broad spectrum of knowledge regarding configuration

management practice, it does not provide the required level of detail regarding an individual company's practices.

This led to the development of the second sub-question:

RQ 2.2: How does a major automotive OEM conduct configuration change management?

This question is answered through a case study on the configuration management practices at a major automotive OEM in Spartanburg, SC (Task 2B). The manufacturer was chosen as the preferred case because the company uses a large, but unknown, number of configurations for each of the vehicle models and, therefore, must be able to identify how configuration changes will impact the system. For example, in the current configuration management method, the OEM uses over 600 rules to manage over 400 options that relate to approximately 1500 parts for a single vehicle model, resulting in greater than 10^8 interactions between the elements. As a result of the large number of elements affecting the possible configurations, proper configuration management is essential.

The case study in Task 2B consists of data gathering through interviews, document analysis, and direct observations of employees executing configuration change management over a one year period. The purpose of the case study is to identify how the manufacturer conducts configuration and configuration change management. Finally, opportunities to improve the existing configuration management practices at the OEM are recommended.

3.1.3 RO 3: Development of an improved method for configuration change management

In order for configuration management to be an effective process, the large amount of data that is available to the engineer must be readily accessible and easy to understand. It was shown in [51] that rule-based configuration management is used in the automotive OEM being studied, as well as in numerous other manufacturers [69,70]. A major issue that was identified with respect to rule-based configuration management is the difficulty in making changes to the system and in determining the accuracy of the system. This is primarily due to the scale of the ruleset that is required to completely specify the system [3]. Previous research has shown that different visualization techniques can simplify the process of analyzing large or complicated data sets. As previously stated, the scale of the problem identified in the case study (greater than 10^8 possible interactions) results in the problem being an ideal opportunity for the implementation of alternate data visualization techniques. Therefore, it is necessary to develop additional resources to support the visualization of the data found in the ruleset when using rule-based configuration management.

The level of complexity involved in rule-based configuration management makes it difficult to understand how changes can have unintended consequences throughout the configuration system. Previous research has shown that data visualization can be useful when considering complex systems [71–73]. This leads to the first sub-question for this research objective:

RQ 3.1: How can data visualization be used to increase the ability to understand component relationships in a system?

This question is answered through a review of data visualization techniques, specifically focusing on graph visualization and their usefulness for identifying relationships in complex systems (Task 3A). The purpose of this task is to determine how data visualization has been used previously and then to determine whether the use of visualizations would be beneficial in configuration change management. It was found that using graph visualizations, based on past studies, could increase the capabilities for understanding and managing changes to the configuration system.

Once it was determined that graph visualizations could be used in the new method, it was necessary to identify which factors would affect the usefulness of the graph visualization. This question is answered through a user study (Task 3B). The user study was conducted with the specific purpose of determining which factors (layout, amount of information, and color scheme) had the greatest effect on the usability of the graph visualizations. The participants were provided with different variations of a portion of the configuration system and were asked questions about different aspects of the rules or how specific rule changes could affect the entire system. From the results, it was found that the amount of information presented had the greatest influence on the participants' ability to answer questions about the rule system. After the completed development of the visualization support tool, the next step was to evaluate its usefulness.

This led to the second sub-question:

RQ 3.2: Does the implementation of a graph visualization design enabler assist in identifying errors and understanding the relationships in a proposed configuration change?

This question was partially answered through a second user study (Task 3C) to determine whether the implementation of a graph visualization tool would increase the accuracy and consistency of rule implementation into the configuration system. Further, training was tested to determine its impact on usability. It was found that with limited training, the graph was comparable to the existing method used by the personnel at the OEM. Additionally, the visualization group showed the greatest improvement in answering questions requiring a greater level of analysis.

The research question was also answered through using the visualization tool in four ongoing configuration changes at the (Task 3D). In these changes, implementing the visualization method allowed the users to better explore the effects of the proposed change and identify potential conflicts. Additionally, a time study showed that the visualization would allow the user to conduct the same analysis in approximately one fourth of the time required in the current process.

While graph visualization is useful for understanding relationships between components, certain aspects of configuration management require different reasoning solutions, such as the ability to validate the system and identify conflicts. Thus, two additional design enablers for conflict detection and complexity analysis are implemented alongside graph visualization in the proposed method. The next step was to evaluate the usefulness of the overall method.

The led to the third sub-question:

RQ 3.3: Does the proposed method assist in identifying errors and understanding the relationships in the possible product configurations?

The research question was answered through implementing the proposed method on three configuration changes (Task 3D). When applying the proposed method to the three configuration changes, it was shown that the proposed method increases the user's capabilities when validating proposed configuration changes. Feedback obtained from a formal interview with a primary user of the method, personnel from the *Launch and Change Control* group at the OEM, showed that implementing the proposed method when evaluating configurations would increase the group's capability to correctly identify errors and prevent future issues resulting from a proposed change. Additional informal feedback received throughout the development of the proposed process supports also this conclusion.

3.2 Dissertation Roadmap

Chapter Three presented the discussed the research objectives and provided an overview of the dissertation. With the structure of the dissertation established, the next chapter (Chapter Four) begins the exploratory portion of the dissertation. In the following chapter, a case study of an automotive OEM is presented to illustrate how companies conduct configuration management. The progress of this dissertation is shown in Figure 3.2 in which the completed portion is highlighted in green.

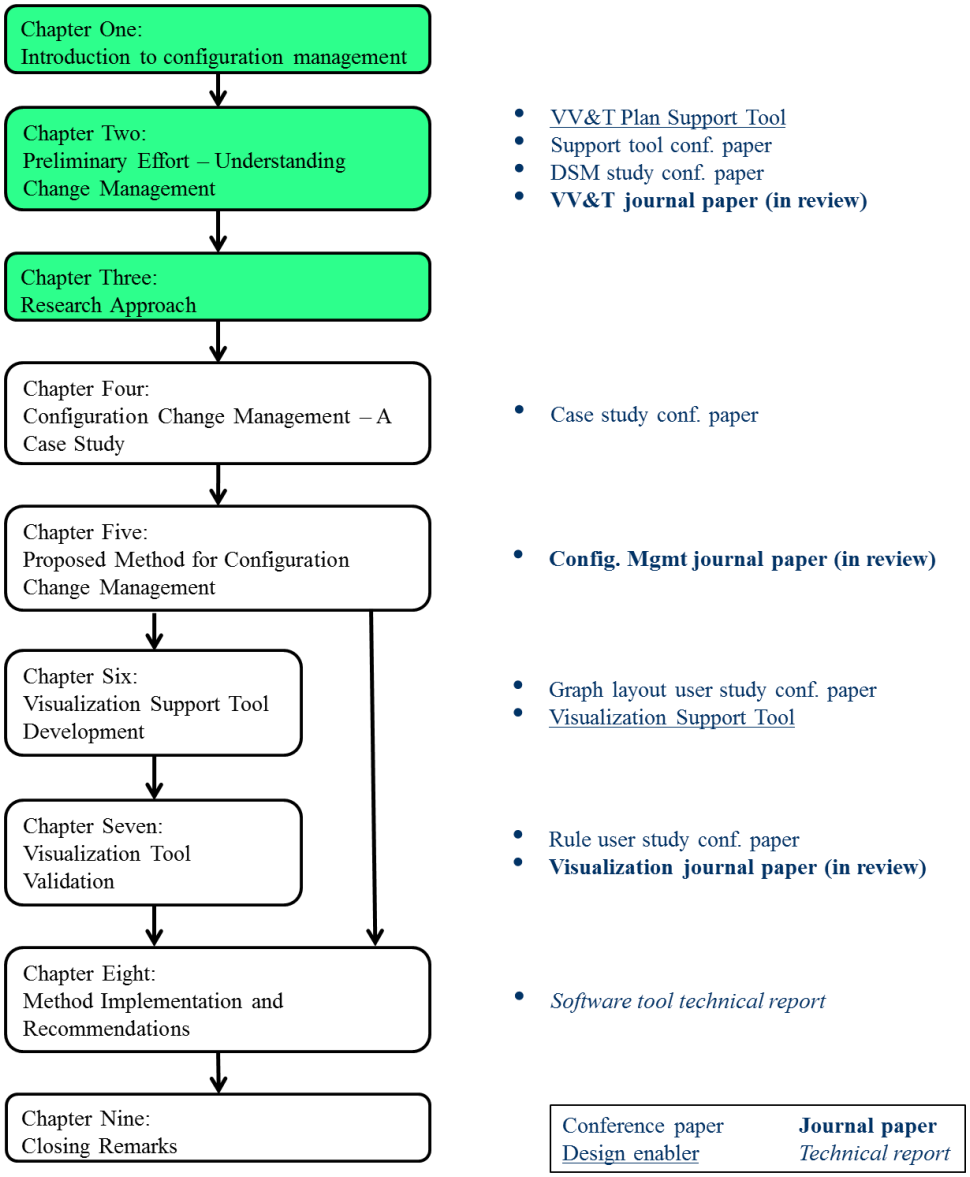

Figure 3.2: Dissertation roadmap

CHAPTER FOUR: CONFIGURATION CHANGE MANAGEMENT – A CASE STUDY

The purpose of the research in this chapter is to identify how a company conducts configuration change management. Specifically, the research aims to better understand how an individual manufacturer that heavily employs mass customization principles in its manufacturing process implements configuration and change management to adapt to the varied and changing needs of production. Based on the findings identified in the research, recommendations are made to increase the effectiveness of configuration and change management practices in industry.

4.1 Current Configuration Management Practice

A variety of techniques have been developed to assist in the implementation of configuration management [5,42,66,74–77]. For the purposes of this research, the classification scheme proposed in [3] is used to facilitate discussion of the different existing methods. To examine the different methods, the type of reasoning is used as the central comparison characteristic, specifically rule-based, model-based, and case-based reasoning [78]. Viewing configuration management as an instance of engineering change management is an additional facet of configuration change management that is discussed in this chapter.

4.1.1 Rule-based reasoning

Rule-based reasoning is one of the earlier forms of implemented configuration management and relies on a series of rules to manage the possible configurations of components within a system. The rules can best be described as a set of conditions and

consequences (if "A" then "B"). Therefore, the condition relates to an existing component or state of the product which, if met, results in an execution of the consequence action or part inclusion. An example of this would be as follows: "If Part A is found in the configuration, then Part B cannot be used in this configuration". As a result, the execution of this type of reasoning is deductive; each condition leads to consequences, which act as conditions for subsequent rules. This allows the configurator to analyze each rule to determine if the condition has been met, and if it has, to assign a consequence based on the rule. The only complication occurs when consequences conflict and the configurator must conduct additional reasoning to find a feasible solution. Examples of rule-based configurators are [60–62].

A significant limitation to rule-based approaches involves the large number of rules required to accurately represent the possible configurations. For instance, a single entity or component within the possible thousands of components is likely to be governed by multiple rules. Complexity is composed of three aspects: size, coupling and solvability [49]. Here, coupling is of critical interest. Therefore, as the complexity of the product increases, both with the increase in the number of possible components and in the degree of coupling, the size of the rule database would increase drastically. This leads to two known challenges: the ability to maintain the rule database and the difficulty in ensuring the completeness of the rule database [3].

The first major challenge with rule-based reasoning is the ability of a rule database to accurately represent all of the possible configurations. This is due to the sheer volume of the database. The rule set for a complex system could have tens of thousands of rules

[3]; ensuring that each of these rules is accurate and that the rule set is complete is nearly impossible.

For the second challenge, any change to a single component within the rule database is likely to result in propagated change to multiple other components due to the interaction of the rules, which in turn could result in additional changes. Therefore, tracking the changes as they propagate through the system is necessary. This will be discussed further in the discussion of product configuration as change management in Section 4.2.4.

4.1.2 Case-based reasoning

Case-based reasoning uses preexisting product variants to assist in the development of future configurations. As such, the configuration knowledge database consists of the previous variants of a specific product and the information regarding each variant, such as requirements met or component configuration [3]. Researchers have proposed a number of steps for the case-based reasoning process [3,63,79,80], with the general approach as follows:

- Classify the cases already existing in the database
- Input the customer requirements for the new design problem
- Attempt to match the requirements to existing cases
- Adapt the identified cases to the stated customer requirements
- Evaluate the new cases for feasibility
- Store the newly created configurations in the database with the information regarding feasibility

Case-based reasoning is useful in situations where there are a limited number of possible configurations [81]. As adapting the existing cases to meet the customer requirements is necessary for case-based reasoning, the case set must span the possible space. Another advantage of this process is the prevention of the loss of historical knowledge, whether employee knowledge of existing products or information concerning previous failed attempts [81]. The retention of engineering knowledge is one of the major issues identified in a case study regarding the presence, or lack, of configuration management in the aerospace industry [64]. One method has been proposed for applying case-based reasoning to mass customization using a tree-structured bill of materials diagram [63]. Others look at the reuse of manufacturing information to assist in developing product platforms, a process similar to that of case-based reasoning, but focusing on the development of the initial cases as opposed to creating variants to meet new requirements [65,67]. By focusing on the creation of a complete initial case, one aims to make the adaption to new product variants a simpler process.

The reliance of case-based reasoning on existing feasible configurations is the primary disadvantage of the method. In order for case-based reasoning to be effective, the customer requirements must be able to be matched with a reasonably close approximation. If no such configuration exists, then either the new configuration must be completely adapted from nothing or a significant portion must be adapted, negating the benefits of using case-based reasoning. On the other hand, if the number of possible and existing configurations is too large, the opposite can occur, where the subset of returned matches is

too large to be easily managed or the amount of adaption is too great, due to the number of total components to be changed.

4.1.3 Model-based reasoning

Model-based reasoning relies on the assumption that each product can be effectively modeled as a system [3,82]. Within the system model are entities that can be decomposed into components and the interactions between the components. Numerous types of approaches have been developed from model-based reasoning [3]; however, only four types will be discussed here.

The first model-based approach is the use of description logics in configuration management. Description logics are a form of knowledge management that allows for the structured storage and reasoning of engineering information [83]. The three elements of description logics are individuals (objects in the domain), concepts (sets of individuals) and roles (relationships between individuals) [84]. Through the use of these elements, it is possible to create complex descriptions of product configurations and use reasoning tools to evaluate the feasibility and functionality of configurations. This aligns with one of the major advantages of description logics for configuration management: the ability to maintain consistency as the model is updated and new components are added to the system [83]. However, a potential limitation of description logics is in the level of specificity of the model. If the description logic system remains fairly general, then it is easy to maintain consistency, but the model may become too simplistic. On the other hand, a specific model may limit the ability of the system to work with complex products.

Another common model-based approach is resource-based configuration management. In the resource-based approach, the primary consideration is the interaction between the technical systems and their environments. Therefore, a specific configuration is only considered feasible if the resources, both concrete and abstract, that the components or environment require are equal to the resources supplied by either the environment or the system [75]. A major advantage of this method is the simplicity of configuring systems using this approach. The required resources of the environment are analyzed; a resource that is not currently balanced is selected and a component is added to the system that can remove the imbalance for the resource. This process continues until all of the resources in the system are balanced. This method works well where only functional characteristics must be considered, which is why it is used extensively in software configuration management, such as the Koala Component Model [85]. However, because of the inability of this approach to effectively consider component geometries, any configurations where there are structural or physical constraints are not ideal for use with this method.

Constraint-based reasoning is another example of an approach derived from model-based configuration management. In constraint-based reasoning, a component is defined by its properties and the interfaces for interacting with other components [77]. The constraints restrict the ways in which the components can be combined to form a configuration. Therefore the goal of constraint-based configuration management is to build a configuration of components that meet the constraint requirements based on a given set of requirements. When solving a constraint problem, there are two basic assumptions: the user knows the functional roles to be fulfilled and the user can identify at least one

component to fulfill each role [76]. Based on these assumptions, the user can use the set of functional roles to determine the required components and use the constraining relationships to identify feasible configurations for the design problem. A major disadvantage for this method is that many of the available configurators using constraint-based requires all possible constraint and functional relationships to be entered into the system prior to use, whether they or not will be used [3].

A final approach is the treatment of configuration management as a multi-objective optimization problem [86]. The basis for this approach is in resource-based reasoning in that the optimization technique uses product and component information that is similar to the resources used in that approach. However, in this method, equations are developed to model the requirements, while connection matrices are used to model the interactions between the available components. Then, through multi-objective optimization, the configuration(s) with the highest overall satisfaction for the objective function (a weighted equation of all of the requirements) is (are) selected for further review. Based on the similarity to resource-based reasoning, the advantages and disadvantages are comparable. An additional disadvantage is the large amount of data required to be input to run the optimization. However, the use of optimization techniques makes the method more adaptable to changes in the requirements and can factor in weighting functions for more important requirements.

4.1.4 Product configuration system maintenance

Little research has been done that focuses on managing the dynamic product information used in the configuration management process [87]. One of the challenges

identified with many of the previous configuration management methods is the difficulty in maintaining the product information as the number and variety of possible components changes over time due to changing customer requirements. A process-oriented approach was proposed to assist in solving this problem [87]:

1. Identify new product configuration knowledge
2. Create a configuration model change request
3. Evaluate the configuration model change request
4. Update the product configuration model (or cancel the request if not approved)

The proposed process was intended for the systematic implementation of new components into the set of possible configurations. It should be noted that the process is similar to the general engineering change process which consists of the following steps [8]:

1. Request for an engineering change
2. Development of possible solutions
3. Evaluate impacts of the change
4. Engineering change approval
5. Implementation
6. Review

Table 4.1 shows how the steps of these two processes coincide.

Table 4.1: Configuration management to change management mapping table

Configuration Management Step #	Change Management Step #
1	2
2	1
3	3
4	4, 5

Therefore, it is possible to consider the process of updating a product configuration as a variation of engineering change management. As such, some of the tools used to

manage engineering changes and their propagation can be similarly applied to assist in managing product configurations [12,31].

4.1.5 Configuration Management Case Studies in the Literature

As a result of the need for effective configuration management in industry, numerous researchers are conducting industry case studies to determine how companies are doing configuration management and how newly developed tools can be used to increase their capabilities. Table 4.2 provides a sampling of industry case studies on configuration management practices.

Table 4.2: Examples of other case-based research in configuration management

Reference	Industry	Tool Proposed	Reasoning	Purpose	Research Method
[63]	Machining equipment	Yes	C	V	II
[88]	Playground equipment	No	M	V	
[89]	Manufacturing equipment	No	C	E	IF, D
[90]	Cement factory	Yes	M	V	
[70]	Automotive	Yes	R	V	
[91]	Power transformer	No	C	E	IF, S
[92]	Electric bicycle	Yes	C	V	
[69]	Custom bicycle assembly	Yes	R	V	

Reasoning Types:
C: Case Based Reasoning; M: Model Based Reasoning; R: Rule Based Reasoning
Purpose:
E: Exploratory; V: Tool Validation; C: Case Based Reasoning; M: Model Based Reasoning; R: Rule Based Reasoning
Research Method:
IF: Interview (formal); II: Interview (informal); S: Software Analysis; D: Document Analysis

From Table 4.2 it is clear that configuration management research is being conducted across a variety of manufacturing domains, ranging from custom bicycle assembly to automotive manufacturing to the design and assembly of modular playground equipment. In the table, the third column (Tool Proposed) asks whether or not the purpose of the case study is to assist in proposing a new tool for configuration management. The Reasoning column specifies the type of reasoning identified through the case study. The fifth column (Purpose) asks the purpose of the case study, whether it is purely exploratory or if it is intended to validate a configuration management method. The final column describes the investigative methods used in the case study, if available. The blank cells in the table indicate a lack of available information regarding that column header.

4.2 Research Methods

When determining the type of research instrument or method to use to explore this objective, the following questions may be asked, as discussed in [93]:

1. Form of the research problem – is it exploratory or explanatory?
2. Does the researcher require control over the events?
3. Is the phenomenon under study a contemporary or a historical event?

Using these questions, Table 4.3 is constructed to determine whether the case study research method is a fit for this research objective.

Table 4.3: Justification for case study research method

Research Question	Question	Answer	Justification
RQ 2.1	Form of the research – explanatory of exploratory?	Explanatory	The research questions seeks to explain the configuration management process at the OEM
	Does the researcher require control over the events?	No	The goal is to learn the existing process. Therefore, no control is required.
	Is the phenomenon under study a contemporary or historical event?	Contemporary	The research is conducted regarding the active configuration management process.

When evaluating the type of research strategy to be used, the first question is the form of the research. Because the research question seeks to understand "how" the OEM conducted configuration management, the research is explanatory. Secondly, the goal of the research is to understand the current processes at the OEM, which means that the process should be studied in its present form, without any external controls in place by the researcher. Lastly, while it is possible to study the configuration management process using document analysis and interviews for a previous configuration change, better conclusions and a more in-depth analysis is able to be conducted by evaluating the configuration management process as a proposed configuration change is validated and implemented.

Based on the answers provided in Table 4.3, a case study research method is chosen to answer RQ 2.1. Additionally, case studies are often used when conducting design

research to understand the current process or how a design enabler can benefit the current process [94–100]. The following sections detail the specifics of the case study research.

4.3 Selection of the Case

The subject of the case study was chosen because of the extensive amount of configuration management conducted at this automotive OEM. Over the course of one year, the manufacturing facility typically will conduct up to three launches per vehicle, where four separate vehicles are manufactured at the plant, with one major launch occurring every year for each vehicle. A launch consists of the addition of new components, options or upgrades to the existing model line. A specific launch can introduce new paint colors, a software upgrade, or an entirely new feature for the vehicle. This means that the OEM has monthly launches with new options and/or packages.

Configuration management is especially important at this OEM in that the 600 possible options lead to more than 10^8 possible configurations for any given model, each of which must, ideally, be validated for feasibility. The OEM asserts that, essentially, each vehicle built in the plant is unique, resulting in over 300,000 unique vehicle configurations built. Therefore, in order to ensure that each vehicle is a feasible configuration, an effective configuration management system must be used.

A brief analysis of manufacturing and configuration management documents at the facility illustrated the large number of possible factors that affect each possible configuration. The total numbers of parts, options, and rules that comprise the current configuration management system at the facility are approximately 1500 parts and 600

available options per vehicle, requiring approximately 800 configuration rules. This results in over 10^8 possible interactions.

4.4 Data Collection

When conducting the case study, the primary means of data collection was through targeted interviews with employees primarily from the *Launch and Change Control* division of the manufacturing facility. At the OEM, *Launch and Change Control* is responsible for planning and verifying all of the scheduled launches at the facility. This includes determining which new components and options are ultimately included in a launch and evaluating potential configurations for functional and assembly feasibility. When conducting the interviews, targeted questions were asked that focused on the process and the systems/tools used in implementing configuration management, with follow-up interviews conducted to ensure accuracy of the information. The majority of the interviews were conducted in person; however, a few interviews were primarily conducted over teleconference due to unavailability of the required personnel as they were housed in the Germany design facility. A summary of the interviews conducted is shown in Table 4.4. The interviews were conducted by pairs from the research team to help increase objectivity through interviewer triangulation. A total of 24 hours of interviews were conducted, with summaries and transcripts generated to support the case study. These interviews were conducted over the course of three months (Spring 2014) and included on site interviews with associates at the US facility and video conference interviews with associates at the European design headquarters. Additional interviews were conducted as needed throughout the development of the configuration management.

Table 4.4: Case study interviews conducted

#	Position	Section	Time (hours)	Topics of Discussion
1	Section manager	Launch and Change Control	6	Configuration management and change processes
2	Launch and change coordinator	Launch and Change Control	15	Configuration management and change processes
3	Launch planning coordinator	Launch and Change Control	5	Launch planning and configuration change process
4	Release quality assurance specialist	Launch and Change Control	3	Vehicle ordering and configuration management systems
5	Launch and change coordinator	Launch and Change Control	3	Launch planning and parts release
6	Electronics specialist	Electrical/Electronics Validation	1	Configuration verification process
7	Product data manager	Product Data	2	Rule database and configuration change process
8	Product data manager	Special vehicle projects	1	Configuration change process

In addition to conducting interviews, a review of historical documents pertaining to the execution of configuration management was done. Document analysis is a case study tool for better understanding the specific systems in place at the case being studied [93]. The primary documents analyzed were the master rules document used to list all of the configuration rules for a specific vehicle (9.2Appendix C:) and the project change request form (9.2Appendix D:) used for updating the rule system.

The purpose behind this was to evaluate the systems used at the manufacturer. The classification system discussed in Section 4.1 assisted in classifying the configuration management method and identifying the associated challenges.

As a goal of the research was to identify the process used for managing configuration changes, ethnographic research was also conducted at the facility in Spartanburg, SC. Ethnographic research is the study of a culture or environment through close, direct observation [101]. The purpose of the ethnographic research was to obtain a first-hand view of how configuration management is conducted and how configuration changes are validated prior to approval and implementation. During this portion of the case study, meetings with the change control personnel were observed to better understand the following: the process by which changes are proposed, the status of ongoing changes is discussed, and the exact method for improving changes at the plant level. Additionally, the individual methods used by the change control personnel were observed as they attempted to understand and validate ongoing configuration changes.

In conducting the case study, the researcher expected to find a robust configuration management process in place that conformed to at least one of the existing approaches identified in Section 4.2. Specific evidence is sought to confirm this pattern and the associated counter patterns, according to best practices from case study research [102]. The findings of the case study are described in the following sections.

4.5 Results

4.5.1 Configuration management method

The foundation for the manufacturer's configuration management system is a rule database that contains the rules governing the possible options and packages for a specific vehicle or "project" in the parlance of the OEM. For each vehicle, the rule database also specifies which rules apply to which model codes. This is shown in the table below (Table 4.5):

Table 4.5: Example rules in the rule database

Opt	If-Part of rule	Then-part of rule	Standard-	Descriptio	KR01	KR02
Z	& + L8AAA	/ + S230A		0000017837	R	
Z	/ + L8AAA / + S(	/ + S866A		0000024151		
Z	& + L8AAA & + (	/ + S866A		0000012504	R	R
A	& + L8AAA	/ + S536A		0000011970	R	

Model codes (in the right-most columns) can represent the country destination for the vehicle specified or the engine type of the vehicle. The format for the rules in the database includes a condition and a resulting consequence. In the above example, the condition is designated by the "If-Part of the rule" (column 2) and the resulting consequence is designated by the "Then-Part of the rule" (column 3). Additional options are shown in the "Standard" column, which implies that a certain option is standard for the prescribed model codes. The far left column describes whether the rule involves an inclusion, Z, or exclusion, A. The values under the model codes dictates if the rule is active for the specified model code, where "blank" is not active and "R" is required. For example, the first rule states that for model KR01, if option L8AAA is present, then option S230A is required. For the last rule, if option L8AAA is present, then option S536A is unavailable

for model KR01. The number in the "Description" column is a unique identifier for each rule to enable quick referencing.

In this way, the process used at the OEM closely resembles the rule-based reasoning approach described in Section 4.1.1. As such, the system is subject to many of the limitations shared by other rule-based reasoning methods. The scope of the rule database (approximately 800 rules per vehicle) makes it difficult to ensure the accuracy of all of the rules and to ensure that the rule database covers the complete set of feasible configurations for each vehicle. This was corroborated in the interviews with the personnel at the OEM, who repeatedly mentioned that the size of the rule document made it extremely difficult to identify individual issues. Additionally, maintaining the rule database, with either updates or changes, is equally challenging due to the amount of possible change propagation and ensuring that all necessary changes have been made. This issue was documented in three of the interviews (#'s 1, 2, and 5) that were conducted with the personnel at the OEM. Current rule database maintenance practices will be discussed in the following section.

The configuration management process also includes the ordering, or specifying, of vehicles. Unlike many automotive OEMs, all vehicles produced at this manufacturer are specified by an external customer. When the customer specifies a vehicle, they have the ability to select all of the possible components or options that are available or feasible based on location and other specified options. The tool used for specifying the vehicles relies on the above rule database and ensures that a customer is not ordering a set of options that is not feasible. Once the vehicle has been ordered, a third system uses the specified options to identify the parts that are required for the vehicle. As all of the systems rely on

the rule database, it is imperative that all of the rules are accurate and complete. While not the focus of this research, an additional issue that was identified is the difficulty of ensuring that all of the varied systems communicate properly.

Throughout the interview process, an important theme that was discussed is the necessity of the correctness of the rule database and how the rules are verified. Much of the verification process is conducted purely based on the individual experience levels of the employees that are familiar with specific aspects of the vehicle. For example, a specialist from the electronics and electrical validation section said that much of the verification was based on his experience with different vehicle systems and he knows to look more closely at certain areas because they had been troublesome in the past. For instance, windshields are often difficult to configure due to the large number of available parts and their reliance on the presence or lack of over 10 different options. As a result, one of the interviewees (# 2) stated that he would give special consideration to changes involving windshields because of the high number of past issues. This view was similarly expressed by all those involved with verifying the rules in the database.

Further, it is not uncommon for an error in the rule database to be identified only when a vehicle is being assembled and either parts are missing or there are complications that prevent two different options from being assembled on the same vehicle. For example, one interviewee (# 2) described to the research team an instance where a vehicle had been ordered in such a way that no windshield part number was ordered for installation on the vehicle. Thus, the current approach based solely on experience in identifying possible conflicts is not sufficient.

The primary limitation identified is that the manufacturer does not have a coherent method for ensuring the accuracy and completeness of the entire rule set outside of manually verifying every rule in the database. However, manual verification is not feasible due to the scope of the rule set. There are approximately 1,500 parts in a typical bill of materials for the vehicle, with nearly 10 variants per component. Additionally, there are a half dozen models with dozens of variants and scores of options in configuring these components. Ultimately, there are appromxiamtely 10^8 possible configurations that must be checked for feasibility every three months.

4.5.2 Configuration change management process

Because managing changes to the rule database is the most difficult aspect of this approach to configuration management according to the interviewees, as well as the research discussed in Section 4.2.1, much of this research has been focused on how the automotive OEM maintains the rule set. As stated previously, the manufacturer in question conducts up to three launches per year per vehicle. Each of these launches contains numerous changes to the possible vehicle configurations. In the launch process, the first step is to determine the intent of the new launch content. The content for each launch is determined by a series of workgroups that consist of personnel from *Launch and Change Control* and representatives from the other sections. This can include personnel from marketing, product data management, and the technical sections (electrical, body, power train, and systems). Once the changes for a given launch is set, the information for updated options and components are entered into a variant planning tool to assist the launch planner in configuring the test cars that will be assembled prior to execution of the launch. The

variant planning tool also identifies the number of test cars that need to be built in order to effectively generate a sample that is representative of the entire set of new possible configurations resulting from the changes in the launch.

Concurrent to the launch process is the maintenance of the rule database to reflect the changes to the possible configurations as a result of the launch. The configuration change management process is shown in Figure 4.1.

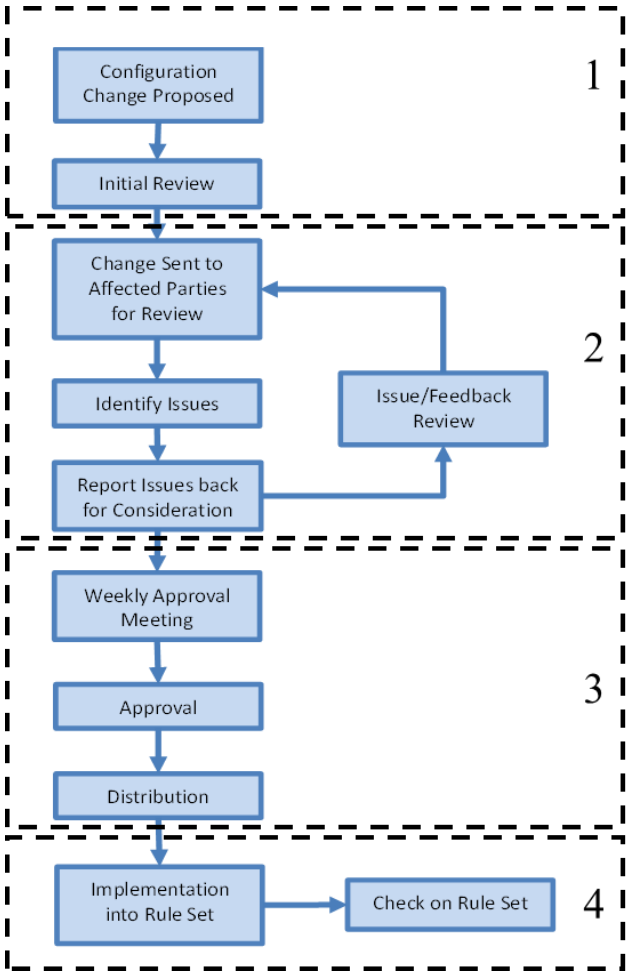

Figure 4.1: Configuration change management process for OEM

This process consists of the following basic steps:

1. The configuration change is proposed, typically by a member of the technical sections (electrical, body, power train, and systems)
2. After an initial review period, the change is distributed for further review by any groups that may be affected by the change. This can include Product Data Management, Launch and Change Control, and any additional affected technical sections. Any issues identified during this step are brought back to the working group for further action and review.
3. Once the review process is complete, the configuration change is discussed at a weekly change approval meeting. If approved, the change is sent out for distribution to any affected parties. If disapproved, the change goes back for additional review.
4. The product data management team receives the configuration change and manually inputs any new rules and options/packages into the rule database.

This process can take anywhere from a couple days to three weeks, though the typical situation is between two and three weeks, according to interviewee # 7. Multiple situations were identified where a product change was rushed at the last minute and the reviewers were not given sufficient time to conduct a full review of the change, which normally takes about a week, but can take up to or greater than a month depending on the complexity of the change. It should again be noted that the verification process is often based primarily on the individual experience of the personnel reviewing the changes. For instance, during one interview, the interviewee (# 2) mentioned that, due to his extensive experience with vehicle windshields, he will often review any changes that include options or rules concerning windshields. The primary issue with a high dependency on experiential knowledge is maintaining that knowledge despite personnel turnover.

The primary disadvantage with the current configuration change approach is the inability to see how new rules will affect existing rules. This includes ensuring that the

proper changes are implemented as a result of the new rules being implemented. One example of a change not propagating properly through the rule database that was identified during the case study involved a change made based on an error during assembly. It was identified on the assembly line that an exhaust system used with the diesel versions of a particular model was not compatible with a sports package due to a geometric constraint with the included fog lights. The change was made as necessary based on the issue. However, months later, it was decided that the fog lights should be added as a separate option. The same problem was again identified during production between the exhaust system and the fog lights because the rule regarding the geometric constraint was not carried over from the sports package to the fog lights.

4.5.3 Historical problems

Numerous problems that stemmed from the use of the current configuration management system are identified from the case study. Two primary problems are the absence of an essential component during assembly (in the given example, a windshield was not assigned to the vehicle) and rule constraints not being correctly translated during the creation of a new ruleset (the fog light issue discussed above). In the first problem, a vehicle was being assembled for which there was no windshield. This can occur because parts are ordered based on the combination of options present for a given vehicle. If the selected options result in a configuration that is not feasible (or for which there is no applicable windshield), then there is an error in the system; the configuration management rule database should prevent the combination of options that are not possible.

In another situation, also involving windshields, a new rule was created (and approved) which artificially limited the possible windshield options for a given model. The added rule disallowed the selection of the option for an anti-glare strip on the windshield for certain models. However, due to limitations with the parts, this meant that the only allowable configuration for customers desiring the anti-glare strip would also be required to purchase the heads-up display option. There is no technical reason for the two options to require the presence of the other option; therefore this is another example of a failure in the current configuration management system to properly configure products.

In a third situation, the OEM is considering a change in the warning advisory labels that are found on the passenger sun visors regarding child restraint. The issue is that some of the visors come from the supplier with the labels already attached, whereas other labels are affixed during assembly. Because the current configuration management system does not include part interactions directly with the other components (rules, options, and packages), the OEM has encountered a series of problems in making the change to the new advisory labels. One issue is that certain options include sun visors come with the label from the supplier, while others have the label affixed during assembly. The difficulty lies in ensuring that any changes to the label are made to both types of options.

Based on the findings of the case study, an improved process with design enabler support is recommended to assist in configuration management at the OEM. A discussion of the conclusions made by the researcher are discussed in the following section.

4.6 Conclusions

The research objective for this chapter is to understand how an OEM conducts configuration change management. This research objective is supported through two sub-questions, which are discussed below.

The first sub-question is: What is the state-of-the-art for configuration management? Answering this question helps to provide a knowledge base when evaluating the configuration management practices at an OEM and can be used to help categorize the OEM's methods. The sub-question was answered through a literature review of current configuration management practice. The literature review consists of a review of configuration management and its importance in modern manufacturing, followed by a review of existing tools and methods used in configuration management. Through the literature review, a classification scheme for configuration management methods was identified, with the capabilities and shortcomings or each category being discussed.

With a more complete understanding of configuration management practice in mind, the following question can now be asked: How does a major automotive OEM conduct configuration change management? To answer this question, a case study was conducted at an automotive OEM facility in Spartanburg, SC. The case study primarily consisted of both exploratory and targeted interviews with personnel from the *Launch and Change Control* group at the OEM. In addition, document analysis and ethnographic research was conducted to help understand how the company conducts configuration management. It was identified that the company uses a rule-based configuration management method. In addition, many of the shortcomings of the existing method at the

OEM matched the shortcomings for rule-based methods identified during the literature review.

Through the course of the case study, a need was identified for a support tool to assist in the configuration management process, to include managing the effects of proposed configuration changes. In order to address the identified issues, the following requirements are proposed:

- Able to easily visualize the interactions between configuration components (including parts) to make it easier for personnel to understand possible propagation pathways
- Able to highlight specific areas of interest to assist in simplifying the rule database
- Able to check for errors in the existing rule database to ensure the validity of the ruleset
- Able to preview how proposed configuration changes would affect the existing rule database to prevent against the creation of impossible configurations

Table 4.6: Visualization requirements and related issues to address

Requirement	Issue
Visualize interactions	Errors resulting from unexpected change propagation between options
Highlight specific areas	Ruleset is too complex to understand in its entirety
Check for errors in database	Errors in configuration result are not found until assembly is attempted
Preview changes	Management of rule database is difficult due to scope of assessing every possible consequence of a change

These requirements were identified through the interviews to address specific issues experienced by the automotive OEM in their current configuration management

process (shown in Table 4.6). Most of the requirements focus on the visualization aspect of configuration management. The proposed development of a visualization method for configuration management will be further discussed as next steps in Chapter Five.

4.7 Dissertation Roadmap

Chapter Four presented the methods and results of the case study on configuration management at a major automotive OEM, concluding with a series of recommendations regarding improvements to the current configuration management process. The next chapter (Chapter Five) builds on the conclusions from the previous chapter by proposing an improved method for configuration management with designer enabler support. The progress of this dissertation is shown in Figure 4.2 in which the completed portion is highlighted in green.

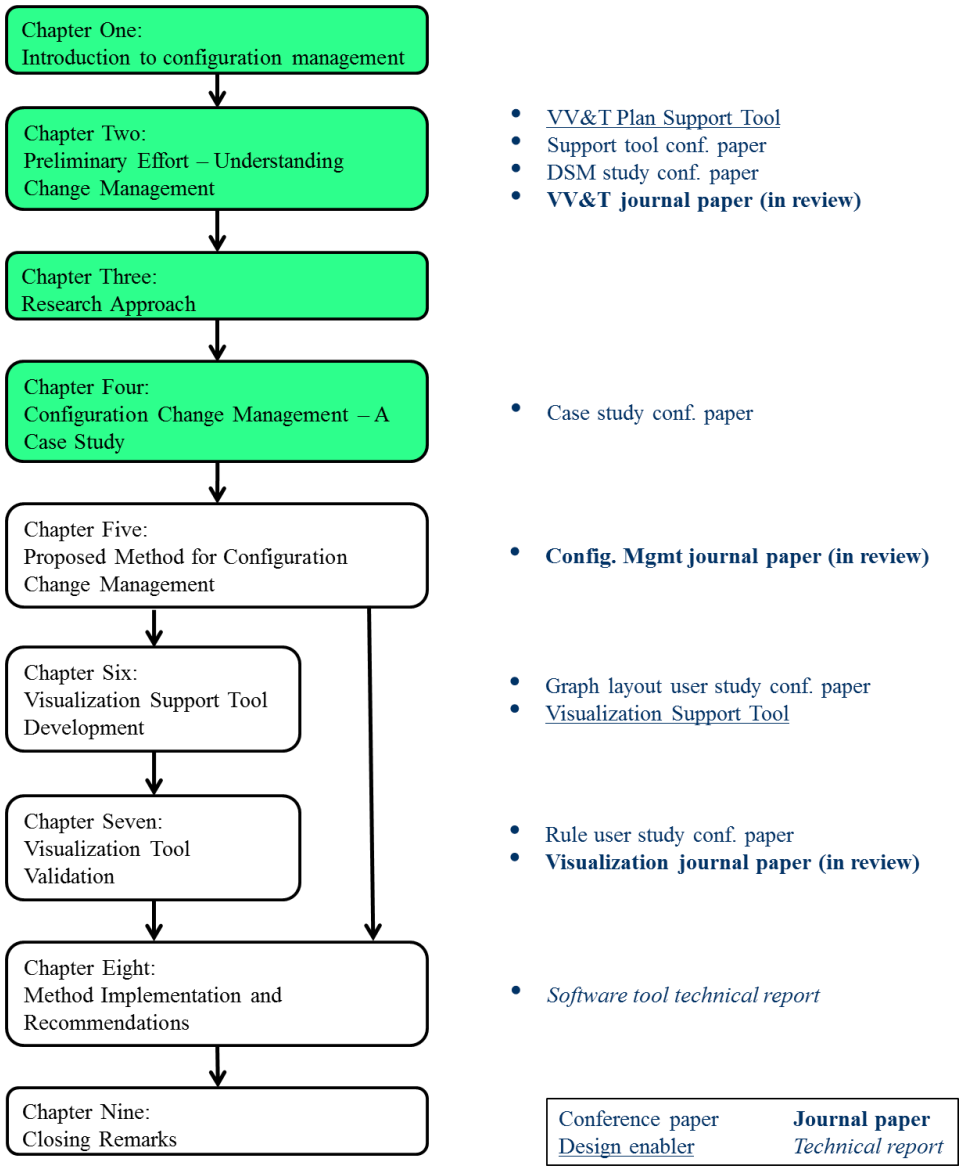

Figure 4.2: Dissertation roadmap

CHAPTER FIVE: IMPROVED METHOD FOR CONFIGURATION CHANGE MANAGEMENT

The purpose of the research presented in this chapter is to develop an improved method for configuration management with design enabler support. The developed approach enables engineers in validating the configuration management system when implementing configuration changes. This is done through (1) identifying possible change propagation pathways when evaluating configuration changes, (2) aiding in identification of errors in the current configuration management ruleset, and (3) determining whether a proposed change will result in conflicts with existing rules. The requirements of the configuration management support tool are established in the case study and described in Table 4.6.

5.1 Proposed Process

In order to address the specified requirements, a series of support tools are developed to enable the configuration and configuration change management processes. The four tools are as follows and are described in more detail below: (1) interaction identification, (2) visualization and interaction (*V&I*), (3) change complexity analysis (*CCA*), and (4) algorithmic validation (*AV*). Figure 5.1 shows how the proposed tools would fit into the current configuration change management process. For the purposes of implementing the tools, a simplified model is used.

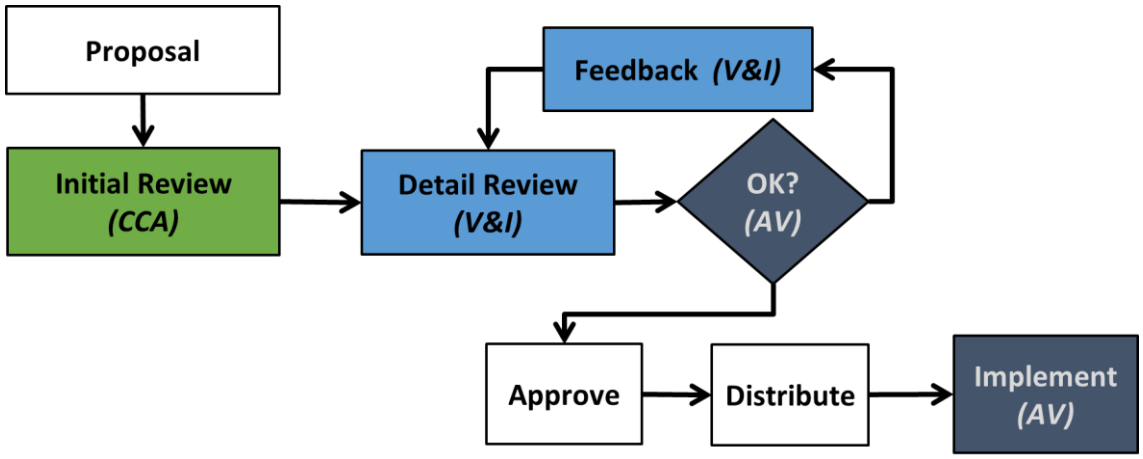

Figure 5.1: Simplified process model with proposed tools

As shown above, after a change is proposed, an initial review period would occur, during which a complexity analysis can be conducted. The purpose of the complexity analysis is to determine an estimate for the difficulty in validating the proposed change. By determining the difficulty to validate the change, it is possible to cancel a proposed change that would be overly difficult to validate but is not necessary. For a complicated change that must be implemented, it allows the change personnel to properly plan for the amount of time/effort required to validate the change. The complexity analysis support tool is described in greater detail in Section 5.4.

If a proposed change is moved forward to the detailed review period, much of the current validation is done through experiential knowledge, guessing how the specified options will affect other options and other parts. The use of a visualization tool can greatly increase the user's ability to understand and explore the interactions between the affected options and parts. Using the visualization within the proposed method is discussed further in Section 5.3. As the use of data visualization for configuration management is a major

contribution by the author, an in-depth discussion on data visualization and the development and implementation of the graph visualization tool will be discussed in Chapter Six.

Before the change is approved, an algorithmic validation should be done to ensure that there are no conflicts that would occur as a result of implementing the change. The algorithmic validation uses satisfiability criteria to ensure that configurations can be built based on the current rule set and that there are no situations where two rules could be in conflict with each other. After final approval and distribution, the algorithmic validation should be conducted a final time prior to implementation to ensure that the change is being implemented correctly and that no changes are made to the rule database that would cause any conflicts. The use of algorithmic validation will be discussed in greater detail in Section 5.5.

5.2 Interaction Identification

To facilitate the implementation of the other tools, it is necessary to have a method for mapping the interactions between the options/parts/packages and to filter the results to only provide the interactions of interest for the specified change. The tool must provide all interactions between the different types of change components (options/parts/packages), including rules as specified in the part and option rule databases, and any options included in functional groups. In order to facilitate this, the tool should be able to access the option and part databases that govern how vehicles are configured and specified for parts. If the database is not available, then the tool must be able to convert the available report

documents to obtain the relationships between the possible change components. An example database model for the relationships discussed above is shown in Figure 5.2.

The primary elements of the database include Models, Options, Parts, and Rules. These are the elements that form the foundation of the configuration management system at the OEM. Release lines are similar to rules in that they govern whether a part is needed for a specific configuration, but apply only to parts instead of options. In order to show how all of these elements interact, the following tables are created: ReleaselineModels, OptionModels, and RulesModels. FClasses are functional groupings of options that carry an exclusive relationship. If the FClass is present in a configuration, one and only one option from that FClass must be present in the configuration.

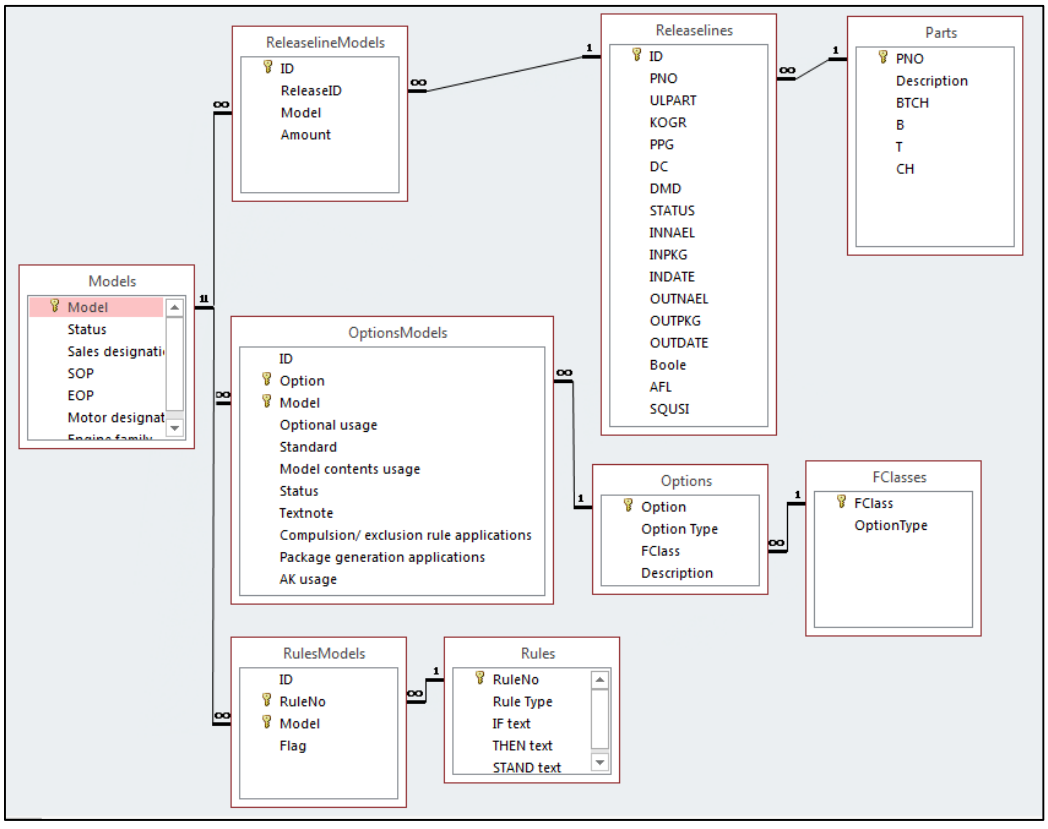

Figure 5.2: ER diagram for integrated database

Once the required rules are input into the tool, the tool should parse the rules into interactions, where any change components in a single rule are considered to have a first order interaction. In addition, the tool should provide the user with the option of selecting a maximum order of interaction for the outputs, as previous research has shown the importance of higher order interactions, and thus the tool should be able to support this.

In order to use the tool, the user inputs the vehicle model and the options or parts of interest from dropdown menus and enters the desired order of interaction for consideration. The output from the interaction identification tool should be a list of all specified and affected options up to the desired order of interaction and lists the other options with which each interacts, and how the options are related. Additional data that may be added is the order of interaction at which the interaction takes place.

5.3 Visualization and Interaction (*V&I*)

Previous research has shown the benefits of visualizing data to assist in understanding and exploring it. When evaluating a proposed change, therefore, it can be useful to use a visualization support tool to graphically depict the affected options and rules. The proposed visualization tool would use the outputs from the interaction identification tool to produce a node-link graph to show the options/parts as nodes with the rules or interactions as edges. An example of a node-link graph for a specific change is shown below in Figure 5.3.

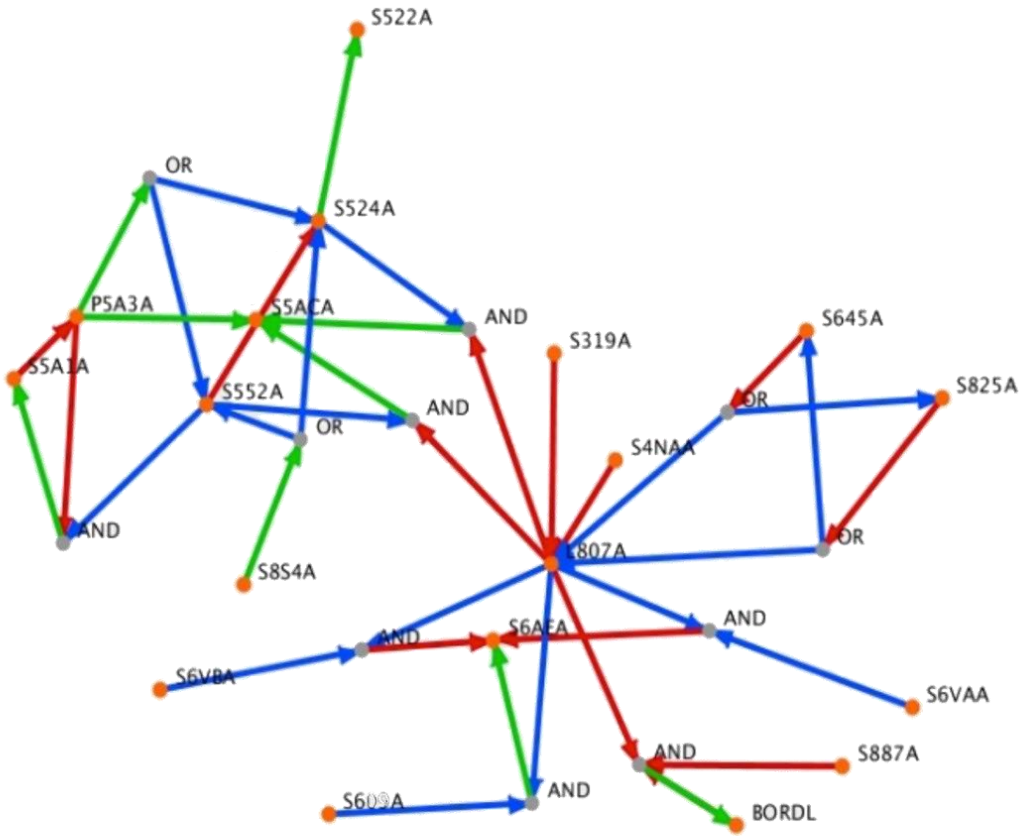

Figure 5.3: Example graph for a proposed change

Another essential component for the visualization tool is the ability to interact with the graph. Therefore, the tool must be implemented in such a way as to be dynamic, rather than simply a static graph viewer. The graph interaction increases the user's ability to explore the data and to better understand the interactions between the components. It is recommended that the visualization tool should facilitate the following interactions:

- Addition/subtraction of nodes to/from the graph
- Relocating nodes to better cluster option/part groups
- Addition/subtraction of rules/interactions between nodes

- Highlighting specific nodes to view the potential propagation pathways
- A method for algorithmically arranging the graph (i.e. force-directed layout)

In addition, the visualization tool should provide the capabilities of outputting a static graph image for reference at a later time and the resulting rule set and/or interaction list that would result from any changes made to the graph by the user. This can aid in automated rule creation based on any knowledge gained from exploring the graph. The development and implementation of the visualization tool will be further discussed in Chapter Six.

5.4 Complexity Analysis (*CCA*)

The use of complexity metrics has been shown to be useful in evaluating change propagation within a system. As such, a complexity analysis tool is recommended to determine the difficulty of a proposed change through identifying the potential change propagation that could result from the change.

5.4.1 Use of Complexity Metrics

Previous research has shown that complexity metrics can be used in prediction. One such example is the use of 29 different graph theory metrics to predict product assembly time [47,54,103]. In the research, the authors used the physical interactions between product parts as the network. By using the resulting complexity metrics to train a neural network, the authors were able to accurately predict additional product assembly times. In a related study, the same complexity metrics were also used to successfully aid in predicting a product's market price [104]. Research in software design has shown that

complexity metrics can also be used to successfully predict errors or bugs in software [105,106]. These examples show that complexity metrics have successfully been used in multiple instances for prediction purposes and should be further explored for this research.

5.4.2 Data Organization and Source

In order to conduct the complexity analysis, one set of inputs is required: the potential change components (vehicle options/packages/parts) and the relationships between them. Because the relationship information required for the complexity analysis includes the distinct components, a single input file can be used that has a list of binary relationships between components. This input is created through a data parsing tool which translates the option and part rules into conjunctive normal form (CNF). The following subsections describe the inputs in more depth.

5.4.2.1 Components

The components, or graph nodes, consist of the vehicle options, parts, and packages that the user is interested in changing or that can be affected by change propagation from the changed components. However, the complexity analysis is only concerned with the nodes and the connections between them, not any of the information regarding the nodes, as was seen in the graph visualization tool. Therefore, the information provided by the edge graph input file, which contains unique numerical identifiers for each distinct node, is sufficient input for this data type.

5.4.2.2 Component Relationships

The relationships, or edges, between the components consist of the rules that govern how the different components interact. These relationships include all of the rules as specified in the option and part rule databases, as well as option functional group information. It is also possible to use new rules as created in the conflict detection tool as relationships. Because the complexity analysis is only concerned with the connections between components and not the types of relationships, only the source and target of the relationship is needed to conduct the analysis. As a result, it is possible to use the same edge input files as for the graph visualization tool.

The source node of the edge refers to the "If" portion of the rule in a binary rule, while the target node refers to the "Then" portion of the rule. In more complex rules (non-binary), a more comprehensive grammar must be used and is discussed in 6.4.2.1. The edge type represents the type of relationship between the nodes. Three different types of relationships are currently used: inclusive, exclusive, and multiple-inclusive relationships. An inclusive relationship means that the source requires the target to also be present. Similarly, exclusive requires that the target must not be present. The multiple-inclusive relationship is used in conjunction with "OR" and "AND" nodes to help delineate that the relationship is not binary. Multiple-exclusive could also be represented separately, but has not been used in the current implementation. An example of an edge input file is shown in Figure 5.4.

ID	Source	Target	Type
1	1	2	3
2	3	2	3
3	1	4	1
4	6	7	2
5	6	8	2
6	5	6	3
7	8	9	2
8	10	9	2
9	11	12	2
10	11	13	2
11	11	14	2
12	9	11	3
13	8	15	2
14	14	15	2
15	15	10	3
16	16	2	3
17	18	7	2
18	18	8	2

Figure 5.4: Example graph edge input file

5.4.3 Methods

The following subsections describe the complexity metrics used in the complexity analysis.

5.4.3.1 Size and Order Calculation

When analyzing a system or graph, the most basic complexity metrics are size and order. The size of the graph is the number of nodes in the graph. The order is the number of interactions between them. While these complexity metrics may seem overly simplified, an analysis of 29 separate complexity metrics showed that an approximation for the complete set of metrics could be found by using the size and order metrics, which are simpler to calculate and easier to understand. The following subsection will discuss the other available complexity metrics.

Using the example input file shown in Figure 5.4 the size of the system is the number of distinct node ID numbers, which would be 17. The order of the system is found by identifying the number of relationships in the edge list, which would be 18.

5.4.3.2 Other Potential Complexity Metrics

In some instances, it may be beneficial to use a broader group of complexity metrics for analysis. While the size and order metrics can assist in identifying a general level of difficulty to validate a change, using the full suite of metrics, in conjunction with a trained neural net, could predict the level of difficulty or resources required for validation more accurately. An example of using complexity metrics for prediction can be found in [47]. However, the focus of this technical report is on a tool used to provide the complexity metrics for user analysis and while the other complexity metrics can be useful in the analysis, the prediction methods are outside the scope of this report. A discussion of additional metrics that have been successfully used by the research group can be found in [107].

5.4.4 Implementation

This section describes the methods used to transform source data into a representation that is easy to understand. Because this tool considers the potential level of change propagation as a result of a configuration change, it is necessary to calculate the complexity metrics at the first order of interaction (the change components and those they directly interact with) and the second order of interaction (this includes any components that interact with the affected components at the first order of interaction). Previous

research has shown that beyond the second order of interaction, the number of components increases to near saturation and is not likely to provide additional utility [56]. Additionally, the complexity metrics will vary significantly between different vehicle models. As such, it is necessary to calculate the metrics for all applicable models that are affected by the change. Once the metrics have been calculated, the tool need only to output the data in a representation that is easy for the user to understand. Recommendations for how the resulting data can best be represented can be found in 6.5.1.

5.4.4.1 Data Representation

The purpose of the data representation is to assist the user in predicting the difficulty in validating a proposed configuration change. In this tool, the measure used to determine the difficulty is the amount of potential change propagation as a result of a change. This is represented by the increase in complexity from the first order of interaction to the second order of interaction. Therefore, the goal of the data representation should be to increase the user's ability to quickly see how the complexity increases for each vehicle model. In order to accomplish this, the researcher recommends a color-coded "flag" that corresponds to the amount of complexity increase for each model. The amount of change is based on the second order complexity metrics divided by the first order complexity metric. Therefore, if the size increased from 13 to 29, the increase would be a factor of 2.2. In the proposed color scheme, a green "flag" represents little or no change propagation (a factor of < 1.1). Yellow represents a small amount of propagation (factor of > 1.1 and < 2.5). Orange is a moderate amount of propagation (factor of > 2.5 and < 5.5). Red is a significant amount of change propagation (factor of > 5.5). These factors are for the size

and order metrics and were identified based on empirical data. It may be useful to modify these values based on company practice for specific complexity metrics. An example output for a larger set of complexity metrics is shown in Figure 5.5

	Metric	Size	Order	DOF	Conn	SP Sum	SP Max	SP mean	FR Sum	FR Max
KR01	1	13	18	18	36	374	4	2.3974	326	5
	2	29	40	40	80	2666	6	3.3	1298	10
	Flag	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
KR02	1	13	19	19	38	370	4	2.3718	342	5
	2	54	76	76	152	7554	6	2.6	3966	42
	Flag	Orange	Orange	Orange	Orange	Orange	Yellow	Green	Orange	Red
KR03	1	12	16	16	32	334	4	2.5303	240	5
	2	12	16	16	32	334	4	2.5303	240	5
	Flag	Green	Green	Green	Green	Green	Green	Green	Green	Green
KR23	1	12	16	16	32	334	4	2.5303	240	5
	2	12	16	16	32	334	4	2.5303	240	5
	Flag	Green	Green	Green	Green	Green	Green	Green	Green	Green
KR61	1	13	18	18	36	374	4	2.3974	326	5
	2	53	86	86	172	8874	6	3.2	4676	27
	Flag	Orange	Orange	Orange	Orange	Orange	Yellow	Yellow	Orange	Orange
KR62	1	17	25	25	50	690	4	2.5368	516	7
	2	260	400	400	800	265270	10	0	89570	40
	Flag	Red	Red	Red	Red	Red	Orange	Green	Red	Red
KR63	1	12	16	16	32	334	4	2.5303	240	5
	2	12	16	16	32	334	4	2.5303	240	5
	Flag	Green	Green	Green	Green	Green	Green	Green	Green	Green

Figure 5.5: Example data representation for the complexity analysis tool

In the figure, the vehicle models are shown in the left-hand column, with the complexity metrics along the top. For each vehicle model, the first and second order metrics are provided, along with the resulting flag for each metric. In the above example, KR62 shows a significant amount of potential change propagation due to the proposed change and is likely to require more resources for validation, whereas the US models (KR03, KR23, KR63) show no propagation and are likely to be easier to validate. The example representation provides maximum information for analysis. A less complicated,

and potentially easier to read representation could be used, such as Figure 5.6 or Figure 5.7.

	Size	Order
KR01	Yellow	Yellow
KR02	Orange	Orange
KR03	Green	Green
KR23	Green	Green
KR61	Orange	Orange
KR62	Red	Red
KR63	Green	Green

Figure 5.6: Simpler data representation for complexity analysis

KR01	KR02	KR03	KR23	KR61	KR62	KR63

Figure 5.7: Simplest data representation for complexity analysis

Each of the above representations has potential advantages and disadvantages due to the simplicity to read and amount of information provided.

5.5 Algorithmic Validation (*AV*)

In addition to exploration and complexity analysis, it may be necessary to determine whether there are any conflicts or impossible configurations that may result from the implementation of a proposed change. In other applications, a satisfiability solver has been used to use a set of constraints to determine whether any conflicts exist. It is recommended that a satisfiability tool be used with the existing rule database to determine whether or not any conflicts exist. A discussion of algorithmic validation is included for completeness as part of the developed method. While the design and use of this tool was done by the

researcher, its implementation was developed by a research project partner. A complete discussion of the algorithmic validation methods can be found in [108].

5.5.1 Satisfiability

First-order Boolean logic provides techniques for reasoning about logical expressions. These expressions are constructed as a series of operators and literals, assembled according to a formal grammar. Literals are Boolean objects, which may take values of either TRUE or FALSE. Within the case of configuration management, objects like options, parts, etc. are literals, as they are either present on a vehicle instance (TRUE) or not (FALSE). Operators are functions like OR, AND, and NOT, used to conjoin literals into expressions that represent system constraints.

If all literals are assigned a truth value, then a Boolean expression containing them may be resolved to either true or false. If, on the other hand, some or all of the literals are unassigned, then the truth of the expression may be unresolved. Indeed, within configuration management literals do not typically take explicit values, as it is the discretion of the customer to choose which options, etc. are chosen for the vehicle. The task for configuration management is to manage the set of system constraints, such that all valid, user-selectable configurations result in correctly specified, buildable vehicles. When working with Boolean expressions that contain unspecified literals, a pertinent question may be "Is there any set of true/false values for literals that results in the expression resolving to true?" This question is known as the Boolean satisfiability problem (SAT). SAT approaches have been successfully applied in non-automotive sectors, for problems

ranging from software configuration validation, electronic circuit design validation, and mathematical proof-checking.

5.5.2 Applications

The algorithmic validation tool will use the six question types discussed previously (rule conflict, object activation, part family allocation, part family matching, antecedent relationships, and implicit relationships) to validate each proposed change. When applying the support tool, the user specifies the type of analysis to conduct from the above question types. Based on the information identified in the case study, the following types of questions should be supported:

1. "Rule conflict." Is there a subset of two or more VRM rules such that no possible configuration may satisfy them?
2. "Object activation." Can all options/parts/etc. that are declared as being available for selection actually be selected?
3. "Antecedent satisfiability." Are there any rules for which the antecedent (IF-part) of the rule cannot be satisfied? If so, then the effects of the rule are inconsequential, as the rule is never active.
4. "Implicit relationships." Are there any binary inclusion/exclusion object relationships that are implicitly enforced, through the collected effects of explicit constraints?
5. "Part family allocation." For a given family of alternative parts (e.g. all windshields), will one (and only one) of the parts be allocated for every configuration?
6. "Part family matching." Consider a suite of several part families, some of which are intended to match to others for geometry or color reasons. Are the rules correctly implemented, or is there a configuration that mismatches parts?

Based on the question type selected, the user is required to input additional data into the rule set. For example, for part family questions, the user would be required to enter

the part family of interest and the members of the part family. Based on the additional input, the satisfiability engine is able to determine whether multiple parts from the family can exist in a single, valid configuration. It is also possible for the engine to evaluate the existing rule set for conflicts without any additional inputs or changes to the rule database. This can be useful not only in evaluating changes, but also in validating the current system. The specifics and applications of each use case listed above are described in the following sections.

5.5.2.1 Rule conflict

Rule conflict is the most basic level of conflict that should be considered. A rule conflict implies that two rules in the database cannot be satisfied concurrently. An example of this would be where option A requires the presence of option B; option B requires the presence of option C; option C requires the absence of option A. While it is clear that the three rules cannot coincide, the satisfiability solver may not return that the ruleset is invalid. This is due to the fact that the absence of all three options is a viable configuration with the above ruleset. The major downfall of this method is that any viable configuration will result in a valid ruleset. One method for minimizing the impact of this issue is to implement the rule conflict check alongside the object activation check discussed in the following section. This check supports question 1 from the list above.

5.5.2.2 Object activation

Object activation tests to ensure a specific option, package or part is able to be included in a valid configuration. This test is conducted iteratively for all of the objects in

the ruleset to check for disabled objects. An object is considered disabled if it is not valid for any configuration. This can occur as a result of legacy options or packages that are no longer in use, but were mistakenly left in the rule database. It is also possible that a configuration change may result in disabling an object. This check supports question 2 from the list above.

Another aspect of the object activation test is to determine if any rules are disabled. In this instance, the solver is checking to see whether the "if" portion of the rule, or antecedent, is capable of being activated (is part of a valid configuration). This determines whether or not any of the rules are disabled. This version of the test can be combined with the rule conflict test to ensure that each rule is considered when determining whether there is a conflict. This check supports question 3 from the list above.

5.5.2.3 Implicit relationships

In any complex system, implicit relationships between two entities will exist. An implicit relationship is a relationship between two entities that is not stated, but still exists. For instance, given the following situation: option A requires option B and option B requires option C; an implicit relationship exists: option A requires option C. While it is possible to manually identify these relationships by tracing the interactions between objects throughout the ruleset, the use of the satisfiability solver simplifies the process. Given two objects, the solver is able to quickly determine whether an implicit relationship exists between them. This check supports question 4 from the list above.

5.5.2.4 Part families

While the object activation test checks to ensure that all parts are active, it is useful to ensure that two different variants of the same part are not able to be in the same configuration. For example, a car can be assembled with many different wheel options. However, the configuration rules should result in only a single wheel variant being called. These groupings of part variants are referred to as part families. Within a part family, a "1 and only 1" relationship exists, where only a single variant should be called from the part family for a given configuration. Therefore, the solver checks that a part from the family is valid and that only one part from the family is valid. This check supports question 5 from the list above.

Another application of part families is that certain parts or types of parts are designed to fit with other parts. For instance, wheels of a certain diameter and width are designed to fit with a tire with a matching diameter and width. An example that was discussed during the case study was the fitting of exhaust tips and bumpers. At the OEM, exhaust tips can either be round or square and must fit through a similarly shaped hole in the bumper. When using the satisfiability solver, part families can be created for round tips and the square tips, as well as for the round-hole bumpers and square-hole bumpers. The solver can then check to ensure that only parts are called where the correct fit is achieved. This check supports question 6 from the list above.

5.6 Conclusions

The third research objective is the development of an improved method for configuration change management. Based on the findings of the case study, a configuration

change management method is proposed, along with design enabler support. The design enablers that are integrated into the overall method include interaction evaluation to help identify the relationships between potential change components, complexity analysis to predict the difficulty of a proposed change and assist in determining the vehicle models that will require the most effort, graph visualization to understand how the proposed change can propagate through the system, and algorithmic validation to check for conflicts or other user-defined queries about the changed system. While this chapter was focused on the over research objective, the sub-questions that help to achieve this objective are presented in the following chapters. The use of graph visualization to assist in configuration management is discussed in greater detail in Chapter Six. Chapter Seven focuses on the validation of the graph visualization design enabler, while the validation of the entire method is presented in Chapter Eight.

5.7 Dissertation Roadmap

Chapter Five presented proposed a method for configuration management and provided the foundation for four design enablers to support the proposed method. As three of the design enablers (interaction identification, algorithmic validation, and complexity analysis) are not the primary contribution of this research, only the visualization support tool will be discussed in detail in the following chapter (Chapter Six). The progress of this dissertation is shown in Figure 5.8 in which the completed portion is highlighted in green.

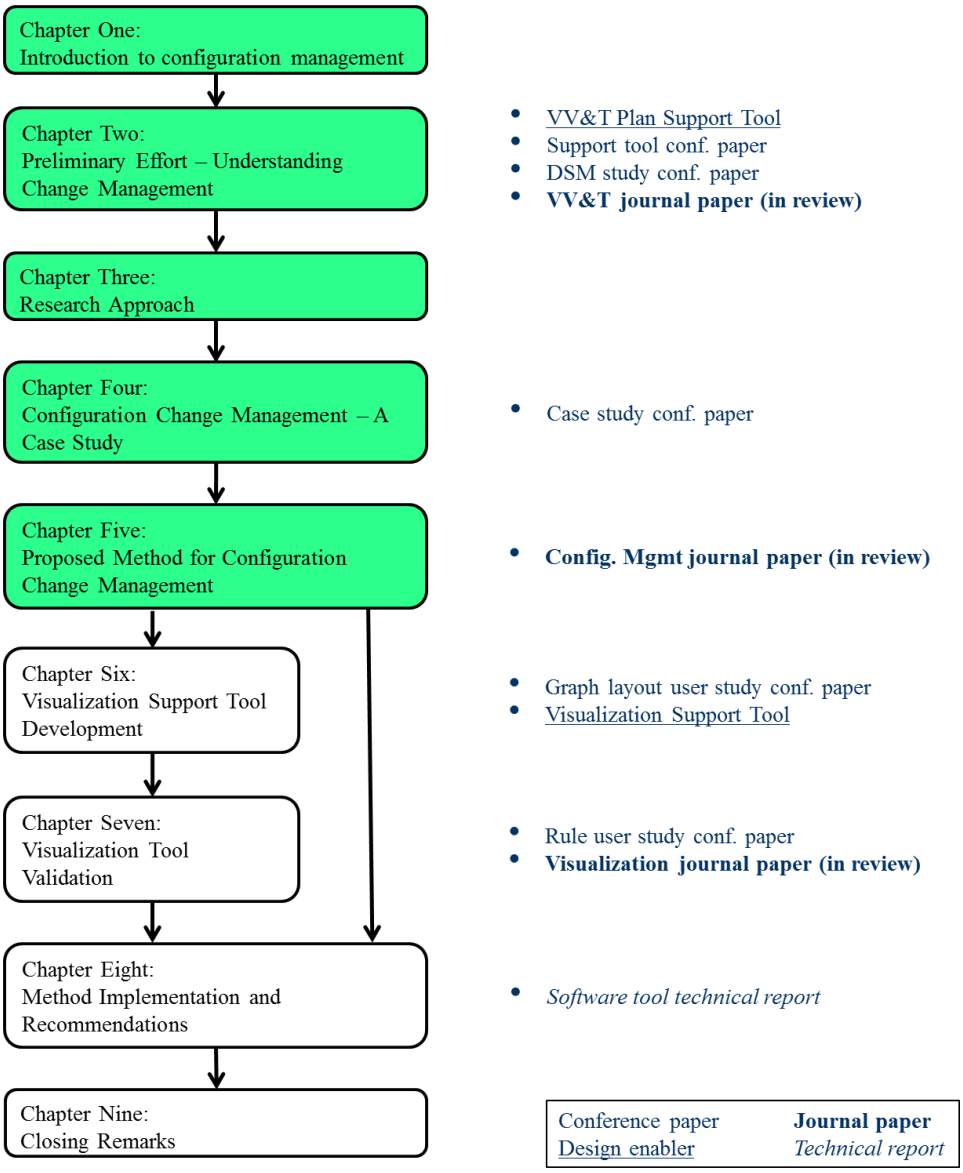

Figure 5.8: Dissertation roadmap

CHAPTER SIX: VISUALIZATION SUPPORT TOOL

The purpose of the research presented in this chapter is to develop a visualization support tool for use in the configuration management method discussed in Chapter Five. First, a review of data visualization and its applications is presented to show why graph visualizations was selected for the support tool. Then a user study is presented to explain why specific design decisions were made regarding the visualization tool. Based on the findings from the literature review and the development user study, a graph visualization support tool is developed to assist in exploring proposed changes as part of the configuration management method.

6.1 Data Visualization: Review of Literature

It is necessary to be able to understand and interact with the data and communicate it to others in a meaningful way [109]. This becomes even more important with increased amounts of data. Previous research has shown that implementing a data visualization method can be useful in increasing the ability to understand complex data systems [110–112]. An example discussed in the literature is a set of computer files. If the files are listed out with their locations, finding a specific file or understanding how the files are stored would be nearly impossible. Using a tree graph, the file hierarchy can be broken down into folders and subfolders to more easily illustrate the structure of the system.

Graph visualization, a subset of data visualization that uses a series of nodes and edges to describe relationships, is applicable and in certain instances, ideal, for any dataset where relationships between entities are a key focus of the data [113]. Graph visualizations

have been shown to be useful when identifying both direct and indirect relationships between entities in a system [71–73,114]. This is a key application of the developed visualization method for use in configuration management. Node-link graphs are particularly useful when considering path finding, which is essential to understanding possible propagation pathways [115]. It was identified that DSMs were useful in identifying change propagation pathways up to a point, but once the data set become too large, the DSMs were too difficult to interpret to be useful.

Graph visualizations have been used to understand change propagation where network relationships are essential. However, in reviewing the literature, it does not appear that graph visualizations have been used for configuration management. Therefore graph visualization in change management is reviewed here. In the most similar instance to the application derived from the case study, design structure matrices (DSMs) and node-link graphs were used to understand change propagation pathways in physical product components [46]. An example graph from this research is shown in Figure 6.1. Other examples of using graph visualizations to understand and interact with data networks are shown in [116–119].

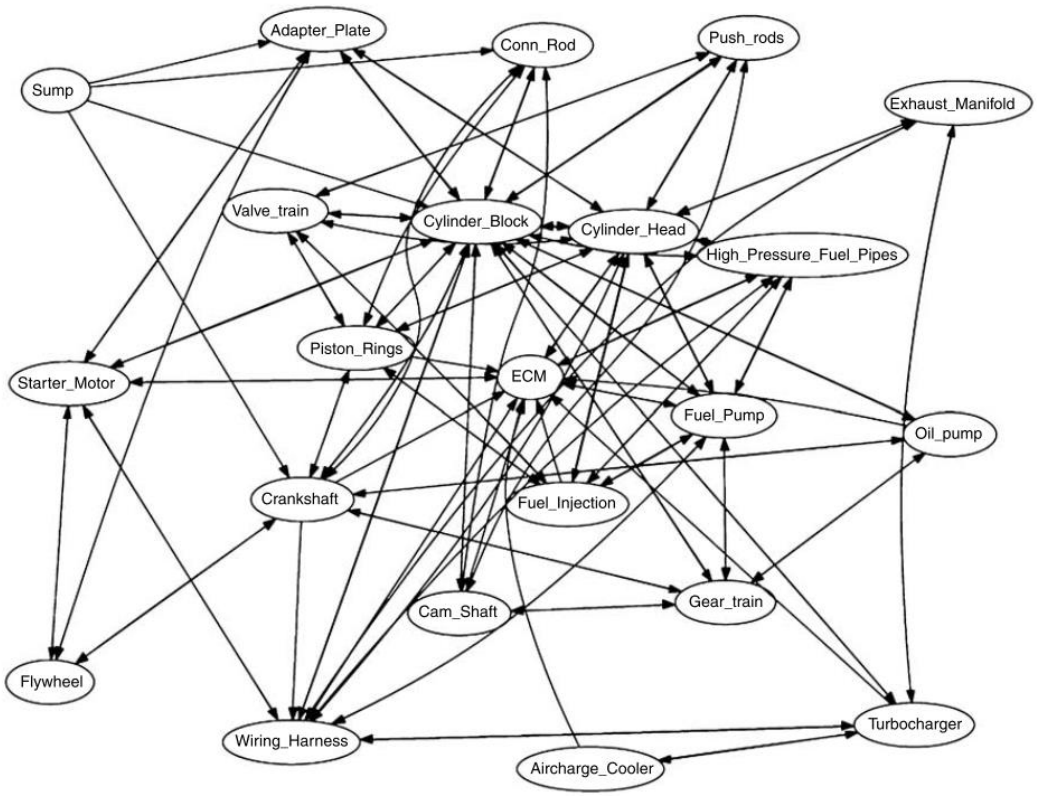

Figure 6.1: Node-link diagram of a diesel engine for predicting change propagation [71]

Though graph visualizations are useful in portraying network relationships and information, many factors can affect the readability of the graph itself. One study into these factors is how the use of straight (Figure 6.2) verses curved (Figure 6.3) edges to connect components in the graph affected the overall readability of the graph [120]. The researchers found that the use of edge curved edges had a detrimental impact on the readability of the graphs.

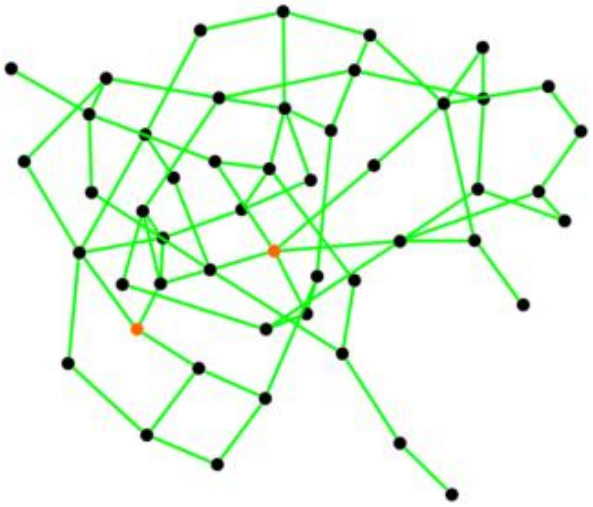

Figure 6.2: Straight-edged graph [120]

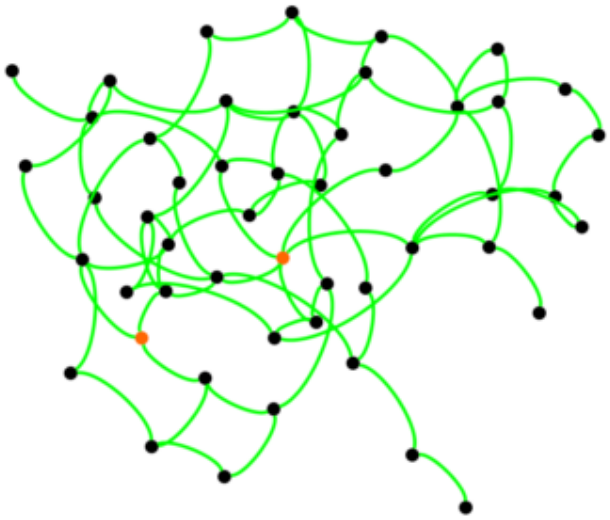

Figure 6.3: Curved-edge graph[120]

Numerous researchers have focused on the aesthetics of graph visualizations [121–123]. However, these studies focused on just the numerical aspects of the data, such as shortest path length, and number of edges, rather than on understanding the indirect relationships between nodes. Graph aesthetics is a term used to describe the appearance of

a graph and includes readability. Archambault used a series of graph visualizations over time to understand whether the "difference maps" were useful in understanding change to a network over time [124]. The researchers found that users generally preferred the difference maps for identifying changes over time. It was also found that use of the difference maps was effective in answering questions about large scale changes over time. Lastly, Holten considered how varying the drawing of edges in a directed graph affected the readability of the graph [125].

Additionally, multiple researchers have provided guidelines on the use of color on the effectiveness of visualizations as a whole and the potential effects of poor or ineffective implementation [126–128]. Purchase et al. conducted a series of studies on the effects of using different graph layout algorithms [123,129]. The researchers found that it was difficult to show that any one algorithm provided the "best" result; however, it was shown that the use of an algorithm, particularly one that minimizes crossing paths, is more effective for improving graph readability. This sentiment is echoed in the review of graph visualization layout techniques by Gibson, et al [130].

6.2 Graph Layout User Study (Development Study)

The first step in developing a visualization method for configuration management is to understand the information requirements for the user interface. Specifically, what is it that the user needs to see when applying the method. In this way, it is possible to backtrack from the required information to the available information provided in the current organizational systems to determine the additional requirements of the visualization method. In order to better understand what information best assists the user in identifying

relationships between configuration components, such as options, parts, and configuration rules, a user study was conducted using different variations on the layout and available information provided to the user. The user study was designed in accordance with the benchmark task method proposed in [131]. The remainder of the section provides additional details regarding the design and execution of the development user study.

6.2.1 Research Questions for Development Study

Research has shown that different types of data representation may be more accommodating for answering different types of questions about the system being represented [121,125,129]. This led to the following research questions:

1. How does the layout of the data representation graph affect the ability of the user to successfully answer questions about the system being represented?
2. How does the coloring of the data representation graph affect the ability of the user to successfully answer questions about the system being represented?
3. Does a change in the amount of information represented affect the user's ability to answer questions about the system?

It is hypothesized that the layout will not have a significant impact, while increasing the color-coding will increase the ability to correctly answer questions. This hypothesis is made because the color-coding should increase the user's ability to easily identify different types of interactions. Additionally, the it is hypothesized that limiting the amount of information will increase the accuracy of responses for those questions that are still answerable, while making it impossible to answer the questions regarding the missing information. This hypothesis is made because limiting the amount of information should remove clutter from the graph, more easily highlighting where the interactions take place.

6.2.2 Variables for Development Study

In order to answer the above research question, a user study was developed and executed. The user study consisted of three experimental variables:

- geometry of the graph used for data visualization
- coloring of the interactions between the nodes in the graph
- amount of information available to the user

The first variable consisted of two levels: the graph is arranged with the vehicle option nodes on the outside in a circle (Figure 6.4 (b)), or the vehicle option nodes arranged based on the functionality of the option (Figure 6.4 (a)). The purpose of this variable was to see if the layout of the graph allowed for easier identification of interactions or if the shape did not matter and any shape would result in the same accuracy of the responses (research question 1).

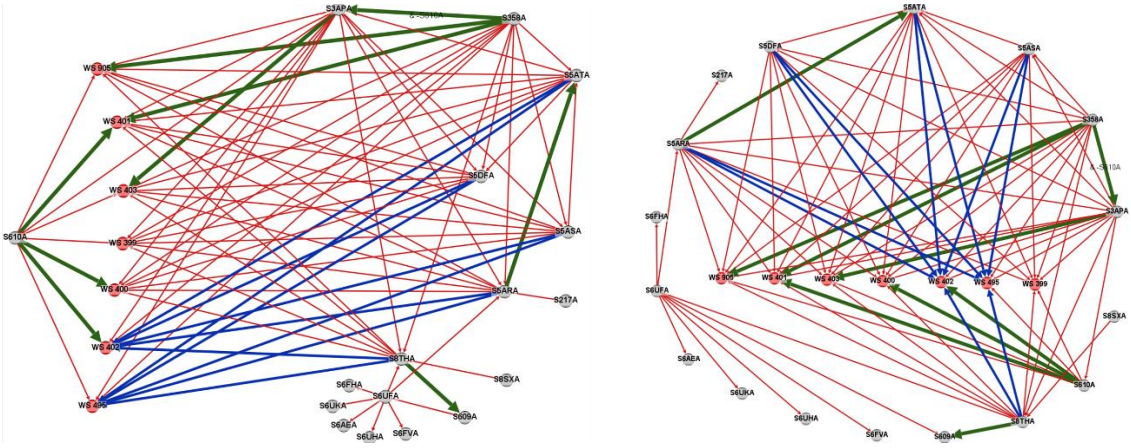

Figure 6.4: Functionally arranged graph (a) and circular graph layout (b)

The second variable included two levels: interactions regarding parts were red with all other interactions grey (Figure 6.5 (a)), or interactions were color-coded based on whether they were inclusions, exclusions, or either/or relationships (Figure 6.5 (b)). The

purpose of this variable was to determine whether the coloring allowed for easier identification of different types of interactions (research question 2).

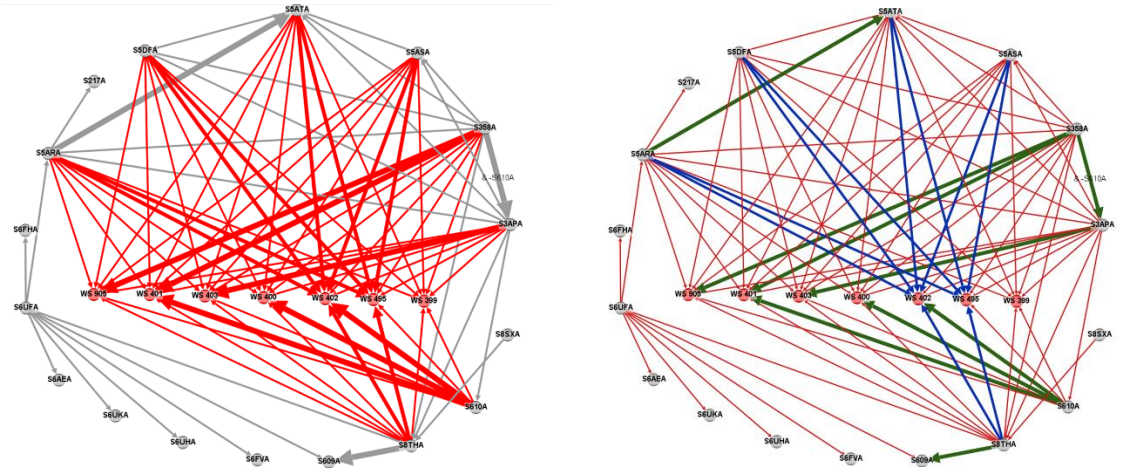

Figure 6.5: Graph colored based on part data (a) or based on interaction type (b)

The third variable included two levels: all information (Figure 6.6 (a)) or reduced information (Figure 6.6 (b)). The purpose of this variable was to determine if removing some of the information increased the user's ability to answer the remaining questions with greater clarity (research question 3).

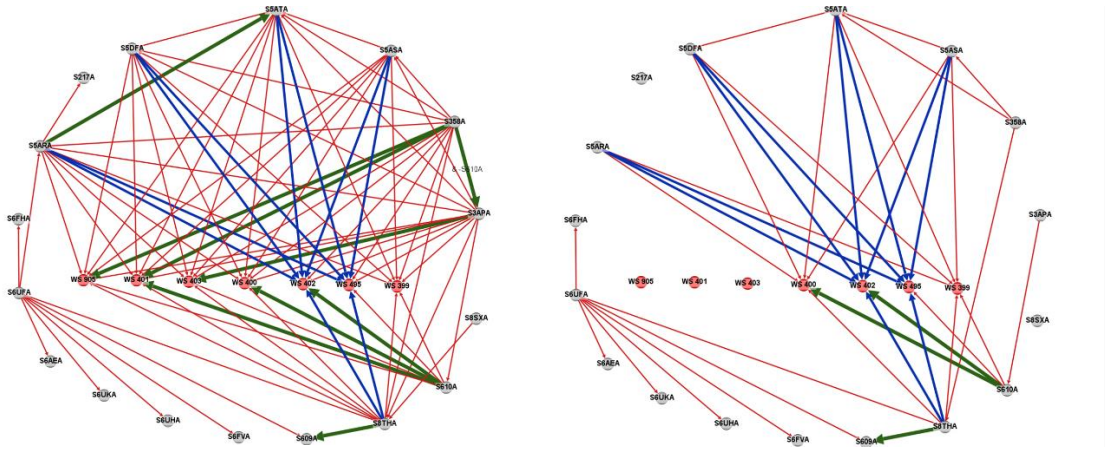

Figure 6.6: Graph will all information (a) and option information only (b)

A final variable consisted of two different orders in which the questions were asked and was simply used to determine whether the question order affected which questions were answered correctly. This variable is not used to answer a research question, but to ensure robustness of the experiment. Limited analysis was needed as the results were comparable.

6.2.3 Participants for Development Study

The participants for this user study consisted of industrial engineering students enrolled in the junior level industrial engineering operational research course (IE 3810 at Clemson University). During the case study (discussed in Chapter Four), it was identified that many of the engineers conducting configuration management at the OEM did not have a mechanical engineering background, but they did have some form of engineering background. Therefore, using junior-level industrial engineering students was applicable for the purposes of this study. The students were selected for this study as they provided a large sampling (78 students) with homogenous educational backgrounds and experience. As such, it was unlikely that any variation in the results of the experiment would be due to differences in educational preparation. The students had varying levels of work experience, but due to the low likelihood of working with a visualization tool similar to the one being used in the study, it was assumed that prior work experience was outside the scope of the study. The students were not rewarded based on the quality of their results. However, participation in the user study was counted as a "quiz grade" in order to ensure participation for the experiment.

6.2.4 Environment for Development Study

The user study was conducted in a single one-hour session during a normally scheduled class period of the junior operational research course. The students were told a week in advance that they would be conducting an in-class exercise. By conducting the experiment in a single session during the normal class period, the researcher was able to ensure that the time of day for the experiment did not affect the outcome of the study while maximizing the availability of the participants. The setting for the experiment was the room in which the course usually met. The classroom layout was a typical, auditorium-style classroom with a presentation stage in the front of the room and tables for the students to sit at, all facing the front of the classroom (as depicted in Figure 6.7). The experience of the students due to environmental conditions was uniform. The experiment was conducted during the twelfth week of the Spring semester of the students' junior year.

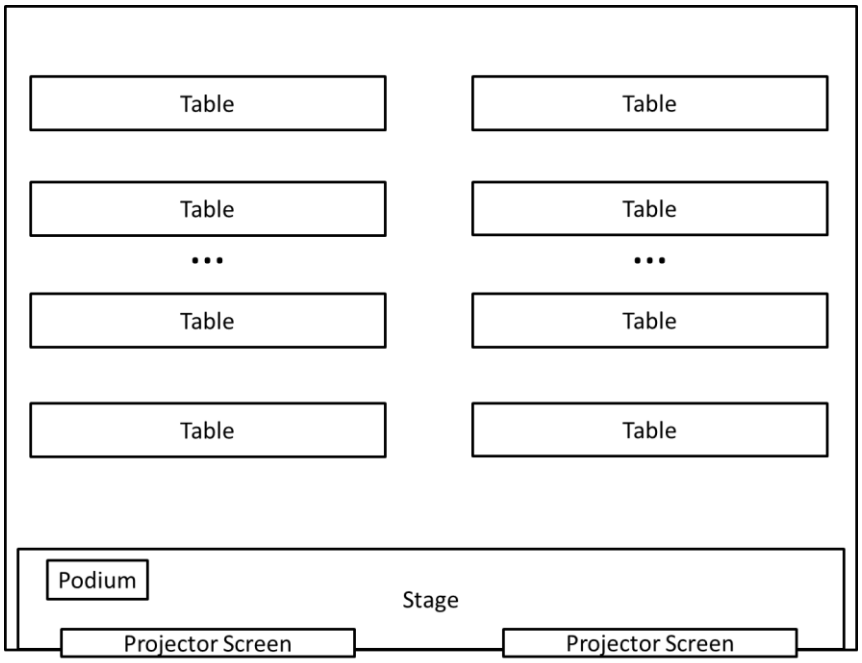

Figure 6.7: Classroom layout

6.2.5 Response Form Design for Development Study

In developing the response form to be used in the experiment, the first step was to determine the type of queries that may be asked of the visualization during the change evaluation process. During the course of the case study discussed in Chapter 4, numerous types of questions were identified that are commonly considered during a change to the configuration system. For the purposes of this experiment, the list of queries was further expanded through additional interviews with *Launch and Change Control* personnel at the OEM. This resulted in the following list of query types:

- availability of additional options based on a specified set of options
- availability of parts based on a specified set of options
- comparing option availability in different models
- effects of adding rules or options to the system
- effects of removing a part from the possible set
- identifying logic errors in the configuration set

A list of queries was then developed from the set of required query types. The response form used in the study is shown in 9.2Appendix E:. The list of queries follows:

1. Which vehicle options are not available to US customers for the available windshields?
2. If a US customer wants option S5DFA, what windshield part numbers are available? Which numbers are not available? Does it change for a customer in Europe and why?
3. If a vehicle option (S123A) was added to the Europe model that requires S5ARA and cannot work with S5DFA, will this cause any problems? Why or why not?
4. Provide a feasible vehicle option combination to result in Part number WS 495 (in Europe).
5. Which part numbers are compatible with option S610A (in Europe)?

6. Are there any option contradiction errors in the connectivity graph? If so, what are they?
7. If a European customer wants S5ATA, how does this affect availability of other vehicle options?
8. If a customer in Europe wants option S358A, what other vehicle options are affected, and how?
9. Which windshields are not offered in the US?
10. Provide a feasible vehicle option combination to result in Part number WS 401 (for Europe).
11. Is there any scenario where a combination of vehicle options will result in two different windshields being required (in Europe)?
12. Are there any valid vehicle option combinations where no windshields are specified?
13. If windshield WS 399 was removed from the European model, would this cause any issues? Why or why not?

Before conducting the experiment, it was necessary to ensure that each type of query was being asked in multiple ways. Triangulating the queries to ensure each type is covered in multiple ways is important when attempting to understand the relationship between the independent and dependent variables within a study [102,132]. The triangulation of questions for the user study is shown in Table 6.1.

Table 6.1: Survey question triangulation

Triangulation	Question												
Question type	1	2	3	4	5	6	7	8	9	10	11	12	13
Option availability	X								X				
Option - part interaction		X		X	X					X	X	X	
US vs Europe availability		X											
Effect of adding rule/option			X										
Using options to choose a part				X						X			
Finding option errors			X			X	X						
Option - option interaction							X	X					
Finding part errors											X	X	X
Effect of removing a part													X

The above table provides an expanded list of possible query types with the question number from the survey that corresponds to that subject. The interaction between options and parts has the highest level of querying as it is the most complex relationship within the configuration model. Also, as the identification of errors in the configuration model is the primary purpose of the data visualization, finding errors in the available parts and options was important. While three of the query types were only given a single question in the form, this was done purposefully as these subjects are not as central to the purpose of the visualization and the number of total questions in the survey was purposefully limited to keep the time requirement within a single class period.

6.2.6 Experimental Procedure for Development Study

The students arrived for the normally scheduled class and sat at tables of their choice. Once all of the students had arrived and were seated, the user study packets were distributed to the students. Each packet contained a form and two visualization graphs. The assignment of groups and the contents of each packet will be discussed in the following section. 12 different packet sets were randomly distributed throughout the class. All work was conducted individually. Once the packets were distributed, the instructions were provided to the participants. Additionally, a brief (approximately 5 minutes) tutorial on the data visualization techniques was provided. This was done because none of the participants had prior experience with the data visualization method being used to represent the system discussed in the form. Following the tutorial, the students were allowed to ask any questions regarding the form or the data visualization technique. The participants were then given 40 minutes to complete the experiment. However, upon completion of the questionnaire, individual students were allowed to submit their packets early and leave the classroom.

6.2.7 Packet Set-Variable Assignment for Development Study

The sets (1-12) were assigned such that each packet set would test a different set of variables. All relevant combinations were provided. It should be noted that the part-base level for coloring variable requires the full level for the information availability level. The assignment of the variables to the packet sets is shown in Table 6.2.

Table 6.2: Packet set-variable assignment

		Group											
	Condition	1	2	3	4	5	6	7	8	9	10	11	12
Graph Geometry	Functional	X	X	X				X	X	X			
	Circle				X	X	X				X	X	X
Information Available	Full	X		X	X		X	X		X	X		X
	Reduced		X			X			X			X	
Coloring	Interaction-based	X	X		X	X		X	X		X	X	
	Part-based			X			X			X			X
Question Order	Order A	X	X	X	X	X	X						
	Order B							X	X	X	X	X	X

The materials that each participant received depended upon the packet set to which they were assigned. However, every student from all of the groups received one form with thirteen questions about the system being presented, and two data visualization graphs (one representing US models and one representing European models). The queries chosen for the survey were selected based on research with a manufacturing company on what types of questions would be asked of a visualization tool used in identifying component interactions and errors within a system. An example of one of the data visualization graphs is shown in Figure 6.8. The depicted graph is the European graph received by Groups 1 and 7. All of the graphs are found in 9.2Appendix F:.

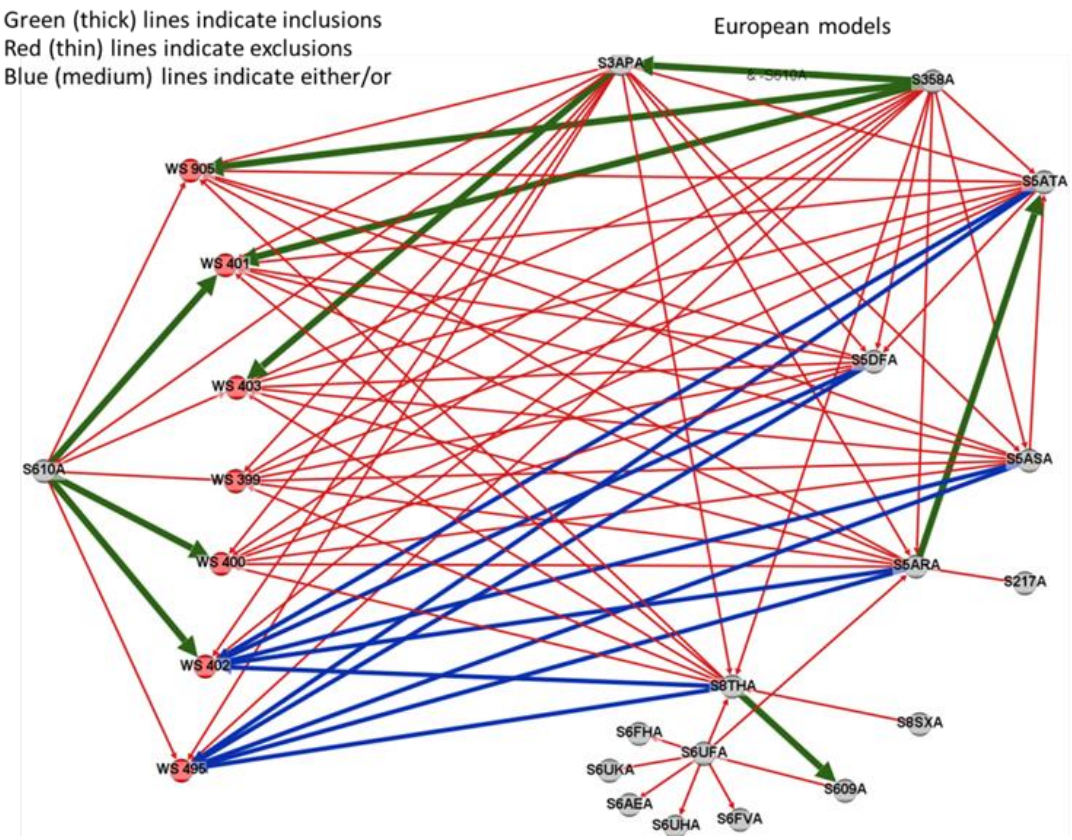

Figure 6.8: Example of a visualization graph (provided to Groups 1, 7)

6.2.8 Pilot Study for Development Study

Prior to the execution of the user study, a pilot study was conducted. The purpose of the pilot study was to determine the time requirements for the user study execution and to validate the queries and procedures for the user study. The time required to conduct the user study was a topic of consideration in that the user study needed to be conducted during a single class period in order to minimize the impact on the students and to ensure that the training and experiment could be conducted concurrently. The queries needed to be validated to ensure that the participants were not confused by the wording and that the novice students were capable of answering the queries.

To execute the pilot study, the procedure described earlier was used. Following the presentation, the participants were given a block of time to finish. In this instance, however, the time was not limited to allow for maximum time to finish. The participants were nine beginning graduate level engineering students with no experience in using graph visualizations for configuration management. The difference in experience level between the participants in the pilot study and in the full study was not expected to be a factor due to the similar level of inexperience with graph visualizations. Additionally, no conclusions were drawn from the pilot study other than time to finish and question answerability.

After evaluating the responses, it was determined that only a few of the queries needed rework in order to ensure that they were clearly understood and could be answered by a novice user. Additionally, the average time requirement was determined to be approximately 22 minutes, with a maximum time required of 28 minutes. The results of the pilot study ensured that the user study could be executed in its present form, with minimal modifications, during a single class period.

6.2.9 Evaluation Protocol for Development Study

The forms were evaluated according to the number of queries answered correctly. In many of the queries, multiple correct answers were possible and varying levels of detail were acceptable. As a result, the possibility existed for subjectivity in the grading process. However, because a single evaluator was used to examine all of the responses, this minimized the amount of variability in the grading process. As such, no inter-rater reliability assessment was conducted.

6.2.10 Evaluation Metrics for Development Study

The metrics that were used for evaluation are correctness and confidence. These metrics were chosen because it was not only important to determine which set of variables produced the most accurate or correct responses, but also to determine the confidence of the users in selecting those answers. As such, it was necessary to include a method for measuring the participants' confidence levels for each individual question.

Determining the correctness for each response was simple. The total number of correct responses was determined, along with the number of possible correct answers (in the packet sets with limited information available, not all questions were capable of being answered). The confidence for each response was collected using a modified 100 mm scale. In the traditional 100 mm scale, the user makes a tick mark along a blank 100 mm line and the distance from the left side to the mark is measured and recorded for the confidence [133,134]. A similar rating method was used in previous studies on confidence in design review decision-making [135]. To simplify the process, the line used in this study was graduated at 10% intervals, from 0 to 100. An example of the scale with a tick mark is shown in Figure 6.9.

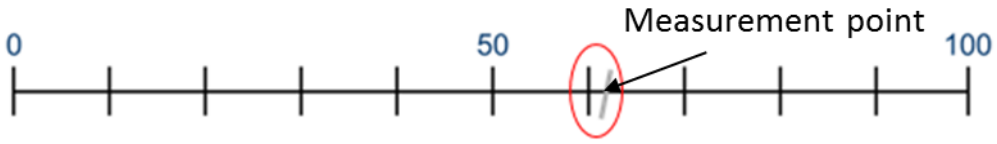

Figure 6.9: Modified 100mm confidence scale

6.2.11 Results for Development Study

A total of 78 forms were collected from the participants and evaluated by a single grader, as previously discussed. The data was tabulated into spreadsheets for ease of analysis.

For correctness, the results were consolidated according to the different variable levels. For instance, all of the groups of individual participants that received the full information in the graph (1, 3, 4, 6, 7, 9, 10, 12) were in one consolidation, while the groups receiving reduced information (2, 5, 8, 11) were treated separately. This was done for each variable in order to see how the different variables affected the accuracy of the responses. The results for each group and the consolidated results are shown in Table 6.3 and Table 6.4 respectively. Blank spaces in Table 6.3 represent queries that were unanswerable due to a lack of available information.

Table 6.3: Number of correct responses for each question by group

			Query												
		# responses	1	2	3	4	5	6	7	8	9	10	11	12	13
Packet Set	1A	7	2	5	6	3	7	1	5	3	6	7	7	1	2
	2A	7	7						6	6				6	
	3A	7	1	5	5	2	5	0	4	2	4	6	5	1	4
	4A	7	4	3	4	1	6	0	6	6	5	7	6	4	1
	5A	7	3	5	3	1	3	1	5	6	6	3	4	3	2
	6A	7	6						5	6				4	
	1B	6	3	3	5	2	5	0	3	2	3	6	4	1	1
	2B	7	7						6	7				7	
	3B	5	3	3	3	0	5	0	4	3	5	3	2	3	1
	4B	6	2	3	6	2	3	0	5	0	6	6	4	1	0
	5B	6	3	4	3	2	4	0	4	3	5	5	3	0	2
	6B	6	4						5	5				4	

Table 6.4: Percent of correct responses by variable

	Query												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Parts	41%	61%	69%	25%	75%	4%	71%	49%	78%	84%	69%	27%	25%
No Parts	89%	0%	0%	0%	0%	0%	81%	89%	0%	0%	0%	78%	0%
% Diff	54%	100%	100%	100%	100%	100%	13%	45%	100%	100%	100%	65%	100%
Circle	56%	58%	62%	23%	62%	4%	77%	67%	85%	81%	65%	41%	19%
Function	59%	64%	76%	28%	88%	4%	72%	59%	72%	88%	72%	49%	32%
% Diff	4%	10%	19%	18%	30%	4%	-7%	-13%	-18%	8%	9%	16%	40%
Colored	54%	36%	54%	21%	54%	3%	74%	56%	51%	67%	54%	38%	10%
Red/Grey	62%	44%	36%	13%	44%	3%	74%	69%	51%	44%	36%	51%	23%
% Diff	13%	18%	-50%	-60%	-24%	0%	0%	19%	0%	-53%	-50%	25%	56%
Set A	55%	64%	64%	25%	75%	7%	74%	69%	75%	82%	79%	45%	32%
Set B	61%	57%	74%	26%	74%	0%	75%	56%	83%	87%	57%	44%	17%
% Diff	10%	-14%	13%	4%	-1%	100%	2%	-24%	9%	6%	-39%	-2%	-85%

Table 6.4 also includes the percent difference between the variable levels, with those questions indicating a noticeable difference between the variables highlighted in yellow.

For confidence, the level of confidence for each query was measured using the graduated scale on the confidence indicator line. This was done for each query and then consolidated for each group. The average confidence levels for each question for each group are shown in Table 6.5.

Table 6.5: Average confidence for each question by group

	Question	1	2	3	4	5	6	7	8	9	10	11	12	13
1	7	63%	64%	71%	71%	88%	81%	59%	59%	63%	63%	78%	69%	81%
2	7	64%						61%	46%				50%	
3	7	57%	86%	65%	44%	77%	71%	52%	29%	125%	74%	49%	64%	71%
4	7	49%	85%	67%	39%	79%	79%	66%	58%	70%	67%	69%	54%	79%
5	7	55%	79%	71%	38%	62%	78%	51%	32%	49%	71%	59%	61%	78%
6	7	57%						63%	42%				57%	
7	6	75%	84%	82%	77%	80%	85%	68%	28%	62%	67%	83%	38%	49%
8	7	66%						76%	56%				80%	
9	5	68%	87%	61%	55%	64%	66%	61%	37%	60%	64%	62%	30%	56%
10	6	69%	73%	66%	68%	80%	77%	68%	63%	68%	68%	51%	66%	53%
11	6	56%	76%	63%	63%	74%	72%	52%	40%	49%	54%	53%	31%	50%
12	6	75%						75%	53%				68%	

6.2.12 Discussion for Development Study

It should first be noted that there are limitations in the analysis due to the responses of the participants. From evaluating the responses, it was identified that some of the participants did not take the experiment seriously or were confused by the instructions. This conclusion was made due to a number of responses being unsuitable based on the question being asked and/or instructions provided to the participants. For example, in multiple instances, the participants would respond to a question asking for vehicle options with a series of part numbers. This is clearly an example of the participants being confused by what was being asked in the question. In such an instance, the response was simply scored as incorrect, even if the thought process might have been correct. Additionally, a number of students turned in their completed questionnaires after only 15 minutes of work. During the pilot study discussed in Section 3, the fastest completion times were 20 minutes or higher, so it is unlikely that multiple participants were able to finish that quickly. It is more likely that the students rushed through the questions in order to be released early. Fortunately, the above situations were in the small minority and should not significantly affect the outcomes.

6.2.12.1 Availability of information

When considering the availability of part information, a definite trend existed where the accuracy of the answerable questions greatly increased when the part information was removed from the data visualization graph. Figure 6.10 illustrates the percentage of correct responses for each question for both the full information and reduced information (part vs. no parts) groups.

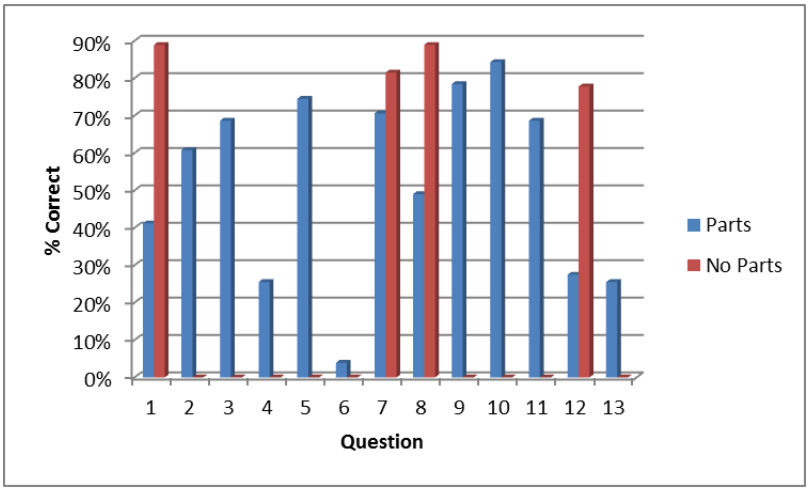

Figure 6.10: Graph of the correctness for each question based on availability of information

In the questionnaires, the only questions that remained answerable after the removal of the part information were Questions 1, 7, 8, and 12. In the above graph, all other questions are shown as having 0% correct responses for the "No Parts" group. However, for the answerable questions, the percentages of correct responses were significantly higher in almost all situations. The percentages for the answerable questions ranged from 78% to 89%, whereas the range for the same questions for the "Parts" group was 27% to 71%. This corresponds with the hypothesis that decreasing the amount of information presented will increase the ability to answer correctly for those questions that are still answerable.

However, it should also be noted that for 9 of the 13 questions (the unanswerable questions for the "No Parts" group), the one group was not even able to attempt the question due to the lack of information. Therefore, there are clearly situations where the full amount of information will be required in order to answer the questions. In such situations, it may

be advantageous, based on these results, to find other methods for limiting the total amount of information presented to the user through the visualization graph.

6.2.12.2 Color-coding of interactions

There appears to be little correlation between the method for color-coding the interactions between the components and the user's ability to accurately answer the questions. Figure 6.11 depicts the percentage of correct responses for each question for the groups based on the type of color-coding used to identify interactions.

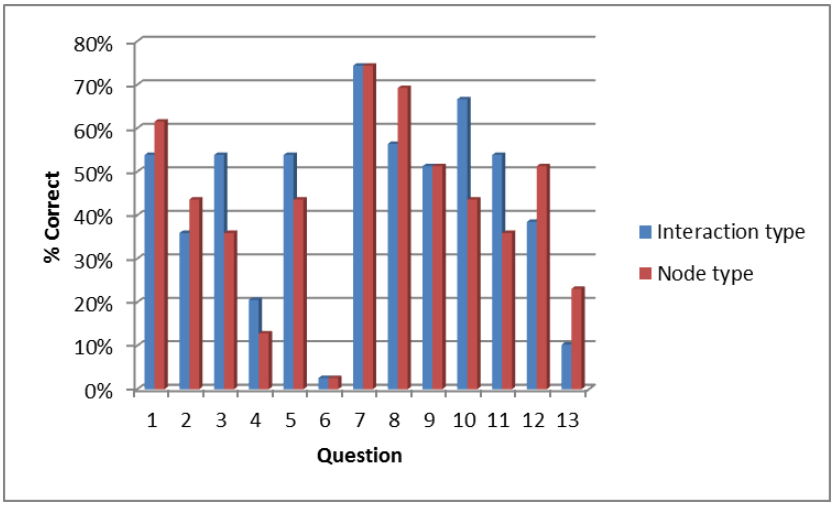

Figure 6.11: Graph of the correctness for each question based on color-coding

As seen in the above graph, the percentage of correct responses for each question do not differ significantly based on the type of color-coding used to identify the interactions. Only 5 of the 13 questions (3, 4, 10, 11, 13) show a marked difference between the percentages of correct answers. Additionally, one of the questions (13) shows a difference in the opposite direction (color-coding based on the node type being superior), and the majority of the non-significant differences also show the node type color coding

being slightly superior. As such, it is impossible to show that there is a direct relationship between the color-coding scheme used and the accuracy of the responses.

6.2.12.3 Confidence

An ANOVA was conducted for the confidence ratings for the different groups. The analysis showed no statistically significant difference in the confidence of the users based on which type of graph they were given. Due to differences in the way the confidence was understood by the participants and a lack of variation in the results for confidence, no conclusions were able to be made regarding the resulting confidence levels of the participants for individual questions.

6.2.12.4 Graph geometry

No correlation was found between the geometry of the data visualization graph and the accuracy of the responses. Figure 6.12 illustrates the percentage of correct responses for each question for the groups based on the graph geometry.

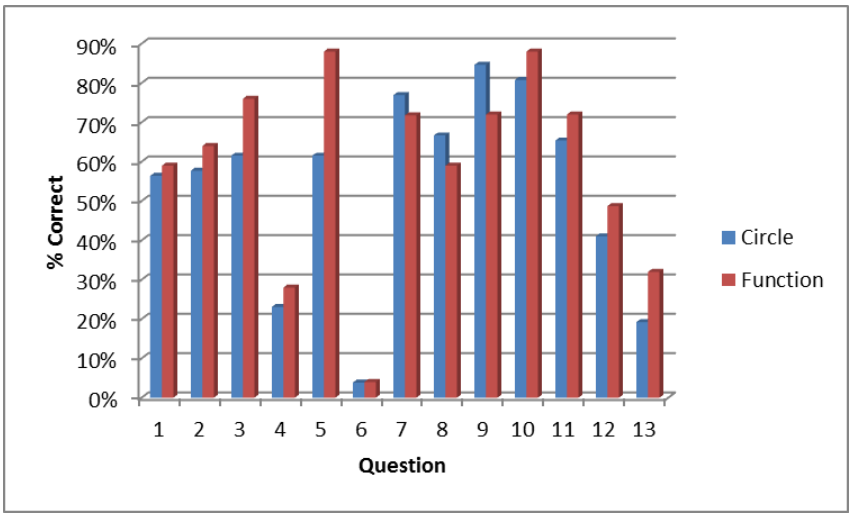

Figure 6.12: Graph for the correctness of each question based on layout

As seen in the above graph, the percentages of correct responses for each question are almost the same, regardless of the geometry of the graph. Only 2 of the 13 questions show a marked difference between the percentages of correct answers. As such, it is suspected that there is no relationship between the shape of the graph and the accuracy of the responses

6.2.12.5 Question order

To ensure that question order did not play a factor in the accuracy of the responses, two different orderings of the questions were used. Figure 6.13 illustrates the percentage of correct responses for each question for the groups based on the order of the questions.

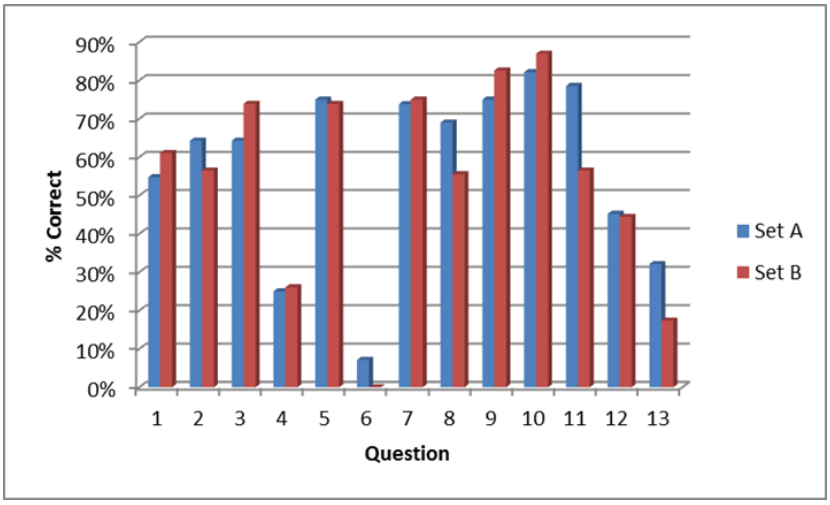

Figure 6.13: Graph of the correctness for each question based on order

As seen in the above graph, there is no trend for response accuracy based on the order of the questions. Therefore, it can be concluded that the ordering of the questions did not impact the results.

6.2.13 Findings of the Development Study

The results generally showed an increase in the percentage of correct answers for those questions that could still be answered when the amount of information presented was reduced. On the other hand, the color-coding scheme did not seem to have any identifiable effect on the results. The most significant limitation in this study was the possibility for variations in the amount of effort put forth by the participants. It was clear, based on the results, that some of the students did not put forth their best effort or follow the instructions of the experiment.

6.3 Development of the Visualization Tool

The purpose of the graph visualization creation tool is to automatically import the output from the previous tool and display a node-link graph visualization. Additionally, the tool will provide a degree of interaction for the user to be able to manipulate the graph. As discussed in the literature review, the ability to interact with the visualization greatly enhances the user's ability to understand the representations being displayed in the graph. A graph visualization software package was developed in order to fulfill the requirements for the design enabler to support the proposed configuration management method. The following section discusses the process for selecting the platform to be used for the graph visualization tool.

6.3.1 Platform Selection

Three platforms are being considered for the development of the graph visualization that will provide the foundation for the visualization method. These platforms are Gephi [136], Data-Driven Documents (D3) [137], and Processing [138].

6.3.1.1 Gephi

Gephi is a visualization tool used for exploring networks, systems, and graphs [136]. Unlike the other platforms being considered, Gephi is a fully functional software package for importing node and edge data and displaying interactive network graphs. The researcher also has some familiarity with Gephi as the early visualization graphs used in the user study (discussed in 6.2) were created using this software. The major benefits of Gephi are that it already exists, is open-sourced, and can be modified through the use of plugins. The major drawbacks of Gephi are that many of its functions are unrelated to the goals of this research, the development of new plugins would require learning a new programming language, and does not provide, even with additional plugins, some capabilities for data encoding that may be necessary for this research.

6.3.1.2 Data-Driven Documents (D3)

D3 is a JavaScript library that is used to visualize data in meaningful ways [137]. Because D3 is a JavaScript library, much of the desired functionality for the visualization support tool is already available, but would require the supporting programming code for interacting with the data and displaying the results properly. This leads to the major benefit, and also drawback, of using D3. On the one hand, the required functionality already exists and D3 is capable of a wide range of possibilities with respect to visualizing graph-based data. The drawback is that D3 is run in HTML, which would require a better understanding of data recovery and programming in HTML.

6.3.1.3 Processing

Processing is an open-source programming language that was designed specifically to assist in adding a visual context to data [138]. Processing is a widely used language within data visualization and has over 100 libraries to extend the capabilities of the original software. The main positive of using processing as the platform is that the software is completely build-to-suit, meaning that the resulting tool can be programmed to be exactly what is required. Other benefits are that the large number of libraries can assist in developing the necessary functions and the researcher is already familiar with the programming language. The largest drawback is that the graph visualization software would have to be built from scratch.

6.3.1.4 Summary

The level of familiarity, availability, and functionality for each of the possible platforms is shown in Table 6.6: Software platform selection overview. Due to the low level of familiarity with programming with D3, as a result of it being HTML-based, D3 is rejected from the possible platforms. Additionally, Gephi is excluded because it is not capable of some of the required functionality for the visualization support method. As a result, Processing is chosen as the platform for the development of the visualization support method.

Table 6.6: Software platform selection overview

	D3	Processing	Gephi
Familiarity	-HTML-based	-Java-based -High level of familiarity	-Have used extensively
Availability	-Open-source -Many examples/shells available	-Open-source -Tutorials available -Largely build-to-suit	-Open-source -Software is complete -Difficult to modify
Functionality	-Capable of displaying and interacting with graphs	-Capable of displaying and interacting with graphs	-Capable of displaying/minor interaction

6.3.2 Visualization Tool Requirements Identification

Through the course of the case study, a need was identified for support tools to assist in the configuration management process, to include managing the effects of proposed configuration changes. In order to address the identified issues, the following requirements are proposed:

- Able to easily visualize the interactions between configuration components (including parts)
- Able to highlight specific problem areas to assist in simplifying the rule database
- Able to check for errors in the existing rule database
- Able to preview how proposed configuration changes would affect the existing rule database

These requirements were identified through the interviews to address specific issues experienced by the automotive OEM in their current configuration management process.

6.4 Implementation of the Visualization Tool

6.4.1 Data Organization and Source

In order to create each graph visualization, two sets of inputs are required: the nodes (items of interest) and the edges (relationships) of the graph. Both of these inputs are created through the additional software tools used to support the configuration management process at the OEM (discussed in 5.2). The following subsections describe the inputs in more depth.

6.4.1.1 Graph Nodes

The graph nodes, or items of interest, consist of the vehicle options, parts and packages that exist in the configuration rule database. Also, the researcher created "AND" and "OR" nodes to assist in representing rules that are not strictly binary. In addition to the node label, the following information is recommended for capture in the input file: a unique ID number for easy recall and data storage, the type of node, the lowest level of interaction from the specified nodes, and the X/Y coordinates for the nodes position in the graph.

Specifying the type of node increases the amount of information that can be visually stored in the graph and allows for easier understanding of what a specific node entails. The lowest level of interaction from the specific nodes identifies the number of interactions required to move from the original nodes to a specific node (for example: in A->B->C, where "A" is a node specified in the change document, the level of interaction for "C" would be 2). This information is useful in that it can assist the user in determining the likelihood of a change propagating to other components. Lastly, the X/Y coordinates are

useful if any prepositioning of the nodes is used for an initial layout of the graph. An example node input file is shown in Figure 6.14.

ID	Label	Type	Int	PosX	PosY
1	S319A	1	0	0	0
2	S302A	1	0	0	0
3	S8S2A	1	0	0	0
4	L807A	1	0	0	0
5	S614A	1	0	0	0
6	OR	6	0	0	0
7	S601A	1	0	0	0
8	S609A	1	0	0	0
9	AND	6	0	0	0
10	S866A	1	0	0	0
11	OR	6	0	0	0
12	L8AAA	1	0	0	0
13	S8LHA	1	0	0	0
14	S8LTA	1	0	0	0
15	AND	6	0	0	0
16	S877A	1	0	0	0
17	S6FHA	1	0	0	0
18	OR	6	0	0	0

Figure 6.14: Example graph node input file

6.4.1.2 Graph Edges

The graph edges, or relationships between the nodes, consist of the rules that govern how the different components interact. These relationships include all of the rules as specified in the option and part rule databases, as well as function class information. It is also possible to use new rules as created in the conflict detection tool as relationships. While it may be useful to label the edges on the graph, a label is not currently included in the information provided in the edge input file. The information provided for each edge is a unique ID number of easy data storage and recall, the source node of the edge, the target node of the edge, and the type of edge.

The source node of the edge refers to the “If” portion of the rule in a binary rule, while the target node refers to the “Then” portion of the rule. In more complex rules (non-

binary), a more comprehensive grammar must be used and is discussed in 6.4.2.1. The edge type represents the type of relationship between the nodes. Three different types of relationships are currently used: inclusive, exclusive, and multiple-inclusive relationships. An inclusive relationship means that the source requires the target to also be present. Similarly, exclusive requires that the target must not be present. The multiple-inclusive relationship is used in conjunction with "OR" and "AND" nodes to help delineate that the relationship is not binary. Multiple-exclusive could also be represented separately, but has not been used in the current implementation. An example of an edge input file is shown in Figure 6.15.

ID	Source	Target	Type
1	1	2	3
2	3	2	3
3	1	4	1
4	6	7	2
5	6	8	2
6	5	6	3
7	8	9	2
8	10	9	2
9	11	12	2
10	11	13	2
11	11	14	2
12	9	11	3
13	8	15	2
14	14	15	2
15	15	10	3
16	16	2	3
17	18	7	2
18	18	8	2

Figure 6.15: Example graph edge input file

6.4.2 Methods

The following subsections describe the two major functions of the visualization tool: graph creation and graph manipulation.

6.4.2.1 Graph Creation

In graph creation, the data from the input files are read and displayed on the screen in a node-link diagram. In order to accurately depict the different types of rules/relationships between nodes, a visualization grammar was required. For binary rules, the grammar consists of an arrow pointing from one node to another. An example of an inclusive, binary rule is shown in Figure 6.16. In the figure, P5A3A is the source node, and S5ACA is the target node, meaning that if P5A3A is present, S5ACA must also be active. The green arrow is being used to represent the inclusivity of the relationship.

O	If-Part of rule	Then-part of rule
Z	& + P5A3A	/ + S5ACA

Figure 6.16: Rule and corresponding graph for an inclusive, binary relationship

On the other hand, an exclusive, binary relationship is shown in Figure 6.17. In this instance, the presence of S5A1A requires that P5A3A not be present for the configuration to work.

O	If-Part of rule	Then-part of rule
A	& + S5A1A	/ + P5A3A

Figure 6.17: Rule and corresponding graph for an exclusive, binary relationship

When considering relationships that are not binary, “OR” and “AND” nodes are used to assist in representing the rules. An example of a rule with an “OR” node is shown

in Figure 6.18. In this graph, the "OR" node is created as the target for the "If" part of the rule and the source for the "Then" part of the rule. The meaning of the following graph is that if S645A is present, then neither S825A nor L807A must be present.

O	If-Part of rule	Then-part of rule
A	& + S645A	/ + L807A / + S825A

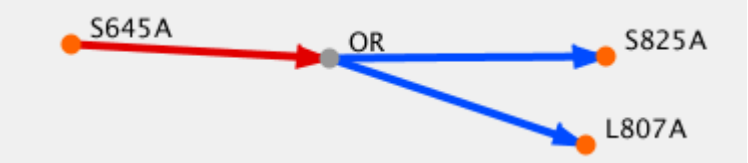

Figure 6.18: Rule and corresponding graph for a relationship requiring an "OR" node

An "AND" node is represented in a similar manner to the "OR" node and is shown in Figure 6.19. The following graph shows that if both L807A and S6VAA are present, then S6AEA cannot be present.

O	If-Part of rule	Then-part of rule
A	& + L807A & + S6VAA	/ + S6AEA

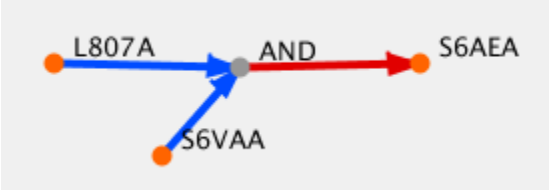

Figure 6.19: Rule and corresponding graph for a relationship with an "AND" node

Another example of an "AND" node is shown in Figure 6.20. In this example though, one of the source nodes has a negative attached to it, changing the type of relationship between the node and the "AND" node. The resulting interpretation is that if L807A is not present, but S552A is present, then S5ACA must be present.

O	If-Part of rule	Then-part of rule
Z	& + S552A & - L807A	/ + S5ACA

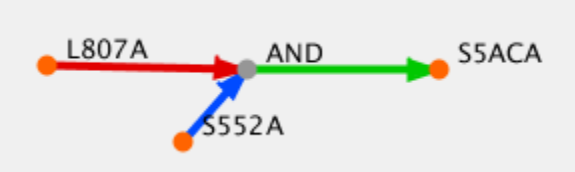

Figure 6.20: Additional rule and graph for a relationship with an "AND" node

Colors were chosen to represent the types of relationships instead of either size or dash-lines because in a more complex graph, it is more difficult to distinguish between or trace different line thicknesses or different types of dashed lines. While red, green, and blue were chosen for the colors in this mapping, a different set of colors could be used in their place. An example of a completed graph is shown in Figure 6.21.

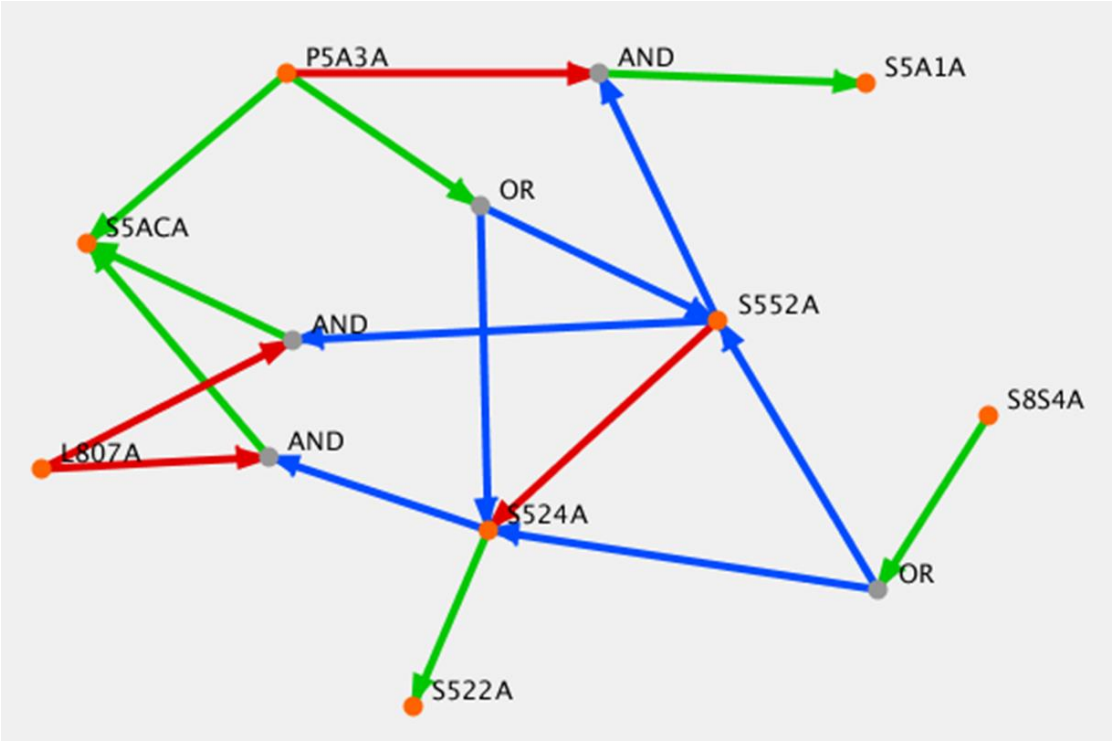

Figure 6.21: Graph visualization for a specific change

6.4.2.2 Graph Manipulation

While it is possible to explore a static graph visualization, the ability to interact with the data greatly increases the user's understanding of the system. As such, the software tool supports graph manipulation. The current level of interaction includes the ability to move nodes on the existing graph, to create new nodes and edges, to remove nodes, to highlight a specific node and all of its interactions, and to rearrange the layout of the graph to increase readability. Additional options are for the user to save the existing visualization or to reset the visualization to its original state.

At the most basic level of interaction is the ability of the user to move the existing nodes. This is necessary as it allows the user to manually position items of interest or to cluster specific nodes based on some criteria. As the edges are directly linked to the nodes, as the nodes are moved, the edges change to accommodate the placement of the nodes.

As one of the required tasks of the visualization is to assist in the evaluation of potential changes to the system, it is necessary for the user to be able to add and remove nodes and edges. At present, the current system allows the addition of both nodes and edges, but only the manual removal of nodes. When a specific node is removed, however, all of the associated edges are removed as well. When adding a node or edge, the user must also have the ability to specify which type of node or edge is being created, along with entering in any information that is to be stored in the associated data file.

When evaluating the potential propagation pathways from one node to another, it is useful to be able to select a specific node for highlighting. When a node is selected, all of its interactions are highlighted, while any relationships not directly related to the node

are dimmed slightly. These represent the first-order interactions for the node. It may also be possible to allow the user to change the order of interaction for this highlighting for increased user specificity. To show the full relationship, the path between nodes should be between two components (options/parts/packages) and not "AND" or "OR" nodes, but should pass through the intermediate nodes. An additional extension of this is that when two nodes are selected, the shortest path between them (or all unique paths) is highlighted to show the level of interaction between the two nodes.

Research has shown that while using a specific layout algorithm is not essential, it is important to use some algorithm for arranging the nodes. This helps to alleviate clutter and greatly increases the readability of the graph. For this visualization, a force-directed algorithm is used and will be discussed further in the following section.

In addition to the ability to save the current visualization (which captures the current image of the graph), it is also useful to be able to output the current data files that go with the graph. The data files could be outputted in the data file format as described in 6.4.1 or in the form of rules that could then be merged with the existing rule database.

6.4.2.3 Force-Directed Graph Layout

The force-directed algorithm is a basic graph layout algorithm that uses a repulsive force between all nodes and an attractive force along all edges. To apply the algorithm, a repulsive force is determined between the nodes and a movement value is created for each node. Then the attractive force is determined for each edge and each nodes movement value is adjusted accordingly. After both forces have been applied, the nodes are moved according to their final movement values. This process is repeated until the user is satisfied

with the dispersion of the nodes. It is also important that outer boundaries are set for the nodes to ensure that the graph does not grow continually, but rather reaches a steady-state.

6.5 Software Development

This section describes the programming methods used to transform source data into a graph visualization and then allow the user to interact with the graph. All of the code found in this section is from Processing (www.processing.org), a common visualization programming language. The first task is to import the data from the graph and edge files and store them locally for editing, as discussed in 6.5.1. A discussion of the data classes that are used for data storage can be found in 6.5.2. From the graph data, the software then creates the graph visualization, as discussed in 6.5.3. Lastly, the tool provides the ability to interact with the graph, as discussed in 6.5.4.

6.5.1 Data Management

For each input file (node and edge), a data table is created. For the data tables, a specific object class is used. The data is stored in a dataTable, along with some meta-data about the table to increase the ability to search through the data. The purpose of this is to store the data in a way that is more manageable both for retrieval and editing.

```
1   class dataTable {
2     int rowCount;
3     String[][] data;
4     String[] columnNames;
5
6     dataTable(String filename) {
7       String[] rows = loadStrings(filename);
8       data = new String[rows.length-1][];
9
10      // skip row 0 (column headers)
11      for (int i = 1; i < rows.length; i++) {
12        // skip empty rows
13        if (trim(rows[i]).length() == 0) { continue; }
14
15        // split the row on the tabs
```

```
16        String[] pieces = split(rows[i], TAB);
17
18        // copy Data into the table starting at pieces[1]
19        data[rowCount] = (subset(pieces, 0));
20
21        // increase row count
22        rowCount++;
23      }
24      // resize the array as necessary
25      data = (String[][]) subset(data, 0, rowCount);
26    }
27
28    int getRowCount() {
29      return rowCount;
30    }
31
32    String getString(int rowIndex, int col) {
33      return data[rowIndex][col];
34    }
35  }
```

6.5.2 Data Classes

To assist in creating the graph and storing information that is specific to the nodes or edges, two additional data classes are used: Node and Edge. For the nodes, the Node class stores the information from graph input file as well as contains a function for how the nodes should be drawn on the graph. Additionally, another variable "selected" is either turned on (1) or off (0) depending on whether or not the node has been highlighted. The coloring of the node is defined according to the type of node.

```
1   class Node
2   {
3     String label;
4     int ID;
5     int selected = 0;
6     int nodeType;
7     float x;
8     float y;
9
10    Node(int _ID, String _label, int _nodeType, float _x, float _y) {
11      ID= ID; label= label; nodeType= nodeType; x= x; y= y;
12    }
13
14    void draw(int selection) {
15      int opacity = 255;
16      if (selection == 1) {
17        opacity = 100;
18      }
19      strokeWeight(10);
20      if (selected == 1) {
21        strokeWeight(12);
22        opacity = 255;
23      }
```

```
24      if (nodeType == 1) {
25        stroke(255, 100, 0, opacity);
26      } else if (nodeType == 2) {
27        stroke(0, 200, 200, opacity);
28      } else if (nodeType == 3) {
29        stroke(0, 0, 200, opacity);
30      } else if (nodeType == 4) {
31        stroke(200, 200, 0, opacity);
32      } else if (nodeType == 5) {
33        stroke(200, 0, 200, opacity);
34      } else {
35        stroke(150);
36      }
37      point(x, y);
38      fill(0);
39      textSize(13);
40      textAlign(LEFT, CENTER);
41      text(label, x + 10, y - 10);
42    }
43  }
```

For the edges, the Edge class stores the information from graph input file as well as contains a function for how the edges should be drawn on the graph. The method for drawing the edges is to create a line from the source node to the target node, with an arrowhead also being drawn on the target end (lines 42-52). Additionally, another variable "selected" is either turned on (1) or off (0) depending on whether or not an associated node has been highlighted. As with the nodes, the coloring of the edge is assigned according to the type of edge.

```
1   class Edge
2   {
3     int edgeType;
4     Node source;
5     Node target;
6
7     Edge(Node  source, Node  target, int  edgeType) {
8       source=_source; target=_target; edgeType=_edgeType;
9     }
10
11    void draw(int selection) {
12      strokeWeight(4);
13      int opacity = 255;
14      if (selection == 1) {
15        opacity = 100;
16      }
17      if (source.selected == 1) {
18        strokeWeight(8);
19        opacity = 255;
20      }
21      if (target.selected == 1) {
22        strokeWeight(6);
23        opacity = 255;
24      }
```

```
25      if (edgeType == 1) {
26        stroke(225,0,0, opacity);
27        fill(225,0,0, opacity);
28      }
29      if (edgeType == 2) {
30        stroke(0,75,255, opacity);
31        fill(0,75,255, opacity);
32      }
33      if (edgeType == 3) {
34        stroke(0,200,0, opacity);
35        fill(0,200,0, opacity);
36      }
37      float xSource = source.x;
38      float ySource = source.y;
39      float xTarget = target.x;
40      float yTarget = target.y;
41      line(xSource, ySource, xTarget, yTarget);
42      pushMatrix();
43      translate(xTarget, yTarget);
44      float a = atan2(xSource-xTarget, yTarget-ySource);
45      rotate(a);
46      strokeWeight(2);
47      beginShape();
48      vertex(0, 0);
49      vertex(-5, -15);
50      vertex(5, -15);
51      endShape();
52      popMatrix();
53    }
54  }
```

6.5.3 Graph Creation

In Processing, a base setup function is run initially, after which, a draw function is run continuously. In the setup function, the data is transferred from the input files into the dataTable classes and additional meta-data is collected about the graph. At the end of the setup, the initial set of nodes and edges are stored through the storeNodes and storeEdge functions.

```
1   void setup() {
2     nodeData = new dataTable("Nodes.tsv");
3     edgeData = new dataTable("Edges.tsv");
4     nodeCount = nodeData.getRowCount();
5     edgeCount = edgeData.getRowCount();
6     size(visHeight + 3 * border, visHeight);
7     day = day();
8     month = month();
9     year = year();
10
11    storeNodes();
12    storeEdges();
13  }
```

The storeNodes function retrieves the data from the nodes dataTable (nodeData) and creates an entity of the Node class (line 11), which is then added to an ArrayList of all nodes in the graph through the addNode function (line 12).

```
1   void storeNodes() {
2
3     for (int row = 0; row < nodeCount; row++) {
4       int nodeID = parseInt(nodeData.getString(row, 0));
5       String nodeName = nodeData.getString(row, 1);
6       int nodeType = parseInt(nodeData.getString(row, 2));
7       float x = parseFloat(nodeData.getString(row, 4));
8       x = centerX + (x * visHeight)/2;
9       float y = parseFloat(nodeData.getString(row, 5));
10      y = centerY + (y * visHeight)/2;
11      Node ni = new Node(nodeID, nodeName, nodeType, x, y);
12      addNode(ni);
13    }
14  }
```

The storeEdges function retrieves the data from the edges dataTable (edgeData) and creates an entity of the Edge class (line 14), which is then added to an ArrayList of all edges in the graph through the addEdge function (line 15). The edge uses the ID numbers of the nodes to identify the source and target. Lines 10-13 show the method for matching the current nodes to the edge.

```
1   void storeEdges() {
2     Node nSource = null;
3     Node nTarget = null;
4
5     int edgeSource, edgeTarget, nodeID;
6     for (int row = 0; row < edgeCount; row++) {
7       edgeSource = parseInt(edgeData.getString(row, 1));
8       edgeTarget = parseInt(edgeData.getString(row, 2));
9       int edgeType = parseInt(edgeData.getString(row, 3));
10      for(Node n: nodes) {
11        if(n.ID == edgeSource) { nSource = n; }
12        if(n.ID == edgeTarget) { nTarget = n; }
13      }
14      Edge e1 = new Edge(nSource, nTarget, edgeType);
15      addEdge(e1);
16    }
17  }
```

Once all of the data has been stored properly, the draw function is run continuously to create the graph. The program draw function executes the Node and Edge class draw functions, populating the items on the visualization (lines 12-13). Additionally, the legend,

instructions for interaction, the date of graph creation, and two interface buttons (reset and save) are drawn (lines 6-10). The checkSelection function checks if any of the nodes have been highlighted. This is used to determine whether the non-highlighted portions of the graph should be dimmed. Lastly, the forceCheck variable is used to determine whether the user has chosen to implement the force-directed algorithm. While the check is active, the force directed algorithm will run continuously, until the user is satisfied with the graph dispersion and turns off the algorithm.

```
1   void draw() {
2     selection = 0;
3     background(240);
4     scale(zoom);
5
6     drawReset();
7     drawSave();
8     drawDates();
9     drawLegend();
10    drawInstructions();
11    checkSelection();
12    for(Edge e: edges) { e.draw(selection); }
13    for(Node n: nodes) { n.draw(selection); }
14    if (forceCheck == 1) {
15      forceDirect();
16    }
17  }
```

The force-directed algorithm starts by looping through all of the nodes (line 10). For each node, an initial movement vector is created. Then the repulsive forces from all other nodes are calculated (lines 25-54). The algorithm first checks to make sure the nodes are within a certain distance of each other (lines 28-33) and uses the magnitude and direction between the nodes to create a movement value in the opposite direction (lines 34-44). Then the node is adjusted accordingly.

After the repulsive forces have been evaluated, the attractive forces provided by the edges are considered (lines 56-84). Again, the distance and direction between the nodes

are determined (lines 63-72) and used to create a move value towards the other node that increases as the distance increases (lines 74-80). The nodes are then moved accordingly.

```
1   void forceDirect() {
2     float k = sqrt((visHeight * visHeight)/nodeCount);
3     float distX, distY, dist;
4     float centerDist, centerDistX, centerDistY;
5     float moveX, moveY, move;
6     float pushX, pushY, push;
7     float direction;
8     float pushFactor = 10000;
9     float pullFactor = 1000000000;
10    for (Node n1: nodes) {
11      distX = 0;
12      distY = 0;
13      dist = 0;
14      direction = 0;
15      pushX = 0;
16      pushY = 0;
17      push = 0;
18      moveX = 0;
19      moveY = 0;
20      move = 0;
21      centerDistX = n1.x - centerX;
22      centerDistY = n1.y - centerY;
23      centerDist = sqrt((centerDistX * centerDistX)+(centerDistY * centerDistY));
24
25      for (Node n2: nodes) {
26        if (n1 == n2) {}
27        else {
28          distX = n1.x - n2.x;
29          distY = n1.y - n2.y;
30          dist = sqrt((distX * distX) + (distY * distY));
31          direction = getDirection(distX, distY);
32          push = (1 / ((dist * dist) + 1)) * pushFactor;
33          if (dist < k && dist > -k) {
34            pushX = cos(direction) * push;
35            pushY = sin(direction) * push;
36            if (pushX > 15) {pushX = 15;}
37            if (pushX < -15) {pushX = -15;}
38            if (pushY > 15) {pushY = 15;}
39            if (pushY < -15) {pushY = -15;}
40            float newX = n1.x + pushX;
41            float newY = n1.y + pushY;
42            float newDistX = newX - centerX;
43            float newDistY = newY - centerY;
44            float newDist = sqrt((newDistX * newDistX) + (newDistY * newDistY));
45            if (newDist > 1.2 * radius) {
46              pushX = 0;
47              pushY = 0;
48            }
49            else {
50              n1.x += pushX;
51              n1.y += pushY;
52            }
53          }
54        }
55
56        for (Edge e: edges) {
57          distX = 0;
58          distY = 0;
59          dist = 0;
60          moveX = 0;
```

```
61          moveY = 0;
62          move = 0;
63          if (e.source == n1) {
64            distX = e.target.x - n1.x;
65            distY = e.target.y - n1.y;
66          }
67          else if (e.target == n1) {
68            distX = e.source.x - n1.x;
69            distY = e.source.y - n1.y;
70          }
71          dist = sqrt(distX * distX + distY * distY);
72          if (dist > k || dist < -k) {
73            direction = getDirection(distX, distY);
74            move = dist * dist * pullFactor;
75            moveX += cos(direction) * move;
76            moveY += sin(direction) * move;
77            if (moveX > 15) {moveX = 15;}
78            if (moveX < -15) {moveX = -15;}
79            if (moveY > 15) {moveY = 15;}
80            if (moveY < -15) {moveY = -15;}
81          }
82          n1.x = n1.x + moveX;
83          n1.y = n1.y + moveY;
84        }
85      }
86    }
87  }
```

6.5.4 Graph Interaction

Processing allows interaction with the visualization through the use of the computer mouse and the keyboard. As such, all graph interactions use a combination of these input devices. When the mouse is clicked, a left click will enable either the creation of a new node (when the keys “o,” “p,” “f,” “t,” or “l” are pressed, depending on the type of node to add) or the selection of a node (if the control key is pressed and the cursor is on an existing node). Additionally, if the mouse is in a specific area (the reset and save “buttons” on the screen) either the visualization is reset or a screenshot of the visualization is taken and saved to the specified location (lines 11-14). A right click of the mouse, with the control key down, will delete the node on which the cursor is placed (lines 16-20).

```
1   void mouseClicked() {
2     if (mouseButton == LEFT) {
3       if (keyPressed == true) {
4         if (key == 'o') { createNode(1); }
5         if (key == 'p') { createNode(2); }
6         if (key == 'f') { createNode(3); }
7         if (key == 'l') { createNode(4); }
```

```
8         if (key == 't') { createNode(5); }
9         if (keyCode == CONTROL) { selectNode(); }
10      }
11      if (mouseX <= 120 && mouseY <= 30) { resetAll(); }
12      if (mouseY >= 35 && mouseY <= 65) {
13        if (mouseX <= 120) { save("output_graph.jpeg"); }
14      }
15    }
16    if (mouseButton == RIGHT) {
17      if (keyPressed == true) {
18        if (keyCode == CONTROL) { deleteNode(); }
19      }
20    }
21  }
```

The selectNode function is used to highlight a specific node the interacting nodes and edges. First, the selected variable is set to "1" indicating it is turned on. If the node is already selected, then it is set to "0" to turn it off (lines 3-10). Then, all of the edges are check to determine if they include the selected node. In the case of "OR" and "AND" nodes, those nodes are also turned on to ensure than the full relationship is highlighted, not just part of it.

```
1   void selectNode() {
2     for(Node n: nodes) {
3       if (dist(mouseX, mouseY, n.x, n.y) < 10) {
4         if (n.selected == 0) {
5           n.selected = 1;
6         }
7         else if (n.selected == 1) {
8           n.selected = 0;
9         }
10      }
11    }
12    for (Edge e:edges) {
13      if (e.source.selected == 1 || e.target.selected == 1) {
14        if (e.target.label.contains("OR") || e.target.label.contains("AND")) {
15          e.target.selected = 1;
16        }
17        else if (e.source.label.contains("OR") || e.source.label.contains("AND"))
    {
18          e.source.selected = 1;
19        }
20      }
21    }
22  }
```

If a node is to be deleted, the deleteNode function is run. This function first identifies which node is under the cursor. Then any edges attached to the node are removed prior to the node itself being removed.

```
1   void deleteNode() {
2     for(int i = nodes.size(); i-- !=0;) {
3       Node n = nodes.get(i);
4       if (dist(mouseX, mouseY, n.x, n.y) < 10) {
5         for (int j = edges.size(); j-- !=0;) {
6           Edge e = edges.get(j);
7           if (e.source == n) {
8             edges.remove(j);
9           }
10          if (e.target == n) {
11            edges.remove(j);
12          }
13        }
14        nodes.remove(i);
15      }
16    }
17  }
```

In order to move a node, the mouse is left-clicked while on a node and dragged to the desired location. To ensure that only a single node is selected, the draggedNode variable is used. As the cursor moves with the node still selected, the position of the node continually updates. Upon release of the mouse button, the draggedNode value returns to -1 and the node is "dropped."

```
1   void mouseDragged() {
2     if (mouseButton == LEFT) {
3       if (draggedNode == -1) {
4         for(Node n: nodes) {
5           if (dist(mouseX, mouseY, n.x, n.y) < 10) {
6             nSelect = n;
7             draggedNode = 1;
8           }
9         }
10      } else {
11        nSelect.x = mouseX;
12        nSelect.y = mouseY;
13      }
14    }
15  }
16
17
18  void mouseReleased() { draggedNode = -1; }
```

Lastly, the user has the ability to create a new edge between two nodes. When the left mouse button is pressed and either the "a" or "z" keys are pressed, depending on the type of interaction desired, the source node is selected. This is determined by a proximity of the cursor to the node (lines 6-10). The newEdgeSource variable is used to ensure that a single source and target are selected. After the source has been selected, the user (while

still pressing either “a” or “z”) selects the target node to create the edge. At this point, the edge is created, added to the array, and newEdgeSource is returned to -1 to prepare for the next edge creation (lines 22-24).

```
1   void mousePressed() {
2     if (mouseButton == LEFT) {
3       if (keyPressed == true) {
4         if (key == 'z' || key == 'a') {
5           if (newEdgeSource == -1) {
6             for(Node n: nodes) {
7               if (dist(mouseX, mouseY, n.x, n.y) < 10) {
8                 newSource = n;
9                 newEdgeSource = 1;
10              }
11            }
12          }
13          else {
14            for(Node n: nodes) {
15              if (dist(mouseX, mouseY, n.x, n.y) < 10) {
16                newTarget = n;
17              }
18            }
19            if (key == 'z') { newEdgeType = 3; }
20            if (key == 'a') { newEdgeType = 1; }
21
22            Edge e1 = new Edge(newSource, newTarget, newEdgeType);
23            addEdge(e1);
24            newEdgeSource = -1;
25          }
26        }
27      }
28    }
29  }
```

6.6 Conclusions

This chapter continues to support the third research objective: development of an improved method for configuration change management. The previous chapter (Chapter Five) proposed the overall method and discussed the design enablers that would be necessary to support the proposed method. The focus of this chapter is on the first sub-question in support of the research objective: How can data visualization be used to increase the ability to understand component relationships in a system? This research question is answered through a review of relevant literature, a user study, and the development of a graph visualization software tool.

The literature review was conducted in order to understand how graph visualization can be implemented for configuration change management. The literature review focused on how data visualization is used to understand and manage large amounts of data. More specifically, graph visualization was identified for its usefulness in understanding the relationships between entities within a system. During the literature review, it was also identified that numerous factors can affect the usefulness of graph visualizations. This led to the second task to answer the above research question.

The user study was conducted in order to understand what aspects of the visualization graph (color, layout, and availability of information) affect the user's ability to understand and identify relationships between vehicle options and parts in a configuration system. The participants were given different graphs and tasked with answering questions regarding the configuration system portrayed in the graph. The results showed that color and layout did not have a significant impact while availability of information (the removal of unnecessary information) greatly increased the users' ability to answer questions about the configuration system. This information was then used in the development of the visualization software tool.

The graph visualization tool was developed using the Processing visualization programming language. Based on a set of inputs from one of the other supporting design enablers (interaction identification), the visualization tool creates a graph visualization of the configuration system. The software tool also allows for a wide range of interactions with the graph, including reshaping, adding and removing nodes and edges, and outputting the resulting graph for future use or evaluation.

6.7 Dissertation Roadmap

Chapter Six focused on the development and implementation of the graph visualization support tool. The next chapter (Chapter Seven) builds on this by presenting the methods and results of three validation techniques: a user study, implementation cases, and user feedback. The progress of this dissertation is shown in Figure 6.22 in which the completed portion is highlighted in green.

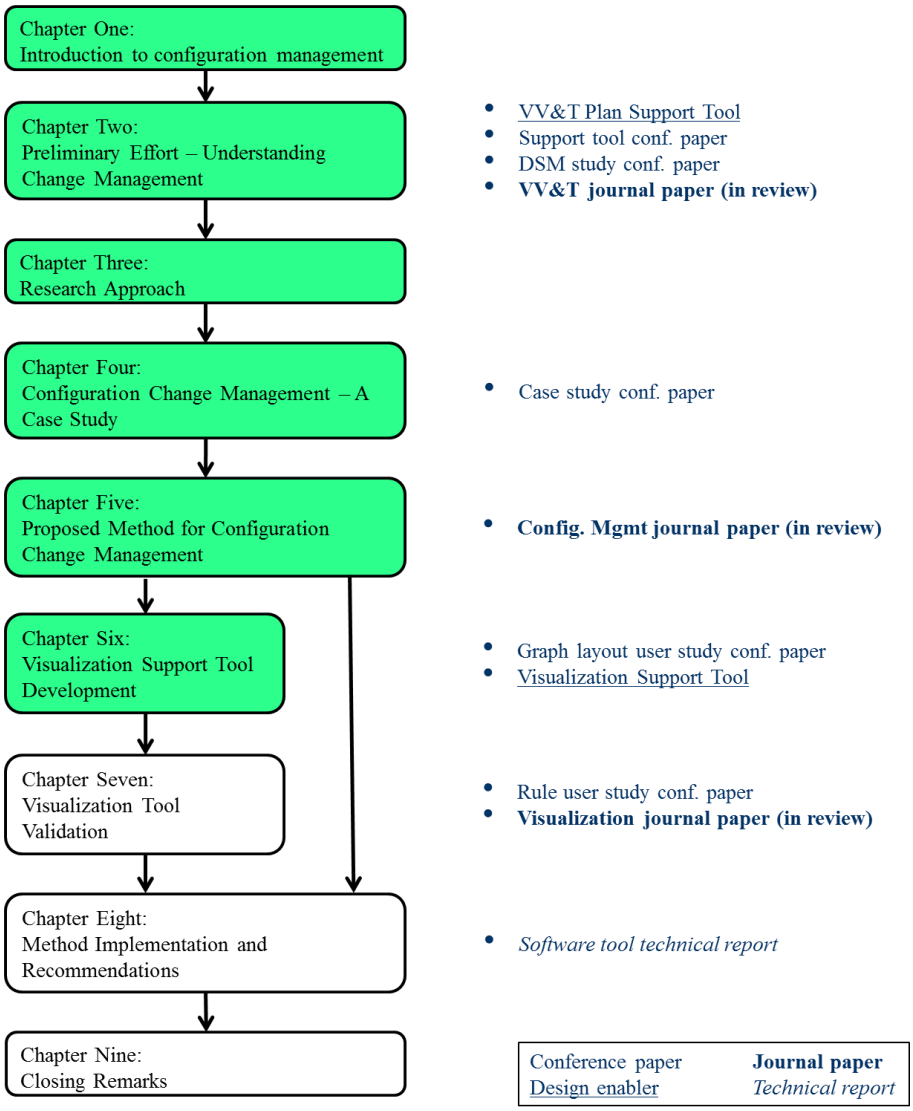

Figure 6.22: Dissertation roadmap

CHAPTER SEVEN: VISUALIZATION TOOL VALIDATION

The purpose of the research presented in this chapter is to validate the graph visualization support tool discussed in Chapter Six. Previous research has shown the need for rigorous validation of design research [139]. As such, the Validation Square [140] is used as a guideline for the validation of the visualization tool. The literature review conducted during the development of the visualization tool in Section 6.1 answers first aspect of validation – *accepting the construct's validity*. The visualization tool was evaluated through four implementation studies of ongoing configuration changes at the OEM, a validation user study on the tool's usefulness in rule implementation, and user feedback.

7.1 Implementation Cases

In order to test the visualization tool throughout its development, the researcher used the software to assist in validating in-progress configuration changes at the OEM. These problems were identified by both the researcher and the OEM users as exemplars appropriate for testing. This ties into the fourth aspect (*accepting usefulness of method for some example problems*) of the Validation Square in that the problems being used for evaluation are representative [140]. Additionally, because the tool was implemented by the researcher alongside the personnel at the OEM conducting their own validation, the fifth part (*accepting the usefulness is linked to applying the method*) is also fulfilled. The following sections discuss how the visualization tool was used to assist in the analysis of four ongoing changes at the OEM.

7.1.1 Case 1: Windshield Option Change

The first change for which the visualization tool was implemented involved changing the rules that governed the relationships between two vehicle options. Previously, the presence of option 358 required that option 3AP also be present. However, this led to an issue in assigning parts for the vehicle, so a change was made that made the presence of option 358 require the absence of option 3AP. This configuration change affected all models for the X5 and X6 vehicle lines in the European markets and was proposed in June 2014. The proposed change affected eight different options and explicitly required the change or addition of ten rules.

One question that was asked regarding the change was whether it would result in any windshields that were no longer valid. Essentially, *were there any windshields that required a configuration that no longer worked due to the change?* To assist in answering the question, a visualization graph for the windshields and all options affecting the ordering of windshields was created (Figure 7.1). In the graph, the available windshields are found on the left with labels of WS###, while the options are on the right and a represented by S###A. The links between them represent the rules according the grammar discussed in 6.4.2.1. A brief review of the graph shows that no windshield requires the both 3AP and 358 to be present. To conduct this review, the options of concern (3AP and 358) are identified in the graph. Then the windshield parts are identified in the graph (along the left hand side). The rules for each windshield part is checked for whether it requires (has a green arrow) to the options of concern. For example, WS905 requires option 358, but not 3AP. On the other hand, WS 401 requires 3AP, but not option 358.

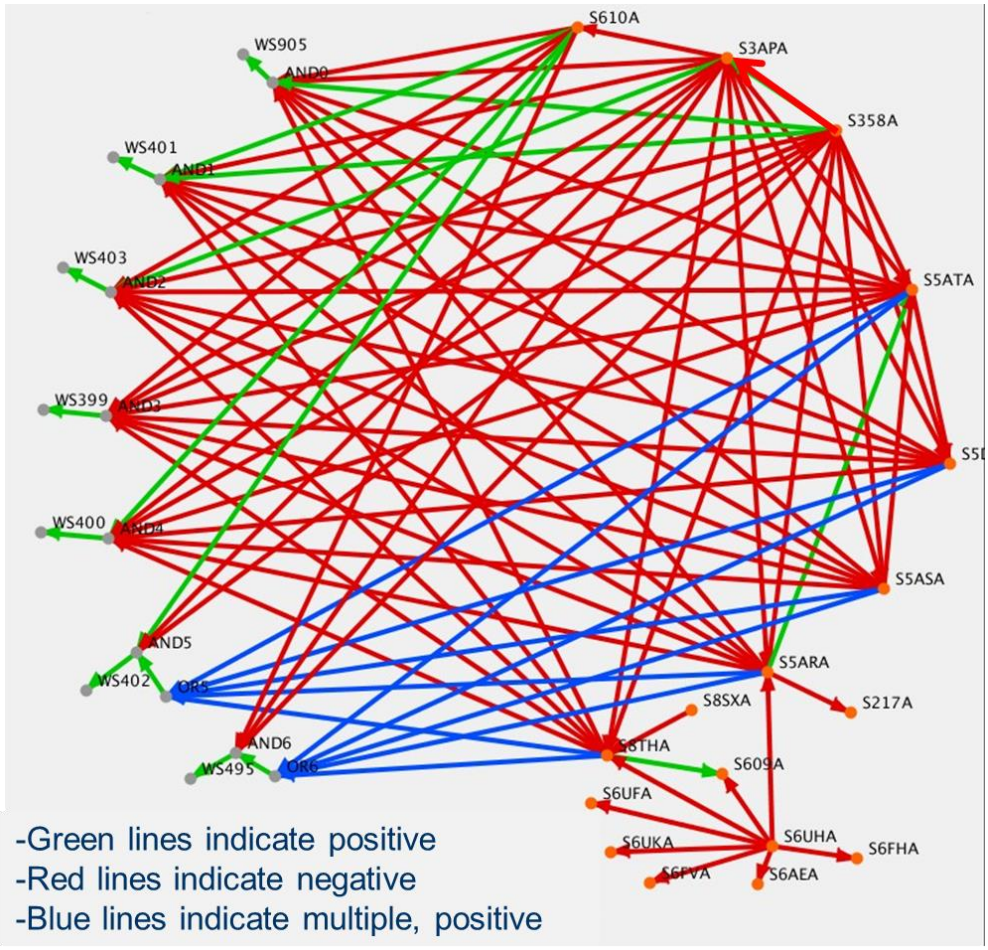

Figure 7.1: Visualization graph for windshield option change (Case 1)

This is the same conclusion that the change control personnel at the OEM came to while working concurrently on the configuration change. However, in the traditional approach, the OEM engineers spent approximately 2 hours analyzing the change. With the graph, the question was answered in minutes. In addition, the use of the visualization assisted the researcher in understanding and explaining to the change control personnel as to why the change was written as is and to validate that there were no other configuration conflicts resulting from the implementation of the change.

7.1.2 Case 2: Indian Country Model Change

Another change in which the visualization tool proved helpful involved changing the standard Indian country model for the one of the diesel SUVs from one model to another. The intent of the configuration change validation in this instance was to determine whether any additional rules needed to be added, other than changing the availability of the option code between the two models.

In order to support the validation of this change, two separate graphs were created, one for each model code that was effected. The graph for the model code that currently existed as the model for use in India is shown in Figure 7.2. It should be noted that this is an earlier instance of the graph visualization tool and the readability of the graphs has since been improved to increase usability.

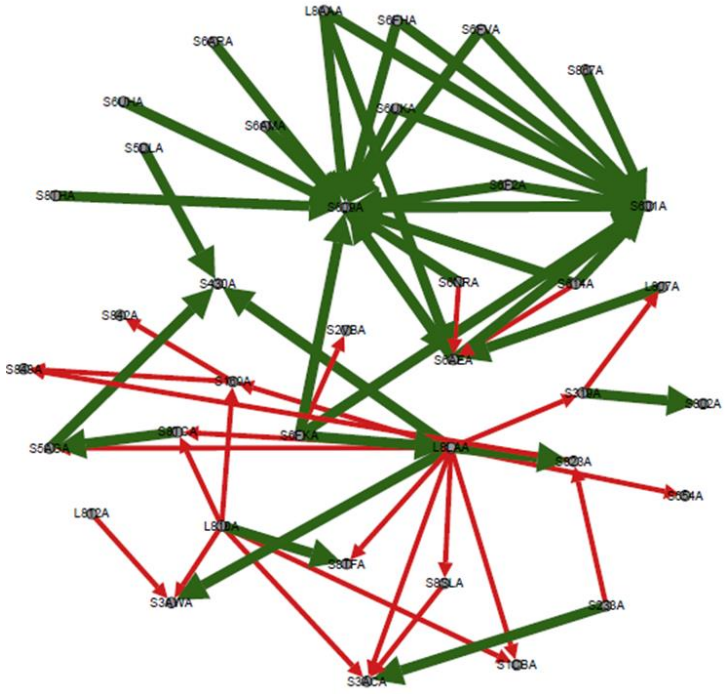

Figure 7.2: Visualization graph for existing model

The graph for the model that would replace the previous model is shown in Figure 7.3 below.

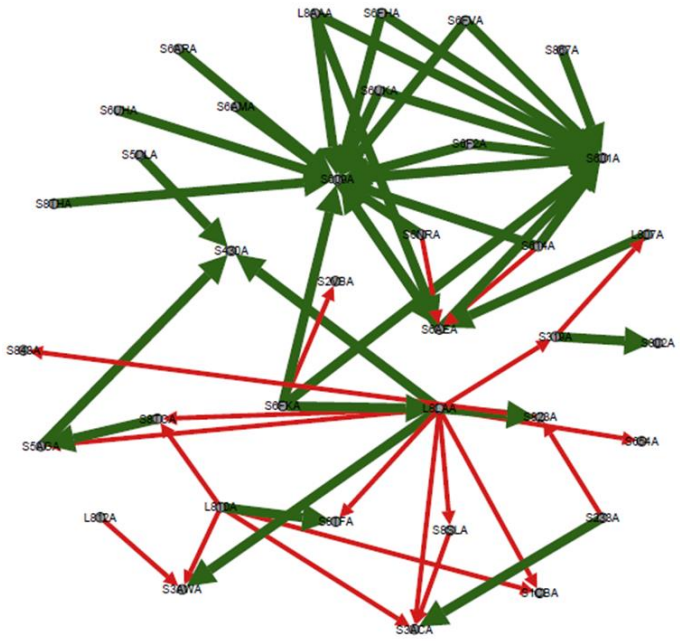

Figure 7.3: Visualization graph for replacement model

By comparing the two graphs, it was possible to determine if there were any differences between the options and rules for the two models.

A brief inspection of the graphs above shows that a series of rules/options are missing from the middle of the left side of the graph. Essentially, this meant that change the engine size (the only significant change between the two model codes) resulted in no longer disallowing a certain emissions standard in the ruleset. When asked if this was intentional, the change control personnel at the OEM were not aware of the inconsistency.

To determine whether it would have been faster to create a list of the options and rules present for each model, an additional study was conducted. In this study, the time was determined to create the visualization and then inspect to determine where any

differences may lie. This time was compared to the amount of time it would take to identify the difference using the methods in place at the OEM. It was determined that the use of the visualization graph reduced the required time by 75%.

7.1.3 Case 3: Emissions Standards Option Change

Because the configuration changes are not written by personnel in the change control group at the OEM, understanding the reasoning and implications behind the change can be difficult when attempting to validate a specific change, even if the validation itself is simple. This was the case with the third configuration change. This change focused on the emissions standard levels (S161A, S167A, and S169A) for four vehicle models (KS01, KS02, LS01, LS02) of the X5 vehicle line. The change was proposed and evaluated in July 2014. After the analysis, it was determined that models LS01 and LS02 were being created to allow a specific emission standard (S167A), which was not available for the other two models.

7.1.4 Case 4: Australian Country Option Addition

The final change for which the visualization tool was implemented was the addition of the Australian country option to a current model. Essentially, the OEM wanted to expand its vehicle offerings in Australia.

In order to validate this change, a model was selected that most closely matched the model being changed, but that already included the Australian country option. This mirrored the method used by the change control personnel at the OEM. Two visualization graphs were then created for the models. The first graph showed the model that already

had the option, shown in Figure 7.4. The second graph showed the model to which the option was being added, shown in Figure 7.5. In addition, a blank node ("New Node 2") was added to the graph to mimic the option being added to the model. Also, the corresponding rules between the new option and other related options were added to the graph to create a close duplicate to the existing model.

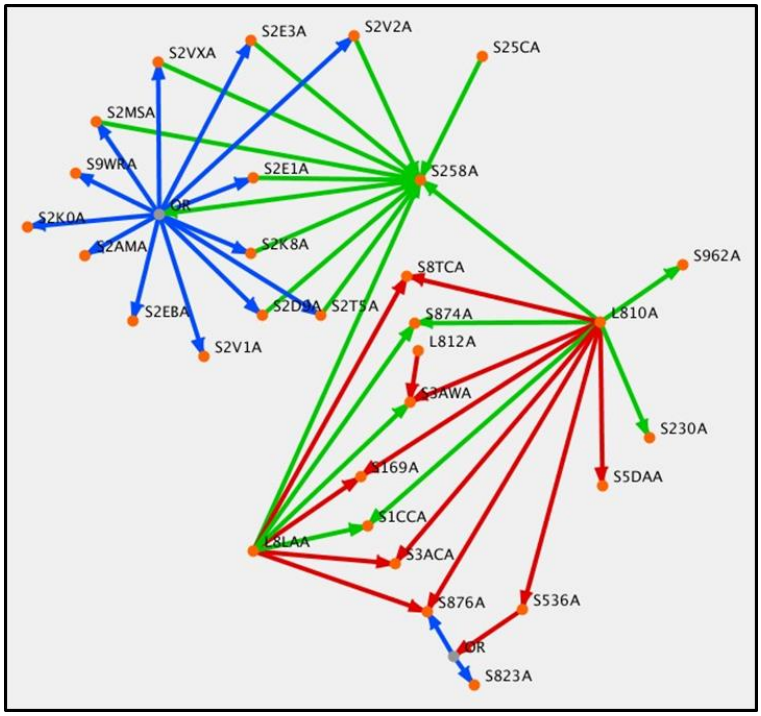

Figure 7.4: Existing model graph with the Australian country option already available

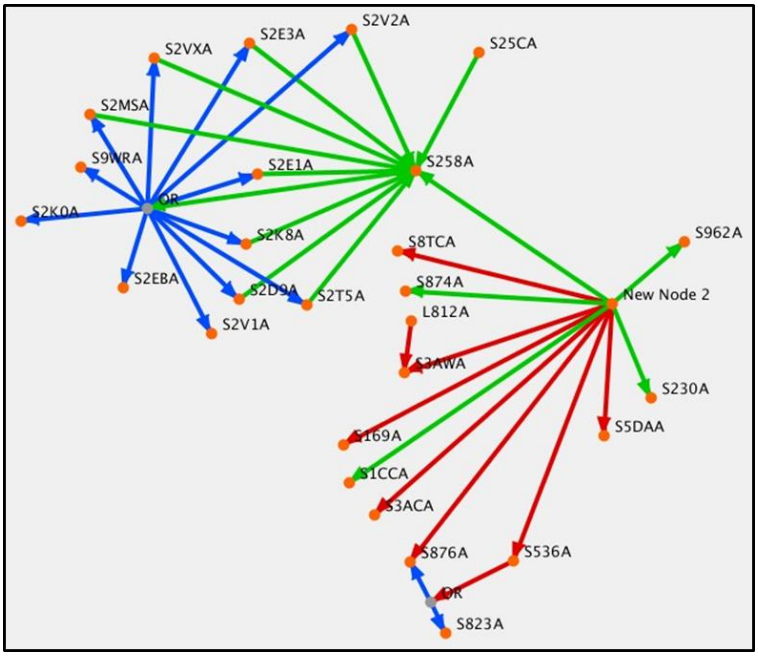

Figure 7.5: Graph of the model to which the country option will be added

Based on an inspection of the above graphs, no issues were identified to result from adding the Australian country option to the new model. The only changes were that two other options (S2AMA and L8LAA) were not available for the new model and those would not be of concern. An additional application of this tool is that the new options and ruleset that were created using the visualization tool could be exported to provide the written rules/options that needed to be modified in the ruleset to implement the change.

7.2 Rule Authoring User Study (Validation Study)

One of the potential applications of the graph visualization support tool is to allow the user to export any rules or options created through the graphical user interface. These new rules or options could then be implemented directly into the OEM's rule database to avoid having to convert the rules to the correct format and enter them manually. As such,

a user study was conducted to evaluate the usefulness of the graph visualization support tool for assisting in rule implementation. In addition, the user study evaluated the ability of an untrained user (the participants) to understand and implement the visualization support tool in conjunction with proposed configuration changes. The details of the validation user study are discussed in the following sections.

7.2.1 Research Questions for Validation Study

Research has shown that different types of data representation may be more accommodating for answering different types of questions about the system being represented. Additionally, the use of a graphical user interface (GUI) for making changes to a system or for implementing changes is a common method for simplifying data maintenance. This led to the following research questions:

- How does the use of a graphical method for rule implementation affect the user's ability to accurately author rule changes in a system?
- How does the use of a graphical method for rule implementation affect multiple users' abilities to consistently author rule changes in a system?

It is hypothesized that the use of a graphical representation for rule implementation will increase both the accuracy and consistency for making changes to the rule database. This hypothesis is made because the graphical representation has been shown previously to increase the user's ability to understand the system better, and a better understanding should lead to increased accuracy when implementing the changes.

Based on the initial results, which showed a marked decrease in the effectiveness using the visualization method, the following research question was added:

- How does the amount of training and familiarity with the visualization method affect the user's ability to implement rules in the system?

It is hypothesized that implementing a small training period will greatly increase the familiarity of the participants with the method and will result in increased effectiveness at implementing the rules.

7.2.2 Experimental Procedure for Validation Study

7.2.2.1 Variables for Validation Study

In order to answer the above research question, a user study was developed and executed. The user study consisted of two variables: the method for implementing the rule changes and the amount of training on the new visualization method. The first variable consisted of two levels: implementation of changes through a graphical representation or implementation using a text-based representation. The purpose of this variable was to see if using a different method increased the user's ability to accurately and consistently implement the changes. The second variable had two levels, and only applied to the group assigned the visualization method: a minimal amount of training on what the new method is and a slightly increased training period (approximately five minutes) showing how the new method can be used to show changes to the system. This variable was developed based on concerns during the initial results that a lack of familiarity with the new method was resulting in decreased scores, as opposed to the actual effectiveness of the new method.

7.2.2.2 Participants for Validation Study

The participants of the user study were senior, undergraduate, mechanical engineering students at Clemson University. All of the students ranged in age between

approximately 19-24 years of age and had less than one year of coursework remaining prior to graduation. The students were chosen for the experiment because, as seniors, they have a similar level of experience to new employees at a company. Additionally, selecting the participants from this course ensured that the students would have a similar educational background. At the time of the experiment, all of the students were enrolled in the senior mechanical engineering design course at Clemson University.

7.2.2.3 Environment for Validation Study

The user study was conducted in two sessions during a normally scheduled class period of the senior mechanical engineering design course, with each group only attending a single session. The control group and the experimental group with minimal training attended the first session and the experimental group with additional training attended the second session. The students were told in advance that they would be conducting an in-class exercise while the instructor was unavailable. The setting for the experiment was the classroom in which the course usually met (for two groups) or in a nearby classroom with a slightly different setup (for the third group). While the classroom layouts were different for the groups, the researcher did not believe this would be a factor in the results as all environments were standard classroom types, with which the participants were familiar. The classroom layouts were typical, auditorium-style classrooms with a projector in the front of the room and tables for the students to sit at, either circular or in rows. Additionally, minimal distractions were present during the experiment. In general, the experience of the students due to environmental conditions was as uniform as possible.

7.2.2.4 Experimental Procedure for Validation Study

For the first session, the students arrived for the normally scheduled class and sat at tables of their choice. Once all of the students had arrived and were seated, the user study packets were randomly distributed to the students. Each packet contained a set of documents according to whichever group the participant was assigned. The contents of the packets will be discussed in the following section. Once the packets were handed out, the participants were separated based on the packet that they had received. Once in separate classrooms, each group was given a brief class instructing the students on the background of the research and the specific instructions for their part of the research. The presentations were developed to provide similar levels of detail regarding the study and to take a similar amount of time to complete. This was necessary to ensure that all participants had a similar level of familiarity with the processes being used; none of the students had experience with the methods begin studied prior to the research being conducted. Following the instructional period, the students were allowed to ask any questions regarding the survey or the data visualization technique. The participants were then given 40 minutes to conduct the experiment; however, upon completion of the study and a brief survey for additional data collection, the students were allowed to turn their packets in early and leave the classroom. While the participants were assigned to groups, the grouping was only conducted to control variables; all work during the study was conducted individually.

The second session mirrored the first session, except only one group was present, so the participants did not have to be divided. Additionally, the second session included the increased training period during the presentation. The increased training period

consisted of providing an example (from a different rule database and product) of how a change could be implemented to the system. The increased training period took less than five minutes to conduct.

7.2.2.5 Packet Contents for Validation Study

The materials that each participant received with their packet depended upon which group they were in, which was assigned randomly during distribution of the packets. The control group, which implemented the changes using a text-based representation, received an instruction sheet that contained the instructions, as well as a brief overview of the rule grammar; three different configuration change documents, which contained information regarding the background, solutions and implementation for the change; and the rule system documents, which would be modified by the participant according to the corresponding configuration change document. Both experimental groups, which implemented the changes using a graphical representation, received an instruction sheet that contained the instructions, as well as a brief overview of the rule visualization techniques; three different configuration change documents, which contained information regarding the background, solutions and implementation for the change (the same documents provided to the control group); a single copy of the rule database, for reference only; and three rule system graphs (Figure 7.6), which would be modified by the participant according to the corresponding configuration change document. The configuration changes chosen for the study were developed based on the types of changes that occur at a local automotive manufacturing facility. Additionally, the documents were created to

mirror the change documents used at the OEM. The full packets received by all groups (Groups A and C received the same packets) are found in 9.2Appendix G:.

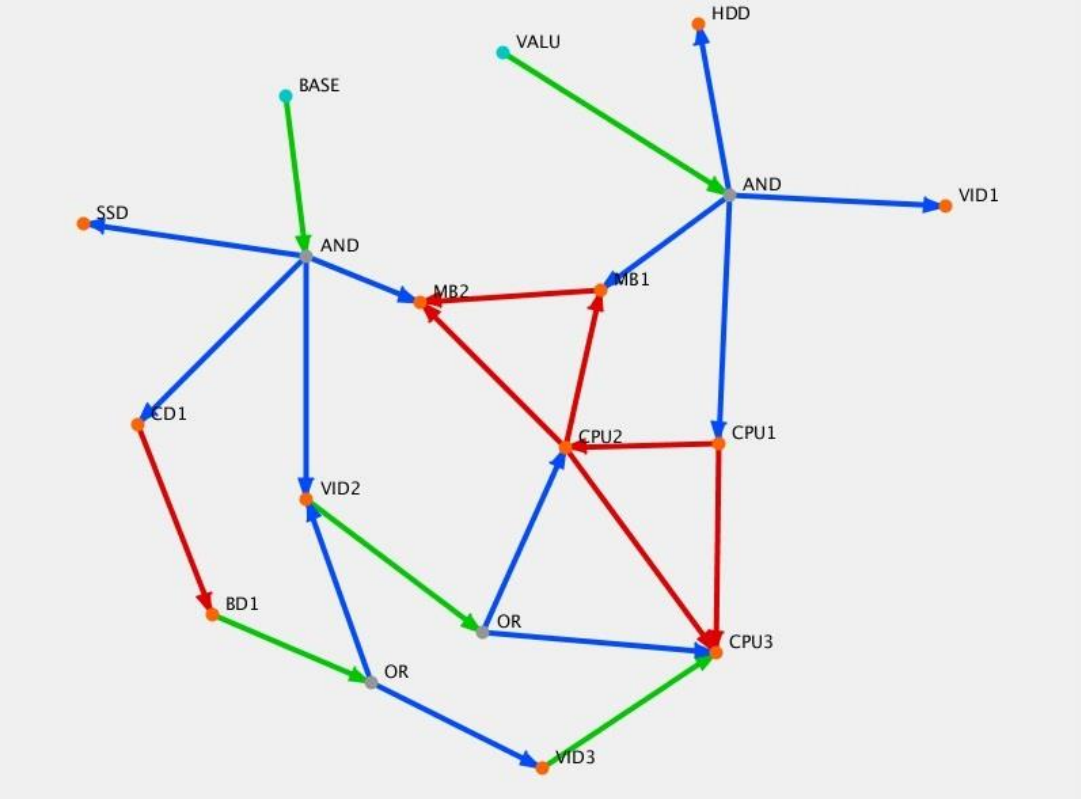

Figure 7.6: Rule system graph provided to the experimental groups

7.2.3 Evaluation Protocol for Validation Study

The protocol analysis of the user study is relatively straight-forward. The resulting rule systems were evaluated as to whether or not the resulting system accurately portrayed the changes specified in the configuration change documents. In many instances, multiple different results could be considered as correct, as long as the allowable configurations that would result from the rule system would be the same. To account for the possibility of multiple, different correct answers, the resulting configuration rule sets were evaluated to determine if the set of allowable configurations would be the same for both the expected

answer and the participants' answers. To assist in identifying the effectiveness of each method, the changes were broken down into components of the change. For example, adding a package to the system requires adding the package, and adding the individual rules that apply to the package. Each of the rules would could as a component of the change. Because a single grader was used to evaluate all of the results, no inter-rater reliability assessment was conducted. Additionally, an intra-rater reliability assessment was not conducted.

7.2.4 Evaluation Metrics for Validation Study

The metric that was used for evaluation is accuracy of the resulting rule database. The researcher considered using a degree of accuracy for this metric, but decided instead that simply correct/incorrect would provide a more consistent method for scoring the results. This was decided because for any given change set, multiple results could be a correct interpretation of the rule set. This would lead to difficulty in determining which correct answer to use as the basis for grading each result.

7.2.5 Results for Validation Study

A total of 74 results (3 configuration changes per result and 4 components per change) were collected from the participants and evaluated during the user study. The results were evaluated by a single grader, as previously discussed, and the data was tabulated into spreadsheets for ease of analysis.

For accuracy, the results were consolidated according to which group the participants were in (control, experimental, and experimental w/ training). This was done

in order to see how the rule implementation method affected the accuracy of the resulting rule sets. The results for each group for changes 1, 2, and 3 are shown in Table 7.1, Table 7.2, and Table 7.3, respectively.

Table 7.1: Number and percent of correct responses by group for Change 1

Change 1	1.1		1.2		1.3		1.4	
Group	#	%	#	%	#	%	#	%
Experimental	26	100%	15	58%	26	100%	25	96%
Control	25	100%	21	84%	24	96%	25	100%
Training	23	100%	20	87%	22	96%	23	100%

Table 7.2: Number and percent of correct responses by group for Change 2

Change 2	2.1		2.2		2.3		2.4	
Group	#	%	#	%	#	%	#	%
Experimental	25	96%	15	58%	18	69%	17	89%
Control	25	100%	25	100%	25	100%	19	79%
Training	23	100%	22	96%	22	96%	17	85%

Table 7.3: Number and percent of correct responses by group for Change 3

3	3.1		3.2		3.3		3.4	
Group	#	%	#	%	#	%	#	%
Experimental	26	100%	23	88%	9	35%	9	35%
Control	23	92%	23	92%	25	100%	25	100%
Training	23	100%	19	83%	12	52%	12	52%

7.2.6 Discussion for Validation Study

It should first be noted that there are limitations in the analysis. While the participants had no previous experience with either method for rule implementation, the use of spreadsheets and the basic logical grammar used in if-then statements is

commonplace. However, the use of node-link graphs to visually represent configuration rules, and the grammar that is associated with it, is something the participants were unlikely to have any experience with at any level. While a similar amount of training was provided to the control and experimental groups, the experimental group that was given the graphs was less likely to fully understand and become familiar with the process during the brief training period. This likely caused the decrease in the capabilities of the graph visualization method for rule implementation and was the reasoning for the second session with an increased training period for the training group.

When considering the accuracy of the results based on the method of rule implementation, a definite trend existed where the accuracy of the answerable questions greatly increased with the use of the text-based (control) method. However, a brief training session with the second experimental group significantly decreased the gap. Figure 7.7, Figure 7.8, and Figure 7.9 illustrate the percentage of correct responses for each question for all of the groups.

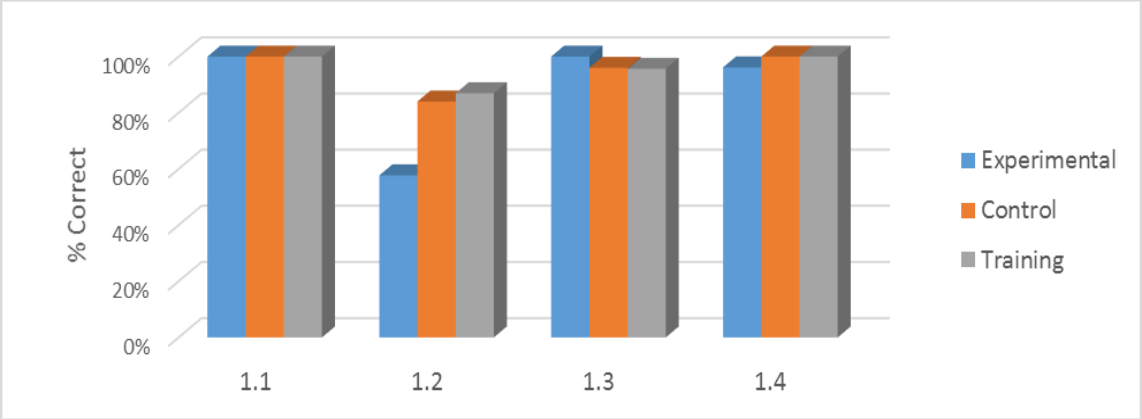

Figure 7.7: Percent correct responses for Change 1

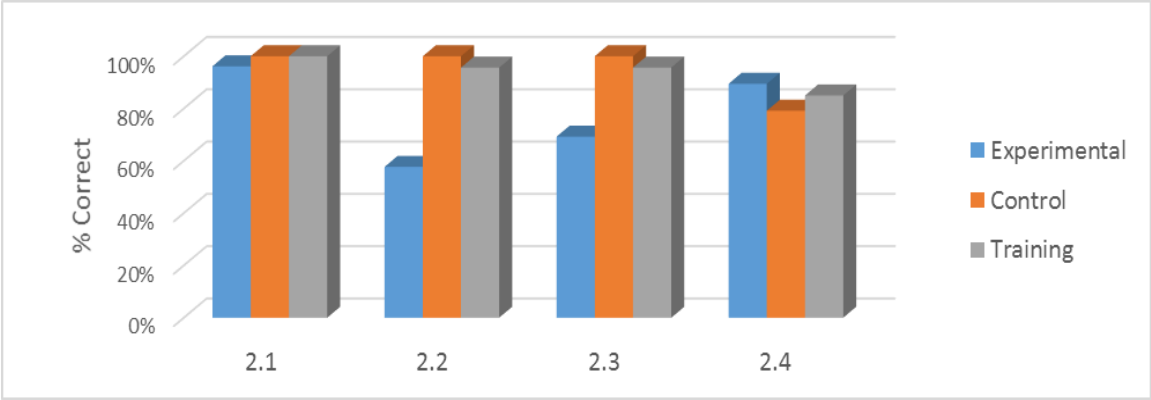

Figure 7.8: Percent correct responses for Change 2

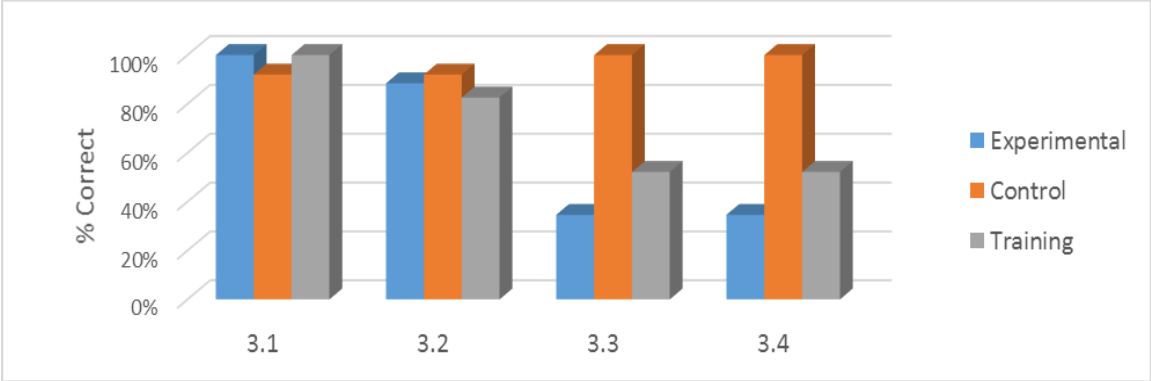

Figure 7.9: Percent correct responses for Change 3

From the above graphs, it is clear that, in each situation, the text-based method for rule implementation surpassed the visualization-based method for accuracy, when the groups received the same amount of training. This was especially true for Changes 2 and 3, the changes that involved the addition or modification of packages. Because package declarations are the most complicated rules in the database, it is likely that the participants were not familiar enough with the visualization method to accurately convey the correct relationships in the more complicated rules.

With the additional training period, the accuracy of the responses for the second experimental group increases significantly and only lags behind the control group for the third change. After reviewing the third change, the authors realized that an issue with the wording in the question resulted in confusion as to how directionality in the visualization was applied. This is likely the cause of the significant drop in accuracy for both of the visualization groups for parts 3.3 and 3.4.

7.2.7 Findings for Validation Study

The purpose of this paper was to describe a user study that was conducted in order to determine whether the use of a visualization-based method for configuration rule implementation would increase the accuracy of the rule sets generated as a result of the proposed changes. The researcher hypothesized that using the visualization-based method would increase the accuracy of the results. The results proved the hypothesis to be false, in that the average accuracy level for the text-based method was higher for all of the changes, and significantly higher for the more complicated changes, or those requiring package rule modification. The most significant limitation in this study was the difference in the difficulty of learning the methods; the text-based method, using a spreadsheet and standard if-then logic, was likely much easier for the participants to understand in the short training period prior to the study. This could have led to a decrease in the familiarity of the participants with the visualization-based method, resulting in decreased scores for that group.

As a result of this limitation, a second study was conducted in which a group of participants was given the same materials as the visualization group, but was also provided

with an additional amount of training (approximately five minutes) on the graph visualization method. It was hypothesized that the increased training would lessen the delta between the experimental and control groups. This hypothesis was proven to be mostly true in that, for the majority of the changes, the experimental group with training performed as well as the control group.

Possible future work includes conducting an additional user study where the participants are not provided with the rules that are to be implemented; instead, the participants would have to use the rule database to figure out what rules had to be implemented in order to correctly implement the required solution. This would require a greater amount of critical thinking about and understanding of the change, which is likely to be better suited for the visualization-based, rather than text-based, method for configuration management. The additional experiment would be structured similarly to this study, with the primary difference being the amount of information provided to the participants

7.3 User Feedback

In order to fully validate the usefulness of graph visualization for configuration management, user feedback was gathered in the form of a targeted interview with a Launch and Change Controller at the OEM. The interview was conducted with interviewee #2 at the end of the development of the configuration management method. The interview lasted approximately one hour. During the interview, the researcher reviewed the visualization design enabler, including its usefulness, potential applications, and potential additional functionality. The interviewee stated that using graph visualizations would be most helpful

when evaluating highly complicated changes to the configuration rule system, as is the case in the example in Section 7.1.1. In these changes, the ability to quickly conduct path tracing through the graph would greatly assist in understanding what other options would be affected by the proposed change. Additionally, visually inspecting for patterns in the graphs would increase the likelihood of identifying rule conflicts or redundancies. However, the interviewee also stated that the addition of a conflict detection algorithm within the graph visualization tool would greatly increase its usefulness. This would remove the need for the user to conduct as many inspections of the graph, allowing the user to focus on the potential propagation pathways.

In addition, the interview also revealed that other common uses of the graph visualization tool would include the implementation of new packages and the introduction of new model codes to the configuration rule database, as is the case in the examples discussed in Sections 7.1.2 and 7.1.4. This is due to the level of interaction that is provided by the graph visualization tool. When adding a new package, the user is able to add the package and any associated rules and see how this can affect the system in unintended ways. When adding or changing model codes, the user is able to create multiple graphs to allow a comparison between an existing (proven) model code and the new (unproven) model code. While discussing the comparison of graphs for different model codes, the interview mentioned that automating the graph comparison and highlighting the difference between two graphs would increase the effectiveness of the tools by not having to rely on visual inspection alone. It was agreed, though, that having the visualization of the systems, with the differences highlighted, would be preferable to a just a list of differences between

the models because of the ability to see how those differences could affect other aspects of the rule database.

In conclusion, the interviewee stated that the graph visualization was a useful tool for configuration management that had already assisted in identifying potential issues in the limited implemented cases (as described in Section 7.1). As a result, the interviewee felt that the graph visualization would be used on a weekly basis in the future, at least once for each proposed change, and more for more complicated changes, to review potential unintended consequences.

7.4 Conclusions

This chapter continues to support the third research objective: development of an improved method for configuration change management. Previous chapters proposed the overall method (Chapter Five) and presented the development and implementation of the graph visualization design enabler (Chapter Six). The focus of this chapter is on the second sub-question in support of the research objective: Does the implementation of a graph visualization design enabler assist in identifying errors and understanding the relationships in a proposed configuration change? This research question is answered through a user study, a limited implementation case study, and user feedback.

The rule implementation user study tasked participants with using the graph visualization method to implement proposed configuration changes into the rule system. During the initial run, the participants using the graph visualization did not perform as well as those using the spreadsheet-based method (the control group) due to a lack of familiarity with the visualization method. With a small amount of additional training, a second group

of participants were able to perform at the same level as the control group. Additionally, the graph visualization method showed promise when evaluating the reasoning behind the rules.

To further test the usefulness of the graph visualizations for configuration management, the method was implemented in four ongoing configuration changes at the OEM. In all four instances, using graph visualization allowed the user to more easily understand the implications of the proposed change and identify any errors resulting from the changes. Additionally, a time study was conducted on evaluating one of the changes with the visualization method versus using the existing method and a 75% time reduction when using the graph visualizations was identified.

Finally, an additional interview conducted with the proposed users of the graph visualization design enabler resulted in user feedback regarding its usefulness. The feedback showed that implementing the graph visualization design enabler would greatly increase the users' ability to understand the implications of proposed changes.

7.5 Dissertation Roadmap

Chapter Seven presented the validation of the graph visualization support tool through three evaluation techniques: a user study, four implementation cases, and user feedback. The following chapter (Chapter Eight) expands the validation to the entire configuration management method, including the other three design enablers (interaction identification, algorithmic validation, and complexity analysis). The progress of this dissertation is shown in Figure 7.10 in which the completed portion is highlighted in green.

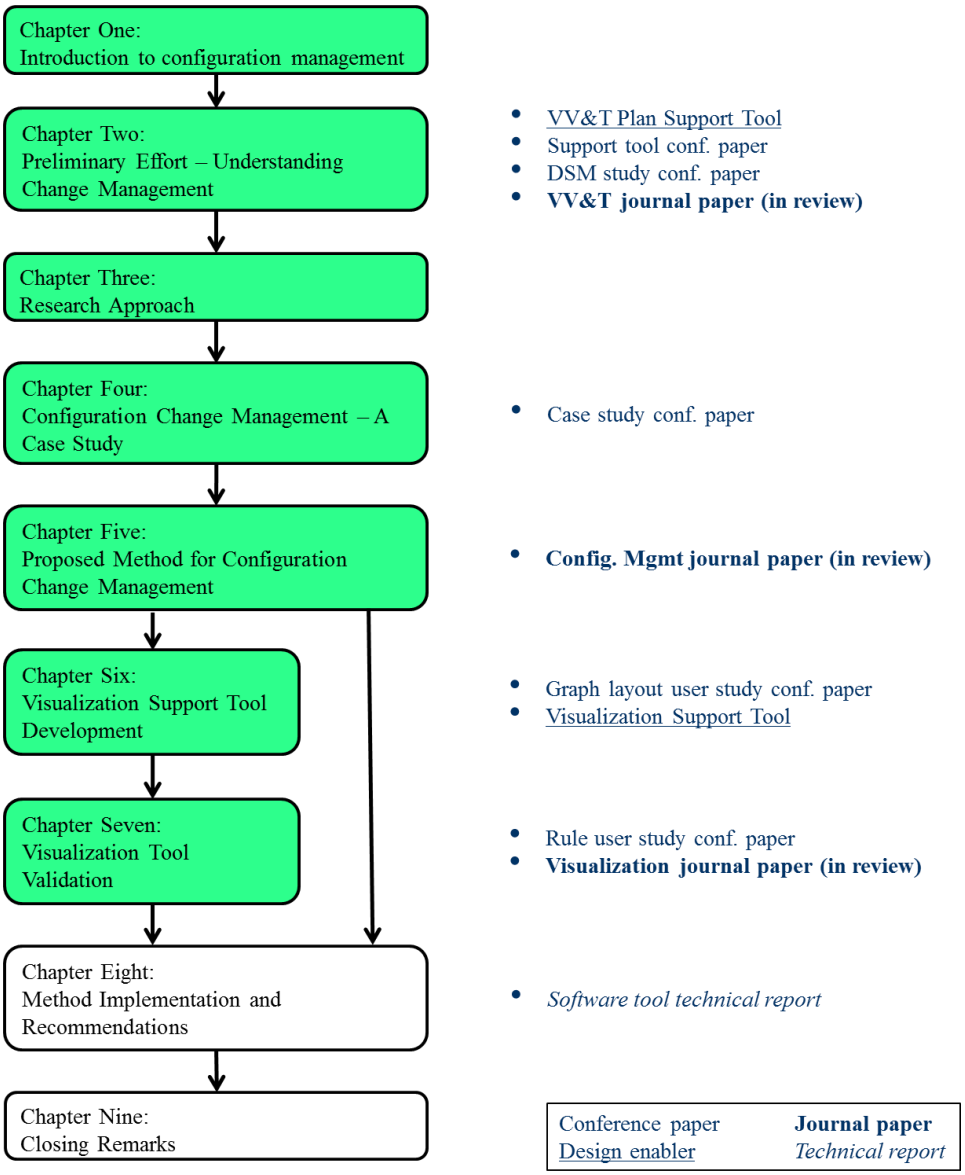

Figure 7.10: Dissertation Roadmap

CHAPTER EIGHT: METHOD IMPLEMENTATION AND RECOMMENDATIONS

The purpose of the research presented in this chapter is to validate configuration change management method discussed in Chapter Five. The configuration management method was evaluated through three implementation studies at the OEM and user feedback. Based on the findings of the implementation cases and the user feedback, a system architecture for to support the configuration management method is presented.

8.1 Implementation Cases

In order to validate the proposed process, a series of implementation cases were presented based on ongoing configuration changes or validation problems. The intent was to show how the proposed method could be used to assist in each of the implementation cases. These cases were presented by the OEM as challenge problems that were representative of the types of problems normally experienced at the OEM. The cases are discussed in the following sections.

8.1.1 Problem 1: Exhaust Tips

When building vehicles at the OEM, two different types of exhaust tips exist. The exhaust tips can either be round or square depending on the options that affect the exhaust system. For this OEM, the exhaust tips pass through the bumper. Therefore, the bumper needs to have a hole that corresponds to the shape and size of the exhaust tip that will pass through it. While there may be additional constraints between the bumper types and exhaust tip types, this is the primary concern due to the large number of tips and bumpers available. The goal of this is to determine whether the proposed method can prove that the

current configuration ruleset is free of any configurations where a round exhaust tip is placed with a square bumper or vice versa.

8.1.1.1 Solution

Because this is a validation of the existing system, as opposed to validating a proposed change, a modified validation flowchart is used (FIGURE). Essentially, only the review loop is being used in this instance.

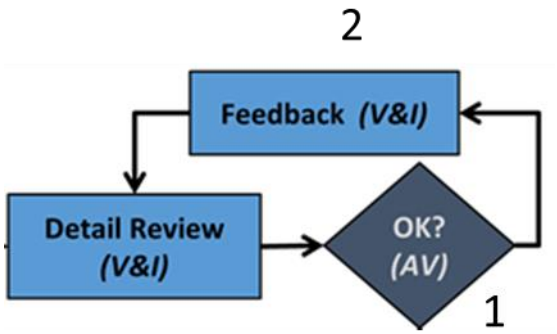

Figure 8.1: Method for evaluating the existing system

In order to validate the current configuration rule set the user would first be required to enter some additional data into the ruleset through the conflict detection tool. This additional information consists of the "part families" for the exhaust tips and the bumpers. For each type of part, two families would be created, one with all parts (bumper or exhaust tip) with a square interface and one with those with a round interface. Once the four part families have been created, the user would define a set of rules that attempt to force a round exhaust tip with a square bumper or a square exhaust tip with a round bumper. At this point, the user would run the satisfiability solver (Step 1 in Figure 8.1). If the satisfiability check is successful, then a configuration exists where the exhaust tip and

bumper are mismatched (round and square in same configuration). If the modified ruleset is not satisfiable, then no configuration exists where there is the possibility for mismatched exhaust tips and bumpers.

While the satisfiability solver will determine whether there is an incorrect configuration, it does not state where the problem lies. One method for narrowing down the configuration is to increase the number of specified rules in the modified ruleset. This can be done by forcing specific model/option/part codes in the ruleset and rerunning the satisfiability solver until the specific pair of parts is identified. From this point, the graph visualization tool can be used to assist in determining why this error exists in the configuration ruleset (Step 2 in Figure 8.1).

8.1.1.2 Conclusion

Based on using the above solution to validate the pairing of exhausting tips and bumpers, the researchers are confident that the proposed method would correctly identify any issues if they exist or validate the configuration set as correct if no errors are present. This implementation case required the use of the algorithmic validation tool to check for errors in the ruleset using user-modified rules and part families. Then the graph visualization tool would assist in identifying why the issue (if one exists) is present in the system. The complexity analysis tool was not used in the above solution as this implementation case does not concern a proposed configuration change, but rather a validation of the existing setup. Therefore, the complexity analysis tool would not help in determining the difficulty of validating the change or for which models the validation would be most difficult.

8.1.2 Problem 2: Passenger Visor Safety Labels

Due to the number of countries and languages for which the vehicles are assembled at the facility, many of the warning labels are required to be available in multiple languages. This results in a large number of part number variations with complicated rules to govern which label part number is used for a given vehicle configuration. In order to streamline the part management for this feature on the vehicle, it was decided that using graphical cues, rather than verbal cues to display the warning would meet the intent behind the safety regulations and would limit the number of different part numbers available. A complicating issue with this proposed change is that some of the visors come with the label already affixed, while others are attached on the vehicle assembly line. The goal of this is to determine whether the proposed method can assist in validating the updated rules and part numbers for the new labels prior to implementing the change.

8.1.2.1 Solution

In order to validate the proposed change discussed above, the configuration management method is implemented as shown in Figure 8.2.

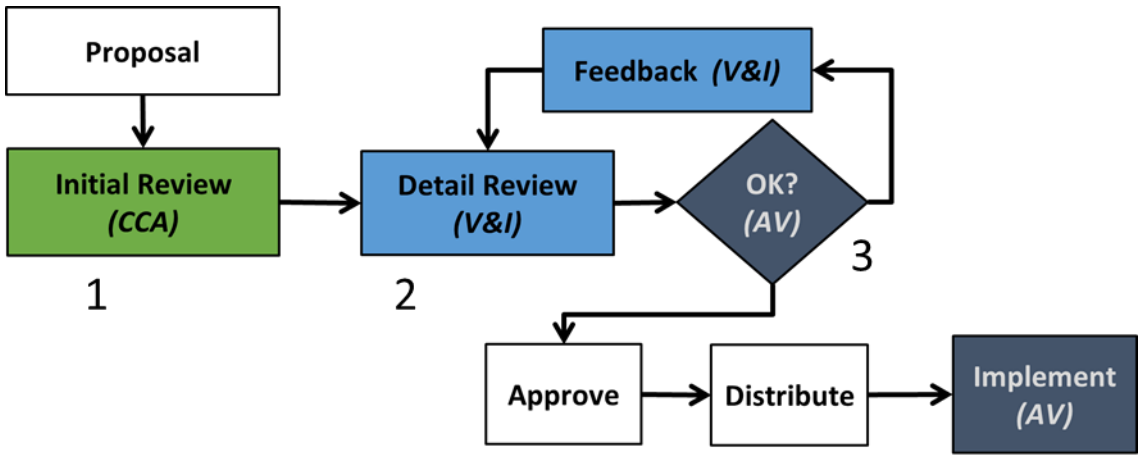

Figure 8.2: Implemented method for Problem 2

As this is a proposed configuration change that is not mandated, the first step would be to determine the difficulty in validating the change (Step 1 in Figure 8.2). This would be conducted using the complexity analysis tool. The user would enter the affected options and parts into the complexity analysis tool and the tool would provide the expected level of difficulty for validating each model that is affected by the proposed change. Based on the software output, the change managers would be able to make a recommendation on whether to move forward with the proposed change.

Assuming that the level of difficulty is not too severe for the assumed gain from implementing the change, the next step would be to conduct an exploration of the proposed change using the graph visualization tool (Step 2 in Figure 8.2). By entering the affected options and parts, the user would be shown a localized graph of the configuration system. From this, the user would be able to identify what options are likely to be affected by the change and which options should be considered when determining the validity of different configurations.

Additionally, the user could also use the algorithmic validation tool to ensure that a single label is being affixed during assembly (Step 3 in Figure 8.2). In order to accomplish this, the user would implement a part family, similar to the families discussed in Section 8.1.1.1. By then forcing this rule, the satisfiability solver would check to ensure that a single part from the family is being called based on the configuration specified. This could also be used to ensure that either a label or a part with the label is called, but not both.

8.1.2.2 Conclusion

Based on using the above solution to validate the proposed configuration change, the researchers are confident that the proposed method would correctly identify any issues in how the new part numbers are called. The graph visualization tool would assist in identifying which options, and potentially parts, would be affected by the change and should be considered when validating the potential configurations. This implementation case also required the use of the algorithmic validation tool to check for errors in the ruleset using user-modified rules and part families. The complexity analysis tool was used at the beginning of the solution to determine the expected difficulty to validate the change for each of the affected models.

8.1.3 Problem 3: Dark Carpet Validation

In United States markets, many customers did not like the fact that the light coloring of the beige carpets would easily show dirt over time. As a result, a change was proposed that would make a darker color the standard coloring for the lower half of the interior on

all configurations with the beige interior. Additionally, this change would only affect US vehicle models, as it was not an issue with foreign markets.

8.1.3.1 Solution

In order to validate the proposed change discussed above, the configuration management method is implemented as shown in Figure 8.3.

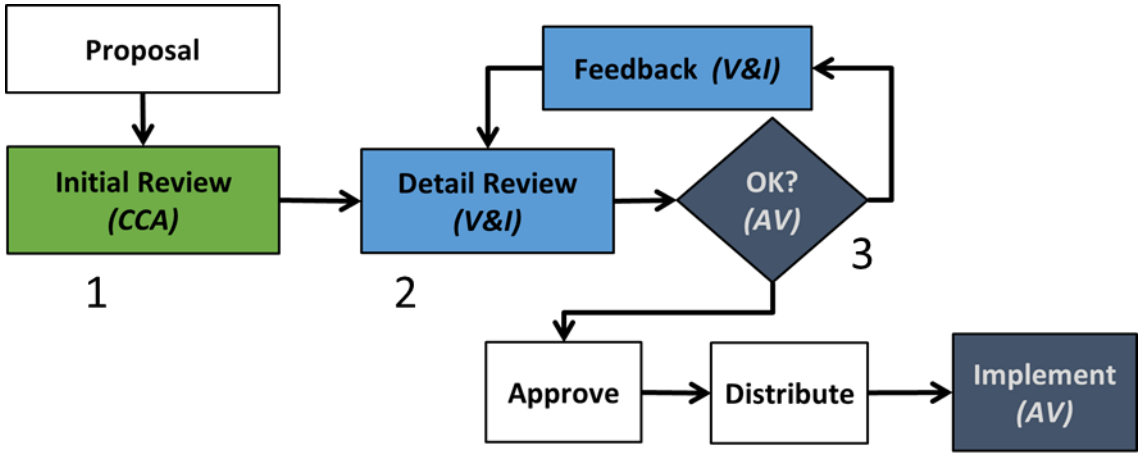

Figure 8.3: Implemented method for Problem 3

This is another example of a proposed configuration change that reflects customer desires as opposed to legal mandates or regulations. Therefore, the first step is to consider the potential difficulty in validating and implementing the change prior to moving forward. This would be conducted using the complexity analysis tool (Step 1 in Figure 8.3). The user would input the parts and options that are affected by the proposed change and the software tool would provide a list of the affected models and the expected difficulty in validating the changes for each. Based on the results, the change planners would determine whether or not to move forward with the change.

The next step would be to use the graph visualization tool to explore the proposed change to identify how the change would affect other options and parts (Step 2 in Figure 8.3). This would provide a subset of options and parts that should be considered when validating the new option and part configurations. Similarly to the previous problem, the change engineer could also use the algorithmic validation tool to ensure that the correct parts were being called and that duplicate parts were not being called (Step 3 in Figure 8.3). To accomplish this, the user would once again input part families, consisting of the darker colored interior parts and specify rules forcing the inclusion of a part from this part family. In the event of any inconsistencies, the graph visualization tool would be used to explore the identified issue to understand why the error occurred.

8.1.3.2 Conclusion

Based on using the above solution to validate the proposed configuration change, the researchers are confident that the proposed method would correctly identify any issues in how the new part numbers are called. The graph visualization tool would assist in identifying which options, and potentially parts, would be affected by the change and should be considered when validating the potential configurations. This implementation case also required the use of the algorithmic validation tool to check for errors in the ruleset using user-modified rules and part families. The complexity analysis tool was used at the beginning of the solution to determine the expected difficulty to validate the change for each of the affected models.

8.2 User Feedback

In order to fully validate the usefulness of the configuration change management, user feedback was gathered in the form of a targeted interview with a Launch and Change Controller at the OEM and from informal feedback received throughout the development of the configuration management method. During the interview, the researcher reviewed the configuration change management method with the interviewee, including its usefulness in the different validation tasks and in potential additional applications. In addition to the applications of the visualization tool (discussed in Section 7.3), the interviewee felt that the conflict detection algorithms would greatly increase the capabilities of the change managers at the OEM. As was identified in the case study, a major challenge with the existing method is the inability to verify the accuracy of the rule database. Using the conflict detection algorithms would enable the engineers to validate the rule database both before and after a proposed change to prevent any issues from arising. The interviewee also felt that the use of part families in the algorithmic validation design enabler would enhance their capabilities. This is due to the ability to do part matching between multiple part families (as in the case of matching the bumpers and exhaust tips) or ensuring a specific number of parts are present, despite multiple variants (as in the case of ensuring a single windshield per vehicle).

The interviewee also stated that the complexity analysis would be a useful tool in predicting which models would be most difficult to validate. The models that are most difficult to validate present a worst-case scenario for a given change and the change engineers could then focus on the identified models when validating the proposed change.

Focusing on the worst-case scenario assists in maximizing the usefulness of the engineer's time. The interviewee stated that this would be conducted early in the validation process to maximize the time focused on the worst-case scenario. However, the interviewee also requested additional functionality from the complexity analysis tool. The two additional functions are the ability to predict the amount of time required to validate a change and the ability to predict the number of test cars required to validate a proposed change. While the complexity analysis tool does not predict the number of test vehicles for a change, it does highlight which models are best suited for test car evaluation. This has the potential for minimizing the number of test vehicles used for validation.

Overall, the interviewee felt that implementing the developed configuration change management method will greatly increase their capabilities when validating a proposed change. Using the existing methods, the validation process is limited to experiential knowledge verification of the potential propagation pathways. Using the developed method provides the change engineers with concrete evidence as to the presence of issues in the database, both present and after a proposed change, and a method for exploring unintended consequences from a proposed change.

8.3 System Architecture to Support the Configuration Management Method

Based on the requirements identified in the study and the feedback received through user interviews and implementation cases, a suite of prototype software tools has been developed, offering decision support and problem investigation functionality. Each tool is specialized to support specific tasks within configuration management. The first three tools (model refinement, visualization and interaction, and conflict detection) orient towards

validation tasks. The final tool (complexity analysis) is oriented toward planning in advance of beginning a change.

The suite of software tools created share the same data sources and over-arching support goals. These tools may be integrated into a single, cohesive software suite, from which a user may choose to apply any one of the tools individually, depending on the user's needs. Figure 8.4 presents a schematic for the integration of these tools under a single interface. From the central interface, a user may launch each of the specific tools in its own module.

Note that data inputs are delivered from configuration rule databases (VRM and TAIS) prior to execution of any tool. This constraint information provides the basis from which each of the tools performs its function. To explore a future configuration change, it may be necessary to experiment upon an altered version of this constraint information. For this reason there are several data models available within the main interface. The current state of the configuration ruleset is represented in only a single data model. Distinct, separate changes may be managed by placing each change in a separate data model, within the array of sandbox models available. Before launching any of the tools it is necessary to carefully control which data model will be investigated.

The model refinement module is not directly called by the user for a specific task, but rather supports the other modules. The purpose of this module is to input the data from the user and from the current data model through the interface in order to output an interaction model that can be used by the other analysis modules. As a result, there is no direct output from this module to the interface.

If the user chooses a task related to complexity analysis, the model refinement module is launched first. This module receives the user inputs regarding the vehicle models in question, as well as the options or parts that are affected by the change. The model refinement module then outputs an interaction model to the complexity module for analysis. Based on the user inputs, a response of the complexity metrics and any flags (as discussed in 5.4) are returned to the user. The user is then able to conduct further analysis as needed.

If the user chooses a task related to visualization, the model refinement module is launched first. This module receives the user inputs regarding the vehicle models in question, as well as the options or parts that are affected by the change. The model refinement module then outputs an interaction model to the visualization module for graph creation an interaction. While in the visualization module, the user has the ability to interact with the graph in order to facilitate increased understanding of the change and its potential impact on the system. The user then has the option to save the modified graph to a separate data model for future evaluation.

When a task requiring conflict detection analysis is selected, the conflict detection module is launched. The user inputs and current data model are sent to the Problem Manager for additional input by the user regarding the specific type of conflict and any additional parameters (as discussed in 5.5). From this point, the query is converted into a satisfiability problem and is solved using the SAT solver. The result is returned to the Problem Manager for any additional queries and is also returned to the interface with the

results of the query. The user is then able to continue to make queries regarding any potential conflicts.

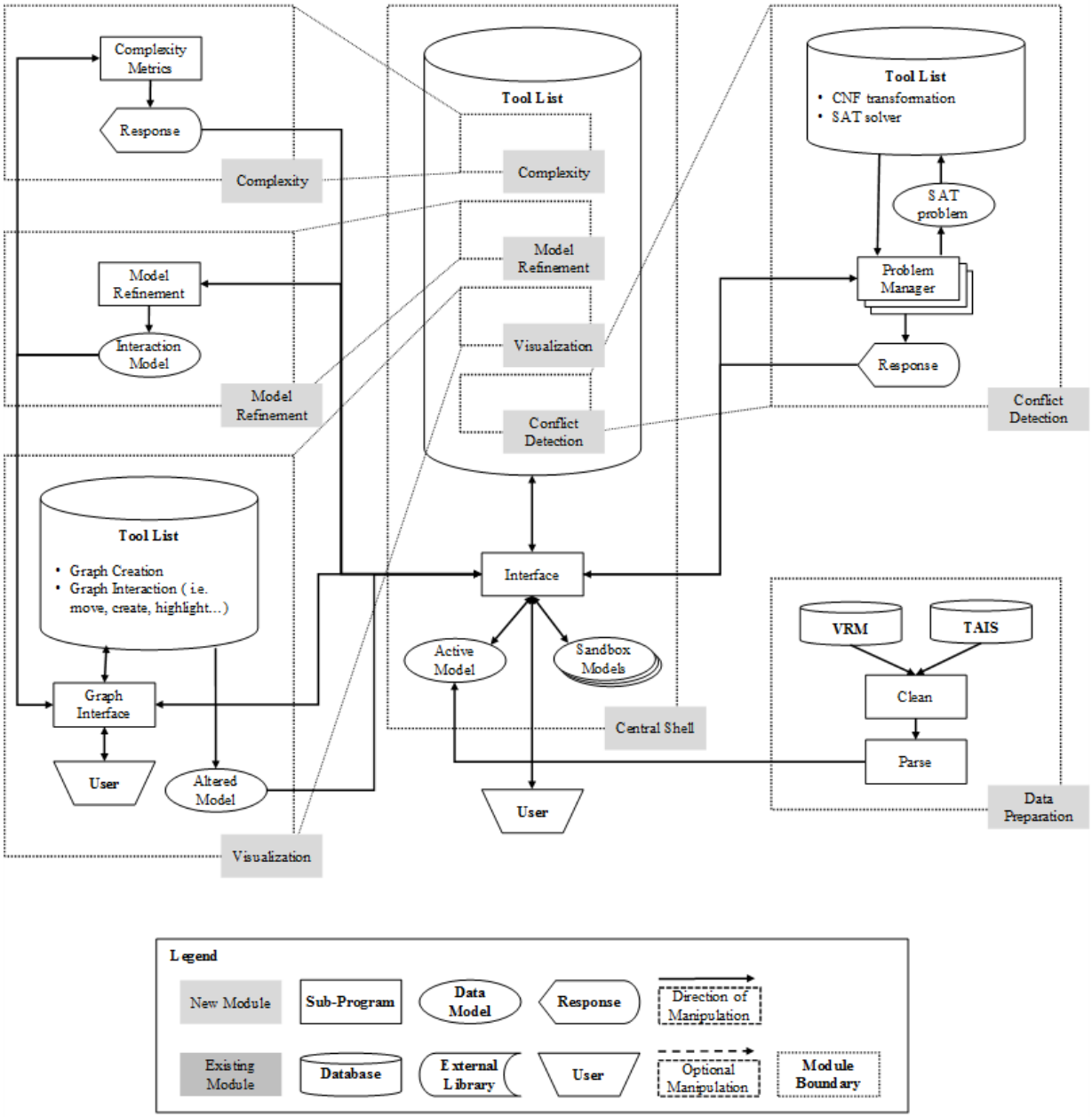

Figure 8.4: Configuration management support tool system architecture

8.4 Conclusions

This chapter continues to support the third research objective: development of an improved method for configuration change management. A previous chapter (Chapter Five) proposed the overall method. While the following chapters presented the development and validation of the graph visualization design enabler (Chapter Six and Chapter Seven), the focus of this chapter returns to the overall configuration management method: Does the proposed method assist in identifying errors and understanding the relationships in the possible product configurations? This research question is answered through user feedback and a limited implementation case study.

An interview conducted with the proposed users of the configuration management method and the supporting design enablers resulted in user feedback regarding their usefulness. The feedback showed that implementing the design enablers in the proposed manner would greatly increase the users' ability to understand the implications of proposed changes. Additionally, the user feedback provided additional functionality recommendations that should be incorporated.

To further test the usefulness of the graph visualizations for configuration management, the method was implemented for three historical configuration changes. In all three instances, the use of the proposed method and associated design enablers would have increased the users' ability to identify errors or prevent conflicts that were not seen when the changes were first evaluated at the OEM.

Based on the evaluation of the configuration management method, a system architecture is proposed for the suite of design enablers that is intended to assist in the

method's implementation. The proposed suite consists of an integrated software tool that combines the functionality of the four modules discussed previously: interaction identification, complexity analysis, graph visualization, and algorithmic validation. By integrating the four tools into a single piece of software, the usability and adoptability of the design enablers is increased.

8.5 Dissertation Roadmap

Chapter Eight presented the validation of the proposed configuration management method with design enabler support and provides final recommendations for the supporting design enablers. The final chapter (Chapter Nine) concludes the dissertation and presents opportunities for future work. The progress of this dissertation is shown in Figure 8.5 in which the completed portion is highlighted in green.

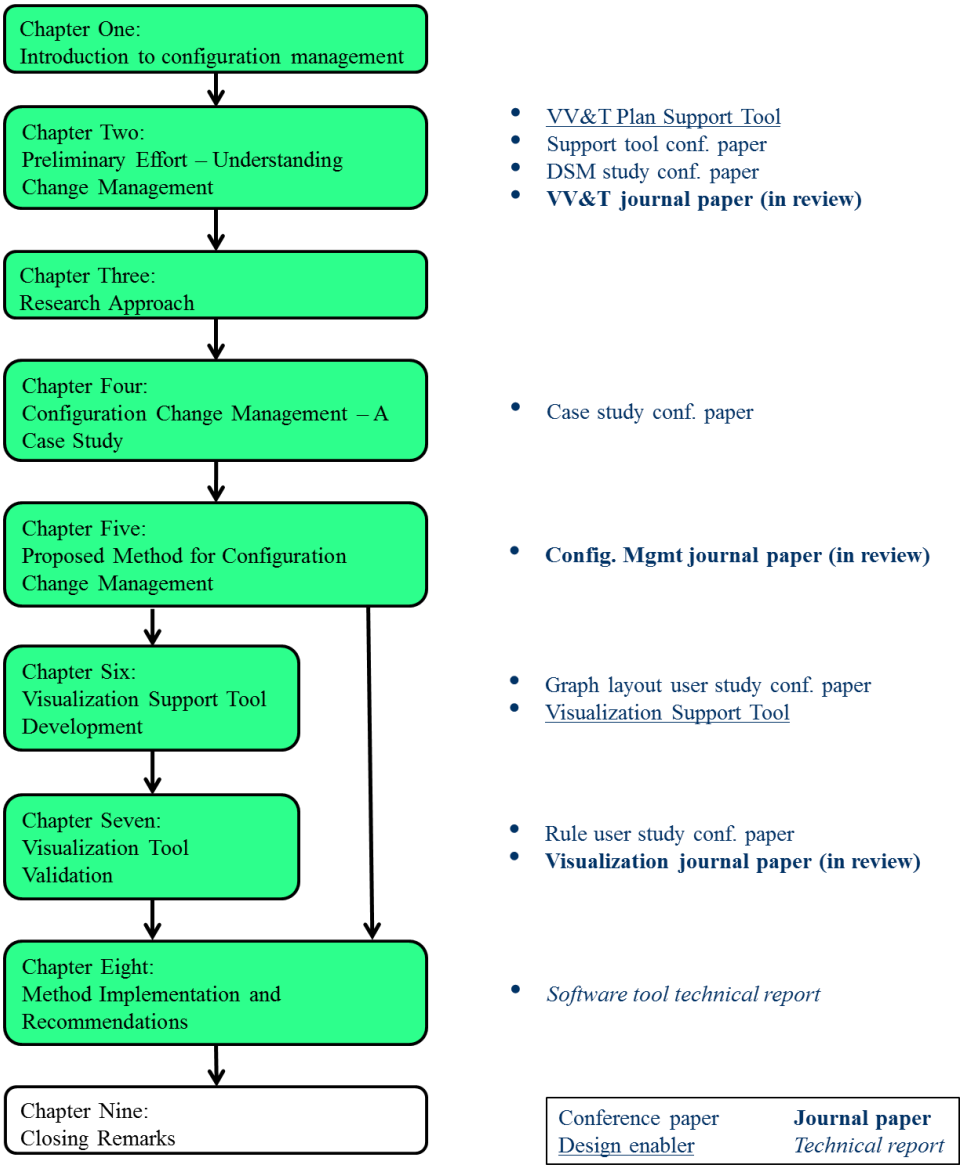

Figure 8.5: Dissertation roadmap

CHAPTER NINE: CONCLUSIONS AND FUTURE WORK

This chapter presents the concluding remarks on this research in Section 9.1 and the future work in Section 9.2.

9.1 Concluding Remarks

This dissertation presented a configuration change management method to explore proposed configuration changes and mitigate the potential negative effects of the proposed change. To achieve this, three research objectives were identified and addressed.

Research objective RO 1 (understanding the current practices for change management) is foundational research that is discussed in Chapter Two. The research objective consists of three research sub-questions that are useful in exploring existing change management practice. Research question RQ 1.1 is answered through a review of literature on current engineering change management practice. During the review, it was identified that while many change management design enablers exist, companies are often hesitant to use them due to a high degree of difficulty and costs in adopting the available methods and/or tools. This led to research question RQ 1.2, which is answered through the development and evaluation of a change management support tool based on an existing change management method (a verification, validation and testing planning method). This method was selected primarily because of its focus on variant change propagation, but also because of its reliance on data entry and engineering experience. The purpose of developing the support tool was to show how existing change management methods could be improved to increase adoptability and usability. By implementing the VV&T planning

method into a support tool, the possibility of human error due to repeated data entry by reducing the number of data points to be entered by 33%.

During the development of the change management support tool, the question was asked as to what depth should be considered when determining the effects of change propagation, leading to research question RQ 1.3. To answer this research question, a study on component interaction was conducted using design structure matrices. In the study, the way in which higher order interactions occurred was examined to determine if patterns could be identified. Based on the results of the study, it was determined that the beyond the second or third order of interaction, the number of component interactions present would likely prevent any meaningful analysis from taking place, though this is dependent on the system in question. Additionally, it was found that both product components and configuration rules in a ruleset exhibited similar patterns when interacting at higher orders of interaction.

The second research objective, RO 2, is to understand how an OEM conducts configuration and configuration change management, and is discussed in Chapter Four. This research objective is achieved through two research questions. The first research question, RQ 2.1, seeks to understand the state-of-the-art for configuration management practices. As such, the question is answered through a literature review of configuration management research. Through the literature review, a classification scheme is identified to assist in evaluating the configuration management practices in place at the automotive OEM. Additionally, challenges with the existing methods are identified that will be of use when evaluating the current methods at the OEM. Research question RQ 2.1 asks the

question of how a major automotive OEM conducts configuration management and is answered through case study research. The case study consists of interviews with personnel in the *Launch and Change Control* group at the OEM, document analysis, and ethnographic research. Based on the results of the case study and the classification scheme identified in the literature review, it was evident that the OEM employs a rule-based configuration management system. In the current system, rule database explicitly states how options can interact within a possible configuration. As such, many of the problems commonly associated with rule-based reasoning in configuration management hold true. The large size of the rule database make it difficult to verify either for completeness or accuracy. Additionally, when making a change to the rule database, it is nearly impossible, using the current methods, to determine the unintended consequences of a potential change. Therefore, it was recommended that an improved process be implemented that incorporates design enablers to assist in validating the existing rule database and exploring proposed configuration changes to better understand unintended consequences.

The third research objective, RO 3, is discussed in Chapter Five through Chapter Eight and includes the development of an improved method for configuration change management. The first research question, RQ 3.1, to support this objective, discussed in Chapter Six, asks how data visualization techniques can be used to assist in exploring a proposed change. This question is answered in part through a literature review of data visualization techniques and their uses. From the literature review, it was identified that graph visualization is a useful method for visualizing data where the relationships between components is important. To assist in developing a graph visualization design enabler for

use in configuration management, a user study was conducted to determine what factors (color, layout, data availability) affect a user's ability to read and interpret a graph visualization of a configuration rule database. Based on the results, it was identified that the amount of information presented to the user had the greatest effect on how well the user could interpret the data; removal of clutter greatly increased the user's ability to correctly answer questions regarding the system.

Research question RQ 3.2 then asks whether the implementation of the proposed graph visualization design enabler assists in configuration management (discussed in Chapter Seven). This research question is answered through a second user study, a series of implementation cases, and user feedback. In the second user study, the usefulness of graph visualizations is compared to the existing method with respect to implementing rules in the configuration rule database. The user study found that, with limited training, the graph visualization method was as effective as the existing method when just implementing rules and showed promise when evaluating the reasoning behind why the rules were implemented. The series of implementation cases consisted of using the graph visualization design enabler to assist in the validation of four ongoing, proposed configuration changes at the OEM. In each case, using the graph visualization resulted in identifying issues in the proposed changes that either were not identified using the existing method or took longer to identify. Additionally, a time study was conducted and it was determined that using graph visualizations resulted in a three-fourths reduction in the time required to identify an issue. Lastly, the user feedback showed that implementing the graph

visualization would increase the capabilities of the configuration change validation personnel at the OEM.

The third research question, RQ 3.3, addresses the effectiveness of the overall configuration management method and is discussed in Chapter Eight. This research question is answered through three additional implementation cases and user feedback. In the implementation cases, the usability of the method is evaluated as to whether it is capable of preventing issues from a proposed change or evaluating the current configuration system for a specific set of criteria. From the implementation cases, it was found that the proposed method would successfully validate the configuration ruleset in each of the three situations more effectively and rapidly than when using the existing method. The user feedback consisted of a targeted interview with a potential user of the proposed method and informal feedback received throughout the development of the configuration management method. Based on the feedback, it was identified that implementing the proposed configuration management method with the associated design enablers would increase the group's capabilities when exploring and validating proposed changes.

While many of the applications of the proposed method have been focused on the automotive OEM from the case study, it is expected that the method would also be applicable in other domains. As stated in the case study, the configuration management system at the OEM is representative of any system that employs rule-based reasoning for configuration management. Therefore, the methods and design enablers proposed in this research can also be implemented in any company that uses rule-based reasoning.

To conclude, the overarching goal of this research to develop a configuration management method for exploring proposed configuration changes and mitigating the negative effects of the change has been successfully developed and tested. In this process, three research objectives are addressed that contribute directly to the body of knowledge in the configuration management field. However, there are areas where the proposed configuration management method can be improved by further research, which is discussed next.

9.2 Future Work

The limitations in the proposed configuration management method are identified for future research work. The first limitation of the research is that while the configuration management method was evaluated for whether it would prevent issues in three historical cases, the proposed method was not validated alongside the existing method for any ongoing configuration changes. Evaluating the method alongside the existing method for an ongoing change would aid in validating the research. This was not done during the current research due to restrictions on the availability of data by the OEM in question. To increase the effectiveness of the method, the system should be capable of tying in directly to an OEM's PDM system. This would be a Master's level research project.

Second, the use of complexity analysis early in the proposed method is a means of predicting the difficulty in validating a proposed change. While complexity metrics have been shown to be useful in predicting other factors (market price, assembly times), no research has been done to prove that they can be used for predicting change validation requirements. Data for historical configuration change requests was collected during the

research, but a suitable metric for change validation difficulty was not available for the previous changes. Thus, prior to conducting research on the predictive capabilities of complexity metrics for change validation difficulty, a numerical value for the level of difficulty must be determined. This is another Master‘s level research project.

Third, in evaluating the depth of interaction required when projecting potential change propagation, the population density was evaluated at each level of interaction until interaction saturation was met. When compared, patterns were identified that allowed for the grouping of products and configuration rulesets based on the curve formed by the population densities. Based on this, it is proposed that an additional complexity metric could be identified that is based on the population density at each order of interaction. While this was initially identified in this research, more substantial testing of the proposed metric is required in order to prove its usefulness. This would also be a Master’s level research project.

Lastly, the graph visualization software is limited to the ability to create the visualizations and allow interaction with the resulting graph. The current degree of interaction is limited to rearranging the layout of the graph to increase readability (either using the force-directed algorithm of manually) and addition and subtraction of nodes/edges. In order to maximize the potential of the graph visualization, increased interaction and analytical capabilities may be necessary. Some examples of additional functionality include the ability to do automated comparisons between multiple graphs, highlighting logical conflicts within a single graph, and automated filtering of different

types of nodes or edges (parts, options, packages, trim types, etc.). This would be a Master's level research project.

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APPENDICES

Appendix A:Complete DSM for Historical Example

The below table shows the completed design structure matrix (DSM) for the historical example for the brake drum discussed in Section 2.1.2.

Table A.1: Full DSM for Brake Drum Example

	Component Name		Internal											External					
			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Internal	Foundation Brake	A			1	1	1							1					
	Brake Drum	B					1								1	1			
	Slack Adjuster	C	1			1													
	Brake Chamber	D	1		1						1	1							
	Brake Lining	E	1	1															
	Air Tanks	F							1		1		1						1
	E Valve	G						1		1								1	1
	Brake Pedal	H							1										1
	Relay Valve	I				1		1											1
	Quick Release Valve	J				1													1
	Governor	K						1									1		
External	Axle	L	1																
	Hub	M		1															
	Tie and Wheel Trim	N		1															
	Engine	O											1						1
	Instrument Panel	P							1										
	Frame	Q						1	1	1	1	1					1		

Appendix B: Trendline Graphs for Component Interaction Study

The following graphs show the trendlines for the component interaction study conducted in Section 2.2.

Figure A.1: Trendline for all product architectures

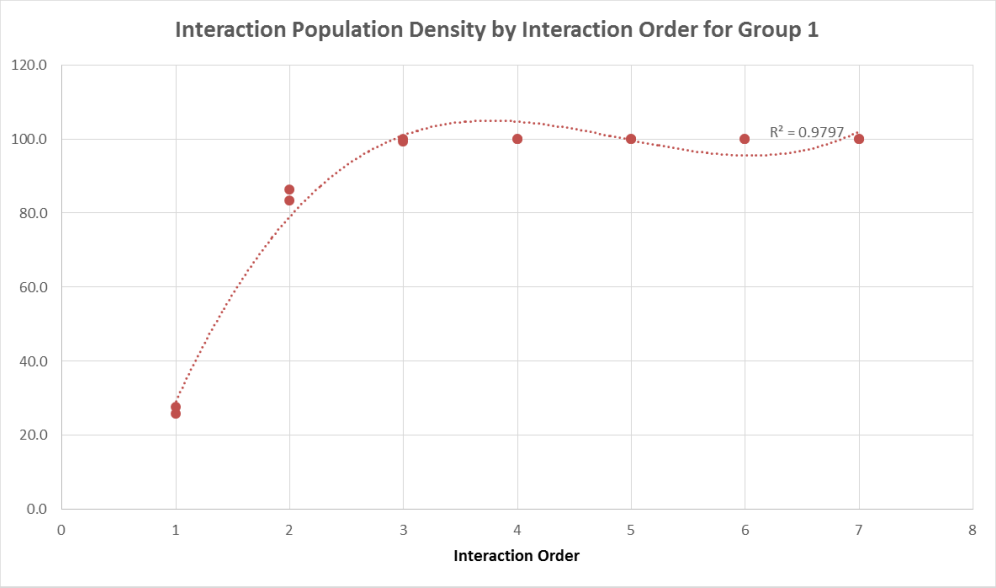


Figure A.2: Trendline for Group 1 product architectures

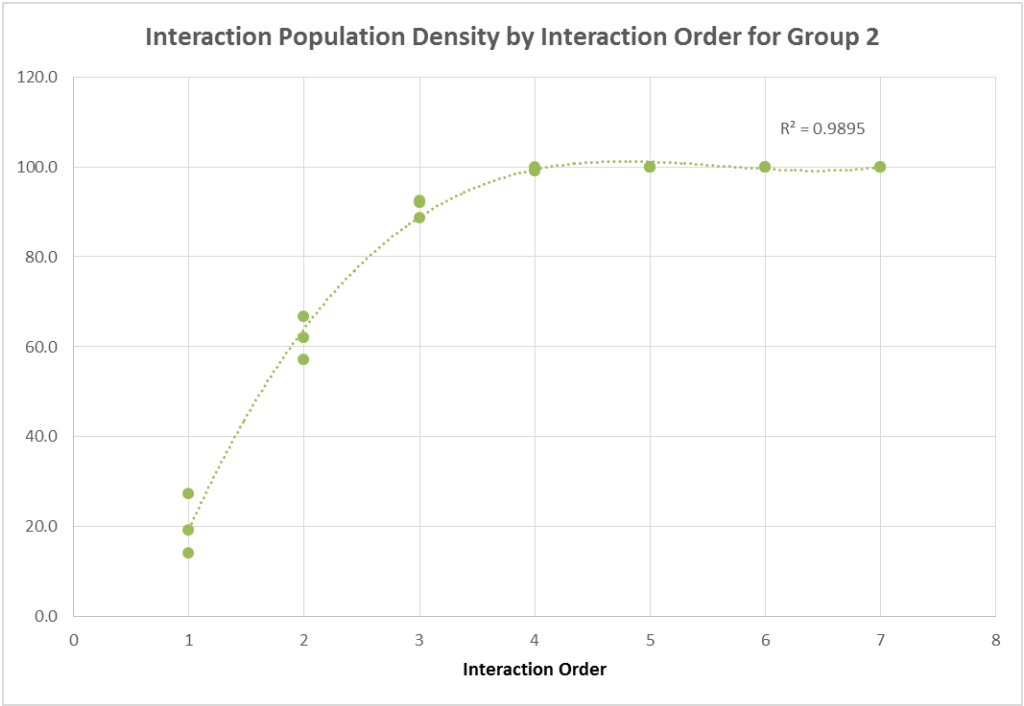


Figure A.3: Trendline for Group 2 product architectures

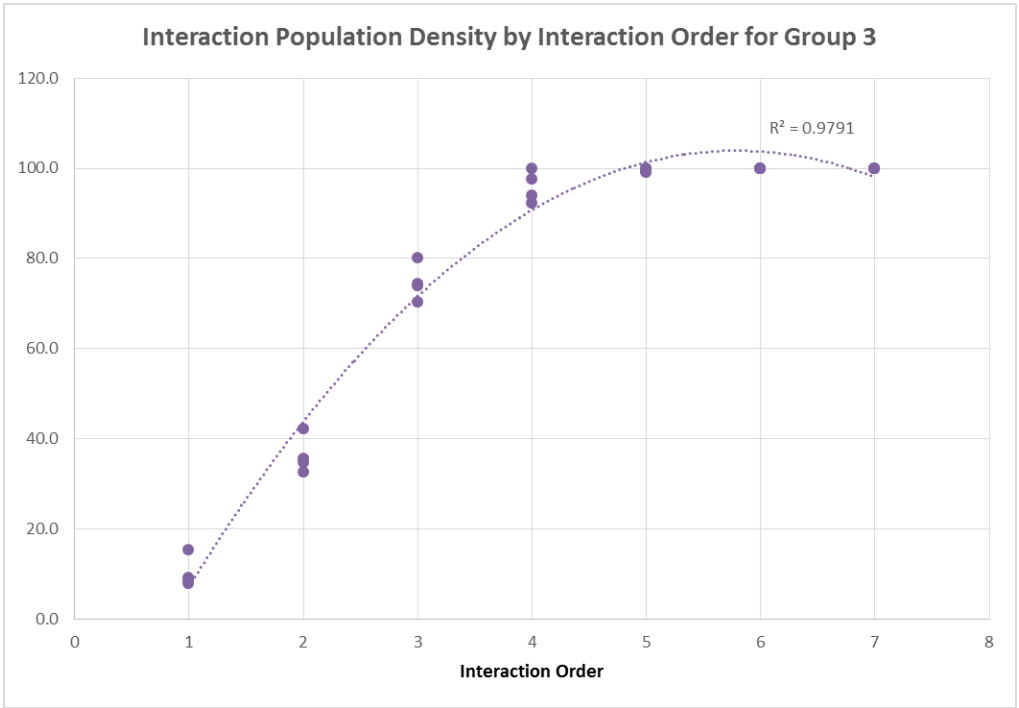


Figure A.4: Trendline for Group 3 product architectures

Figure A.5: Trendline for Group 4 product architectures

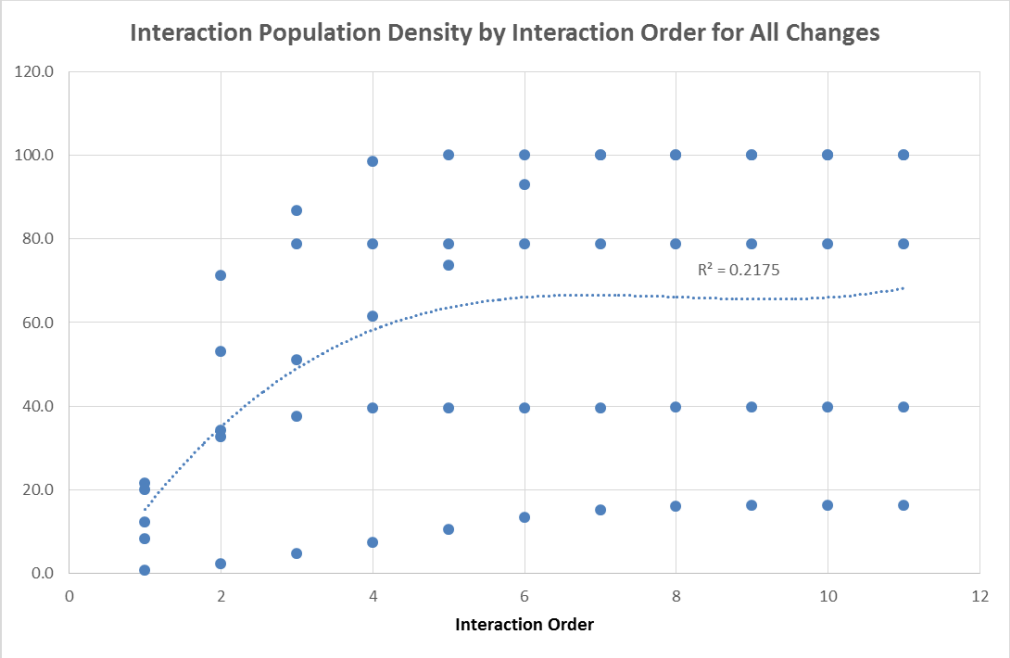


Figure A.6: Trendline for all product changes

Figure A.7: Trendline for Group 1 with 1 added product change

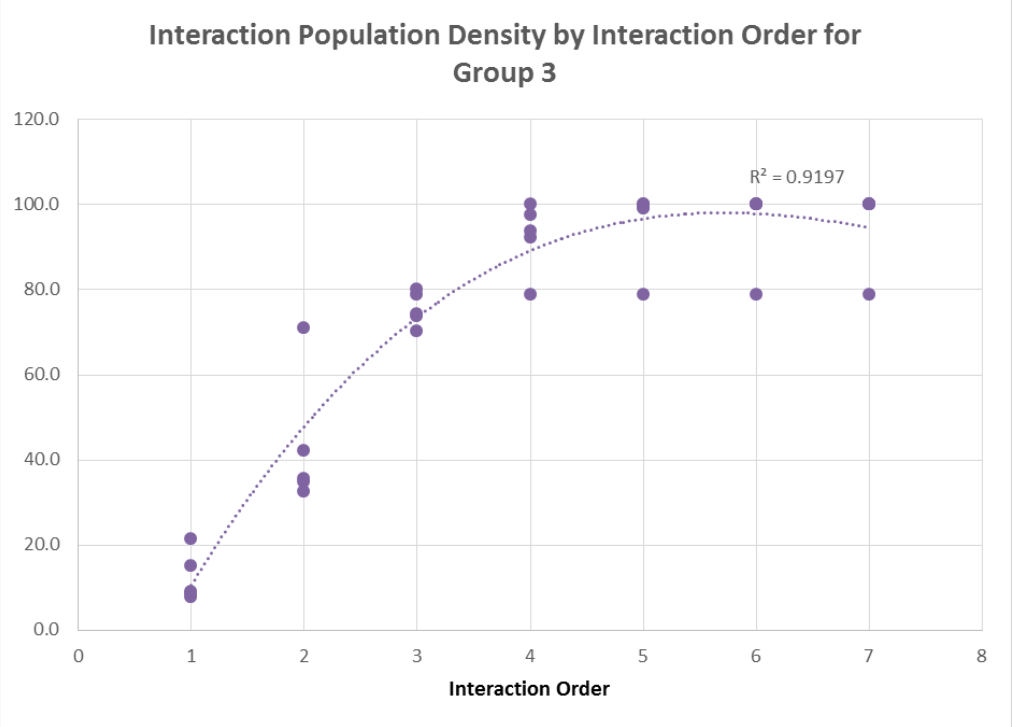


Figure A.8: Trendline for Group 3 with 1 added product change

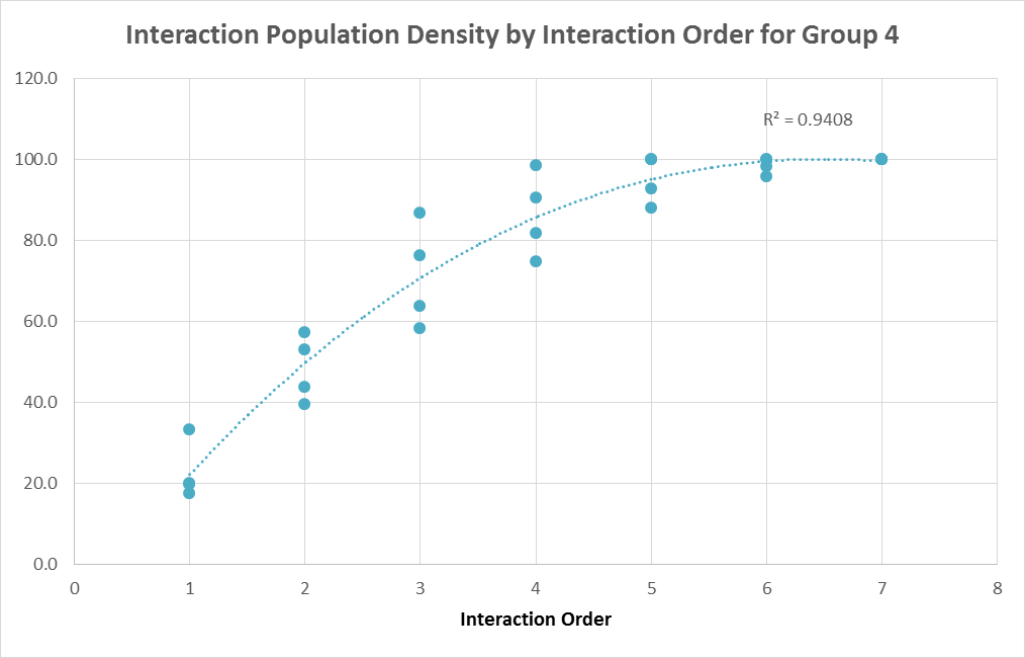


Figure A.9: Trendline for Group 4 with 1 added product change

Appendix C: Example of a Configuration Rule Database

An example of the configuration rule database discussed in the case study in Chapter Four. As the full document is over 1500x40, an abbreviated example is used.

Table A.2: Example of a configuration rule database

Opt	If-Part of rule	Then-part of rule	Standard-part of the ru	Descriptio	Text a	Equal	KR01	KR02	KR03	KR23	KR61	KR62	KR63	KR81
TA				Status		-	50	50	50	50	50	50	50	50
TA				SOP		-	01.12.20	01.12.20	01.08.20	01.08.20	01.08.20	01.08.20	01.08.20	01.08.20
TA				EOP		-	31.07.20	31.07.20	31.07.20	31.07.20	31.07.20	31.07.20	31.07.20	31.07.20
TA				Motor designation		-	N55B30N	N55B30N	N55B30N	N55B30N	N63B44C	N63B44C	N63B44C	N63B40C
TA				Engine family		-	R6	R6	R6	R6	V8	V8	V8	V8
TA				Sales designation		-	X5 xDrive	X5 xDrive	X5 xDrive	X5 sDrive	X5 xDrive	X5 xDrive	X5 xDrive	X5 xDrive
SA		S9ACA		CAMOUFFLAGE NSC		=	O	O	O	O	O	O	O	O
SA		S9ADA		LOCKABLE CAMOUF		<								
SA		S9AEA		DEVELOPMEt		=	O	O	O	O	O	O	O	O
SA		S9AGA		MODEL YEAR EXPOI		<	O	O			O	O		O
SA		S9C1A		CKD MONTAGE AEG		<					O			
SA		S9C2A		CKD MONTAGE INDIE		<		O						
SA		S9C3A		CKD MONTAGE INDC		<		O						
SA		S9C4A		CKD MONTAGE MAL		<		O						
SA		S9C5A		CKD MONTAGE RUS		<	O							
SA		S9C6A		CKD MONTAGE THAI		<								
SA		S9WRA		WINTER WHt		<	O				O			O
SA		SXD5A		IND. HEADLINER ALC		<	O	O			O	O		O
SA		SXE7A		IND.INTERIEUR T.PIA		=	O	O	O	O	O	O	O	O
SA		SXEWA		IND. FINE WOOD TRI		=	O	O	O	O	O	O	O	O
SA		SXL4A		BMW INDIVIDUAL LE		<	O	O			O	O		O
SA		SXL5A		BMW INDI.LEATHER		<	O	O			O	O		O
SA		SXT1A		IND. I-PANEL FINISHE		<	O	O			O	O		O
Z	& - BORDL & - I	/ + BORDL		0000011843		<	R	R			R	R		R
Z	& - COWAR	/ + COWAR		0000015803		=	R	R	R	R	R	R	R	R
Z	& - DVD	/ + DVD		0000012350		=	R	R	R	R	R	R	R	R
A	& + ILEIS	/ + LEIST		0000012990		<			R	R			R	
A	& + LEIST	/ + ILEIS		0000029960		<	R	R			R	R		R
Z	& - SAT	/ + SAT		0000013343		<			R	R			R	
Z	& + M416	/ + P337A		0000008866		<	R	R	R	R	R	R	R	R
Z	& + M416	/ + S715A		0000028640		<								
Z	& + WS34 & - F	/ + S778A		0000030673		<	R	R			R	R		R
Z	& + WS34 & - F	/ + S778A		0000036852		<			R	R			R	
Z	& + WX01 & - P	/ + S778A		0000036855		<			R	R			R	
Z	& + WX01 & - P	/ + S778A		0000030674		<	R	R			R	R		R
Z	& + WX03 & - P	/ + S778A		0000036854		<			R	R			R	
Z	& + WX03 & - P	/ + S778A		0000030676		<	R	R			R	R		R
Z	& + WX13 & - P	/ + S778A		0000036853		<			R	R			R	

Appendix D: Example Configuration Change Request Form

BMW Group

AC9591	Projektnachtrag	Veröffentlicht am 03.06.2014 von Andreas Klein
F15/F16 IR FS mit KAFAS		

Betroffene zielvereinbarte Projekte:	**(Verantwortlich: Andreas Klein)**
A071/F15 A111/F16 R787/F86	A341/F15 R611/F85

Problem (öffentlich): **(Verantwortlich: Oliver Dietze)**

Translated version below / übersetzte Version unten

Translated version below / übersetzte Version unten

In den Euro NCAP Märkten kann derzeit keine SA 358 Klimakomfort-Frontscheibe (IR-Scheibe) mehr angeboten werden, da die Zusteuerung der SA 5AS Driving Assistant zu Erreichung der NCAP Anforderungen zwingend ist.

KAFAS und IR-Scheibe schließen sich gegenseitig aus.

****

In the Euro NCAP markets the SA 358 Climate comfort windscreen (IR windscreen) currently cannot be offered, because the SA 5AS Driving Assistant is mandatory to reach the NCAP requirements.

KAFAS and IR windscreen rule each otherout .

Lösung (öffentlich): **(Verantwortlich: Oliver Dietze)**

Translated version below / übersetzte Version unten

Translated version below / übersetzte Version unten

Die bestehenden IR Scheibenvarianten Klimakomfort-Frontscheibe mit Graukeil (SA358 + SA 3AP) sowie Klimakomfort-Frontscheibe mit Head-up Display (SA 358 + SA 610) entfallen, verbleiben aber für Ersatz.

Neu angeboten wird die Kombination IR mit KAFS:

SA 358+KAFAS sowie SA 358+SA 610+ KAFAS.

****

The existing IR windscreens Climate comfort windscreen with grey shade band (SA 358 + SA 3AP) and the Climate comfort windscreen with head-up display (SA 358 + SA 610) will be replaced, but will still be available for spare.

New is the combination IR windscreen with KAFAS:

SA 358 + KAFAS and SA 258 + SA 610 + KAFAS

Nutzen: **(Verantwortlich: Oliver Dietze)**

Translated version below / übersetzte Version unten

Translated version below / übersetzte Version unten

AC9591	Projektnachtrag	Veröffentlicht am 03.06.2014 von Andreas Klein

F15/F16 IR FS mit KAFAS

Kunde kann in den Euro NCAP Märkten weiterhin die SA358 bestellen.
****

Customer can still order SA 358 in the NCAP markets.

Regelwerk: (Verantwortlich: Andreas Klein)

Der Ausschluss der S358A zur S8THA ist aufzuheben.(Regel 27323)
Der Ausschluss der S358A zur S5ATA ist aufzuheben.(Regel 30582)
Der Ausschluss der S358A zur S5ASA ist aufzuheben.(Regel 27322)
Der Ausschluss der S358A zur S5ARA oder S5DFA ist aufzuheben.(Regel 34833)
Der Ausschluss der S358A zur S5ASA oder S8THA ist aufzuheben.(Regel 24126)
Der Zwang der S358A ohne S610A zur S3AP ist aufzuheben. (Regel 24127)

Folgende Regeln
S3APA hat einen Ausschluss zu S5ARA oder S5DFA (Regel 36041)
S3APA hat einen Ausschluss zu S5ASA oder S5ATA oder S8THA (Regel 30276)
S3APA hat einen Ausschluss zu S610A (Regel 11858)

sind zu ersetzen durch
S3APA hat für ECE Typen einen Ausschluss zu S5ASA oder S5ATA oder S5DFA oder S8THA oder S610A oder S358A

Legende:

S358A: Klimakomfort-Frontscheibe
S8THA: Speed Limit Info
S5ATA: Driving Assistant Plus
S5ASA: Driving Assistant Plus
S5ARA: Stauassistent
S5DFA: Aktive Geschwindigkeitsregelung mit Stop&Go-Funktion
S610A: Head-Up Display
S3APA: Graukeil-Frontscheibe

Aktivitäten: (Verantwortlich: Andreas Klein)

Anpassung der Freigaben EK-19
Anpassung der Stammdaten im VRM TV-121
Anpassung der Verkaufsliteratur und Betriebsanleitung BP-LG, BP-20, UA-76

BMW Group

AC9591	Projektnachtrag	Veröffentlicht am 03.06.2014 von Andreas Klein
F15/F16 IR FS mit KAFAS		

Einsatztermine / Bauphasen: (Verantwortlich: Andreas Klein)

F15	/ -	/ VS2	/ 01.04.2015	F15	/ - / AP /01.04.2015
F16	/ -	/ VS2	/ 01.04.2015	F85	/ - / VS2 /01.04.2015
F86	/ -	/ VS2	/ 01.04.2015		

Kommentar: (Verantwortlich: Andreas Klein)

Anlagen: (Verantwortlich: Andreas Klein)

Betroffene KIFA: (Verantwortlich: Oliver Dietze)

EA	EF	EI	EK
			X

Genehmigung:

Bayerl, Herbert, ZS-E-X, +49-89-32903-2196- / 26.05.2014
Thiel, Gerhard, LG-W-4, +49-89-382-33607- / 28.05.2014
Ahlers, Michael, LG-2, +49-89-382-43285- / 26.05.2014

Appendix E: User Study Response Form

Answer each question and provide your confidence in the answer you have provided.
"vehicle option" signifies a node marked S___A.
"windshield" or "part" signifies a node marked WS ___.

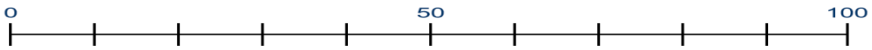
1. Which vehicle options are not available to US customers for the available windshields?

2. If a US customer wants option S5DFA, what windshield part numbers are available? Which numbers are not available? Does it change for a customer in Europe and why?

3. If a vehicle option (S123A) was added to the Europe model that requires S5ARA and cannot work with S5DFA, will this cause any problems? Why or why not?

4. Provide a feasible vehicle option combination to result in Part number WS 495 (in Europe).

5. Which part numbers are compatible with option S610A (in Europe)?



6. Are there any option contradiction errors in the connectivity graph? If so, what are they?

7. If a European customer wants S5ATA, how does this affect availability of other vehicle options?

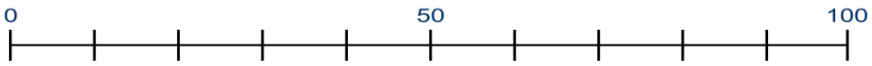
8. If a customer in Europe wants option S358A, what other vehicle options are affected, and how?

9. Which windshields are not offered in the US?

10. Provide a feasible vehicle option combination to result in Part number WS 401 (for Europe).

11. Is there any scenario where a combination of vehicle options will result in two different windshields being required (in Europe)?

12. Are there any valid vehicle option combinations where no windshields are specified?



13. If windshield WS 399 was removed from the European model, would this cause any issues? Why or why not?

Appendix F: Visualization Tool Development User Study Graphs

The following graphs were used for the visualization tool development user study discussed in Section 6.2.

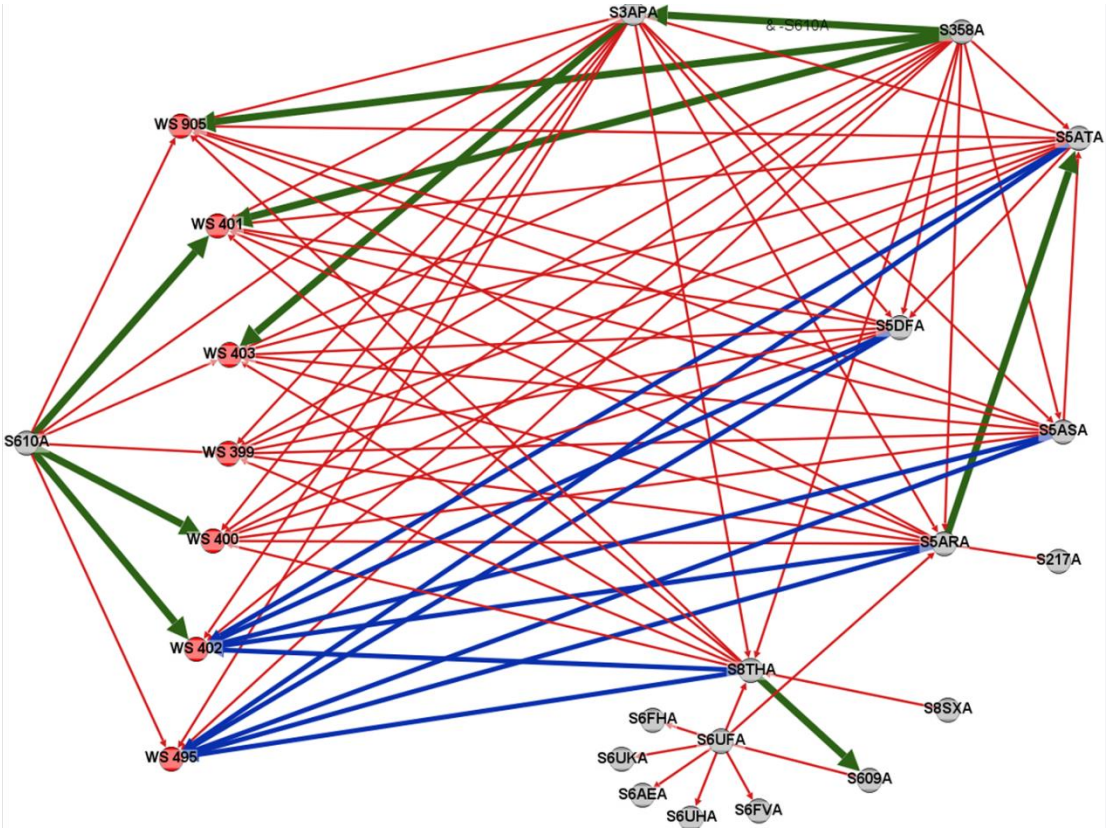


Figure A.10: Graph for European models with functional grouping and coloring based on interactions

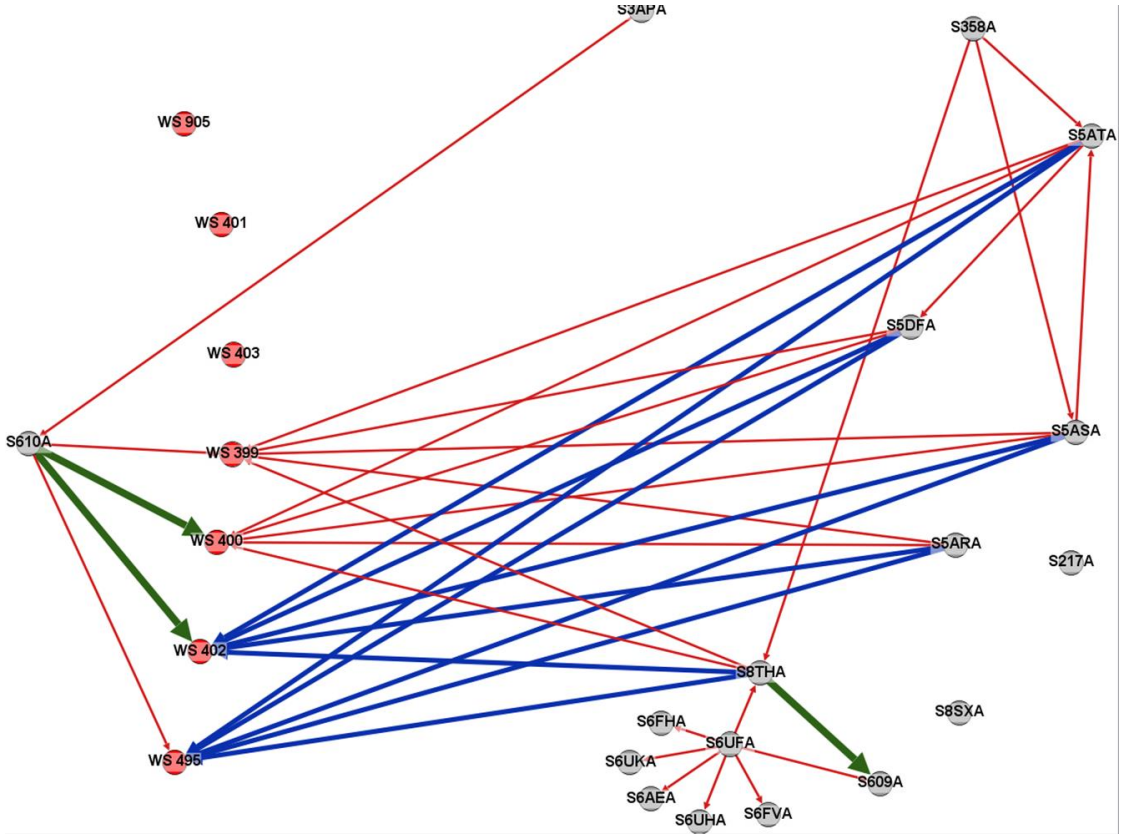


Figure A.11: Graph for US models with functional grouping and coloring based on interactions

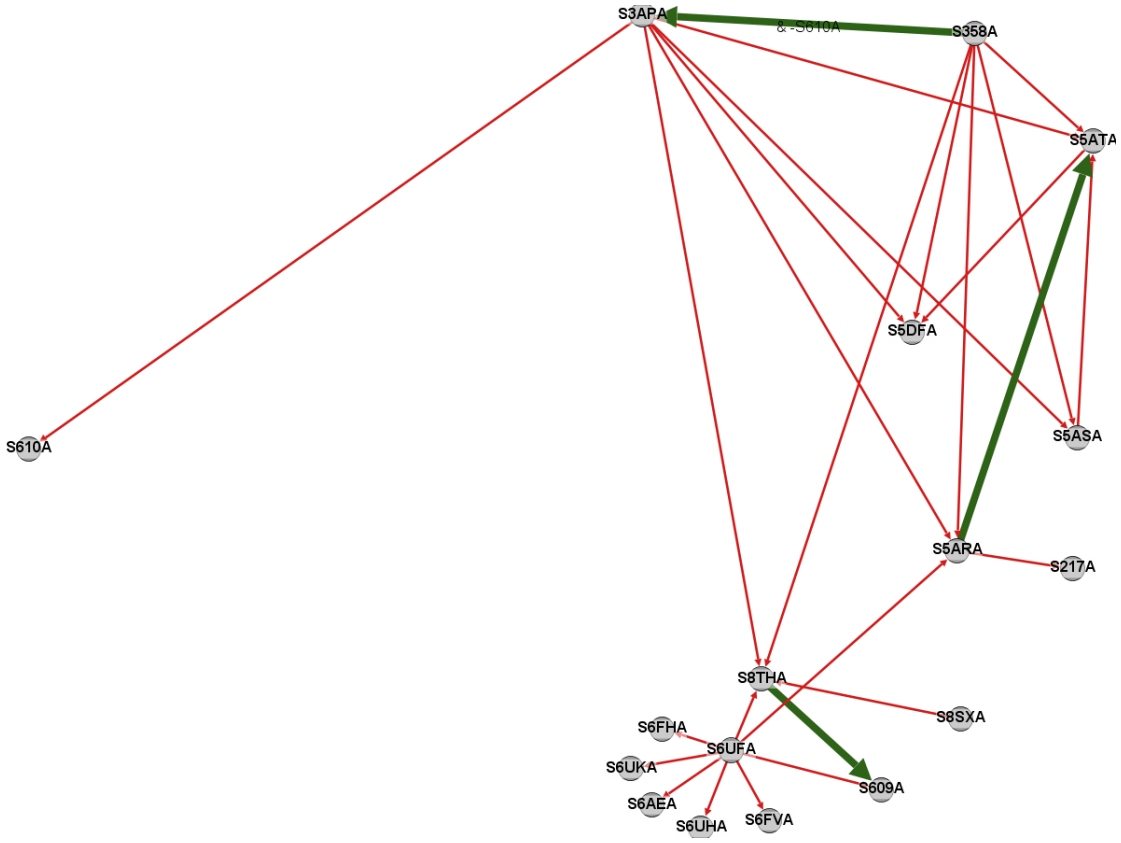


Figure A.12: Graph for European models with functional grouping and coloring based on interactions (options only)

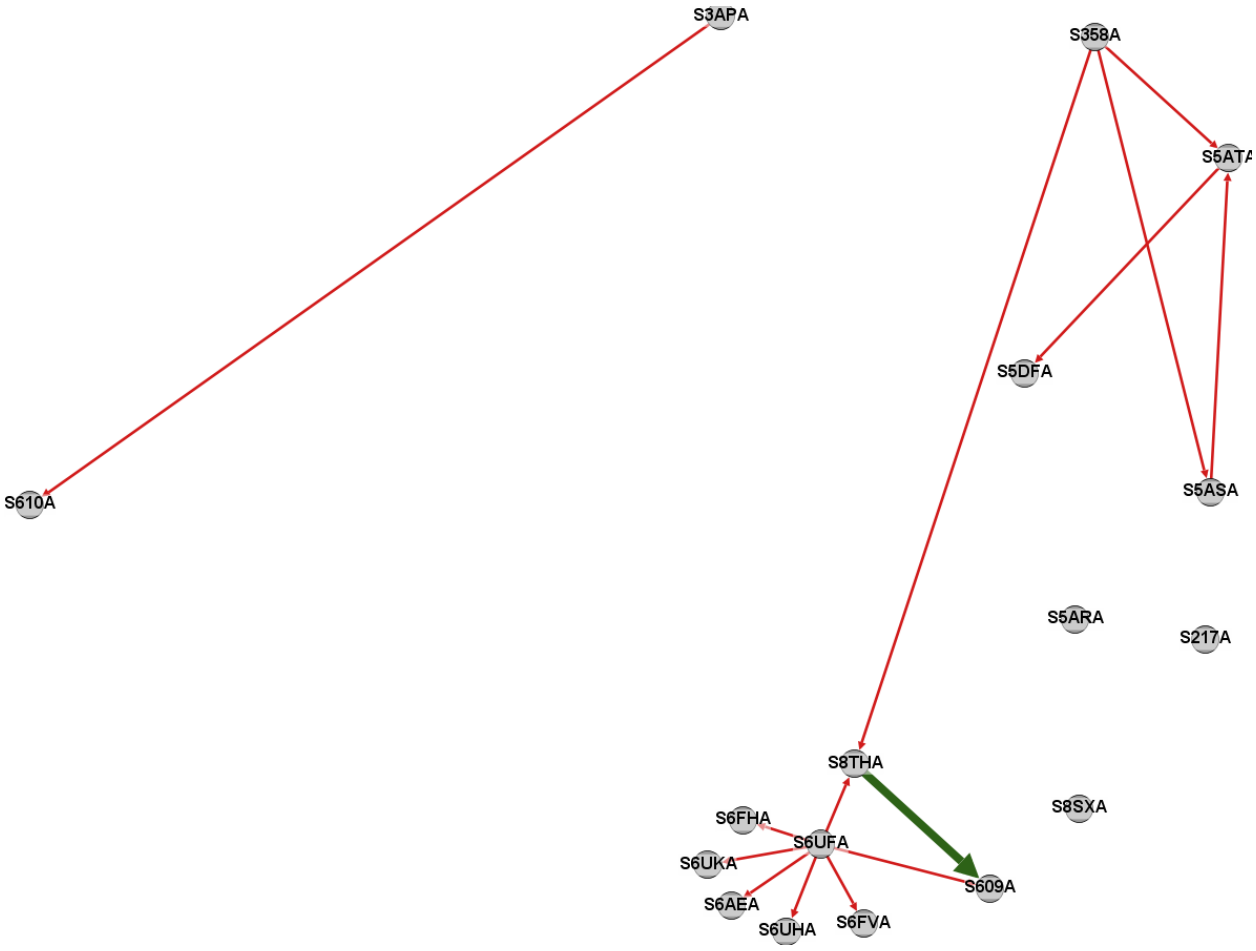


Figure A.13: Graph for US models with functional grouping and coloring based on interactions (options only)

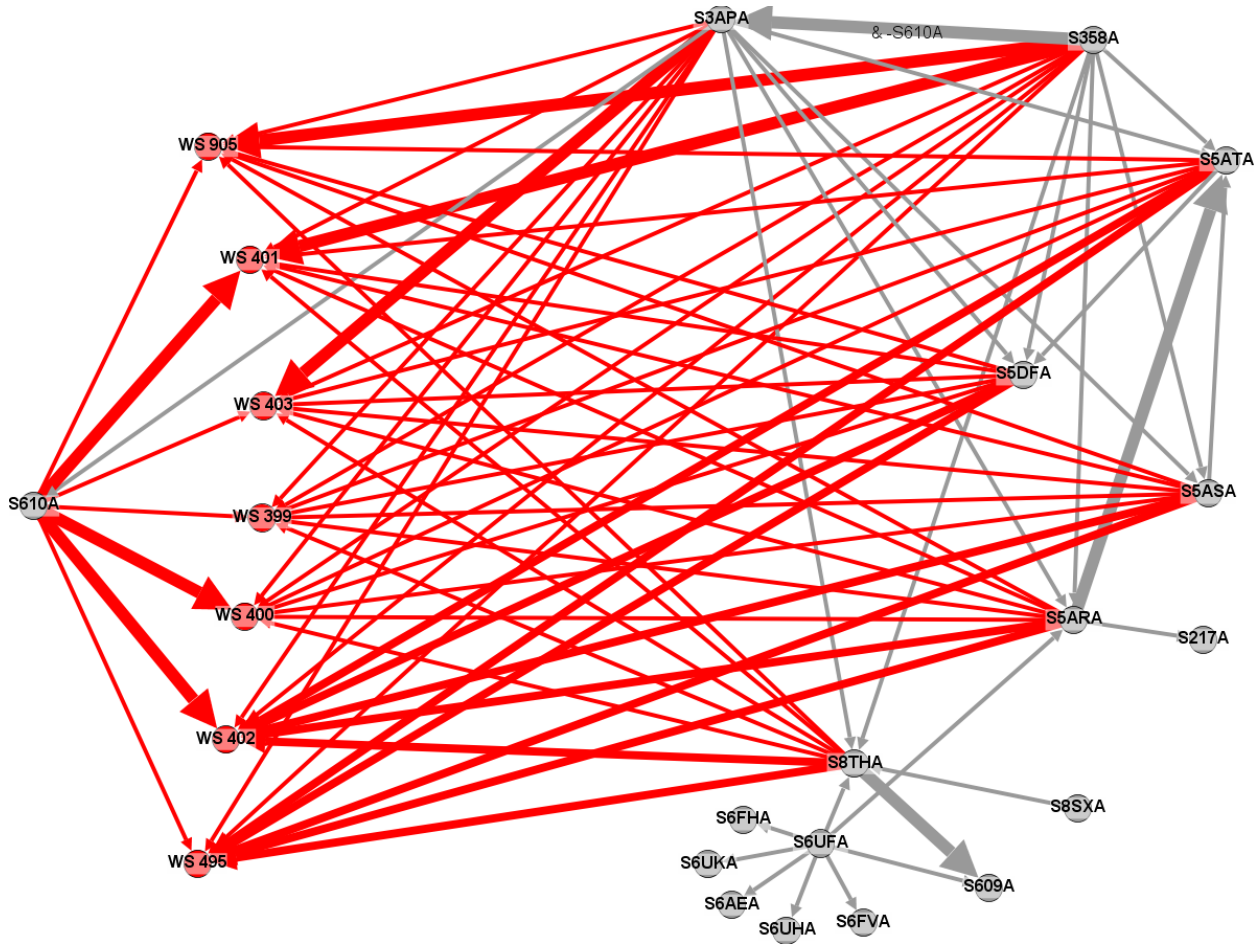


Figure A.14: Graph for European models with functional grouping and coloring based on parts

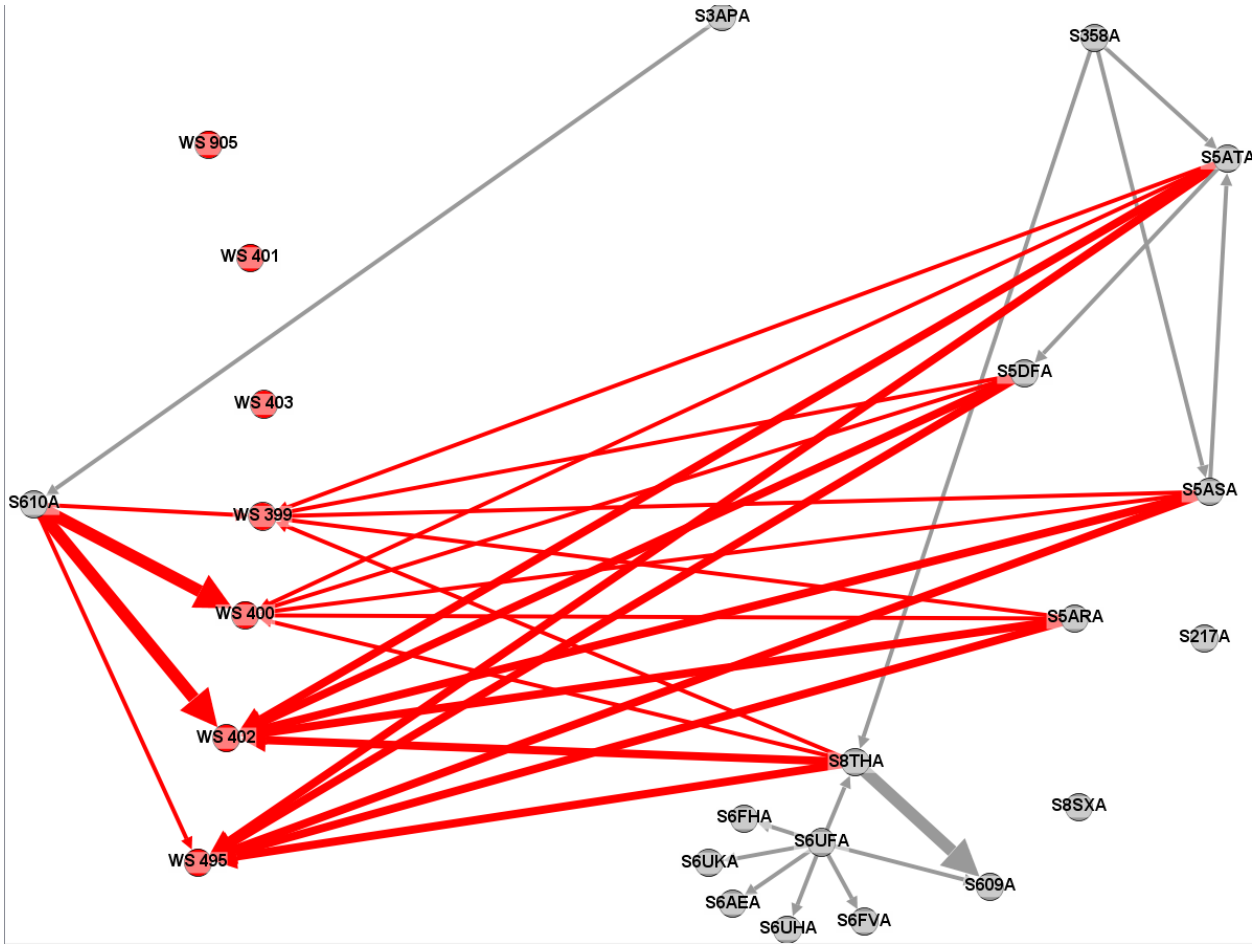


Figure A.15: Graph for US models with functional grouping and coloring based on parts

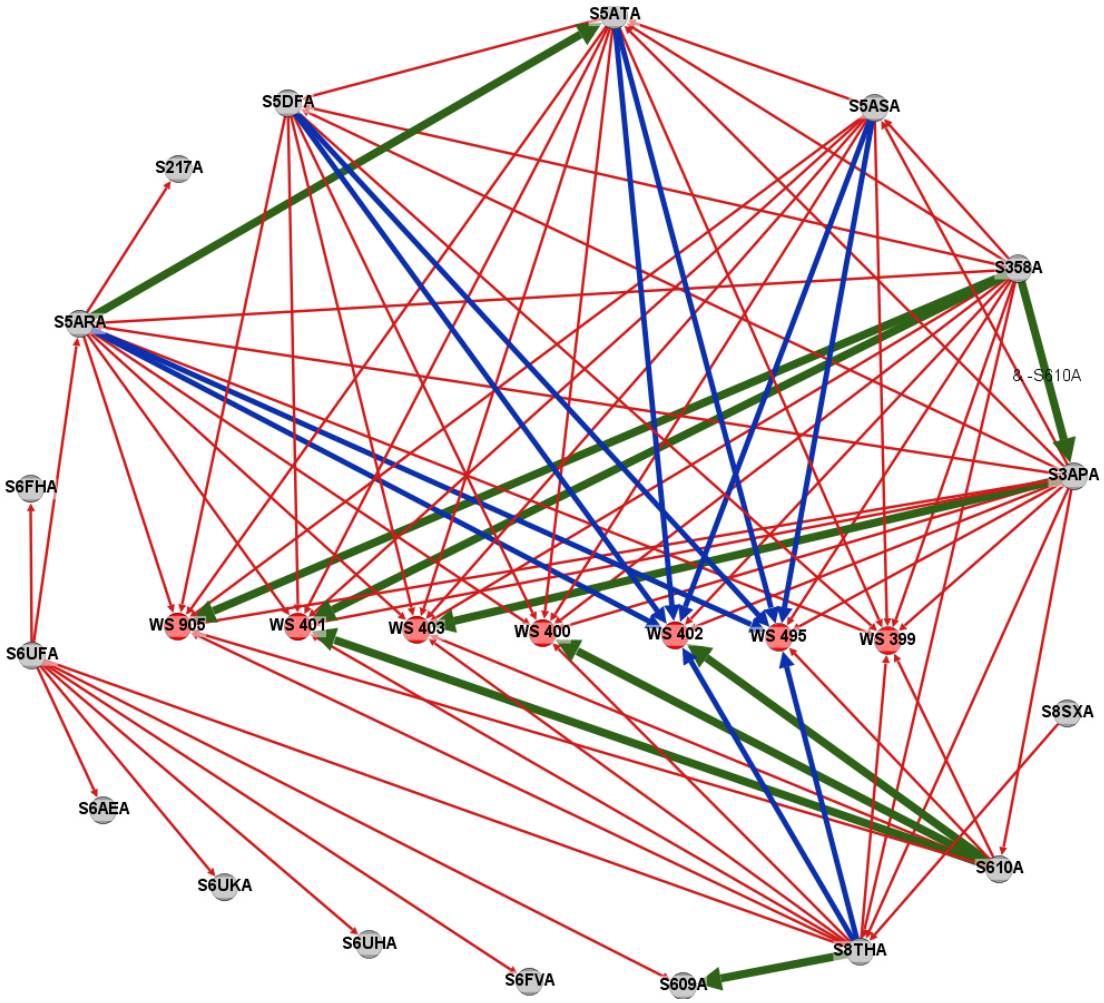


Figure A.16: Graph for European models with circular layout and coloring based on interactions

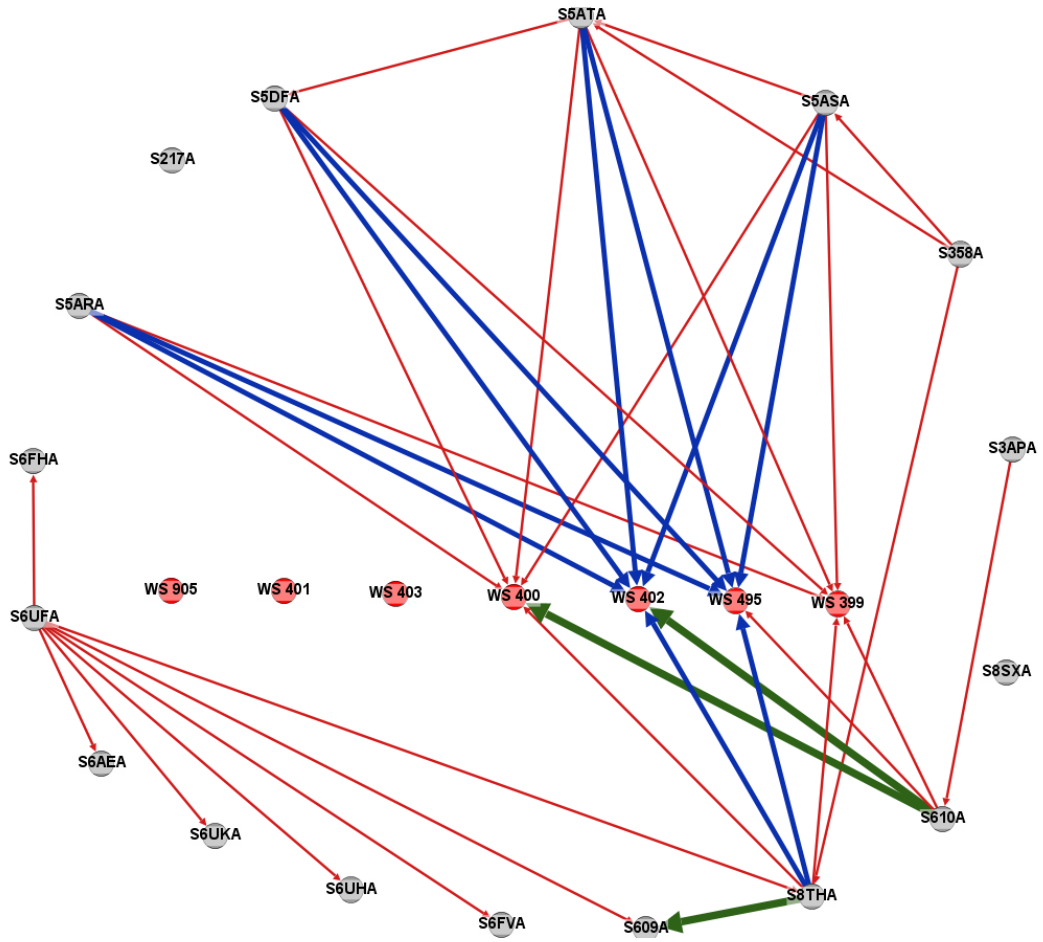


Figure A.17: Graph for US models with circular layout and coloring based on interactions

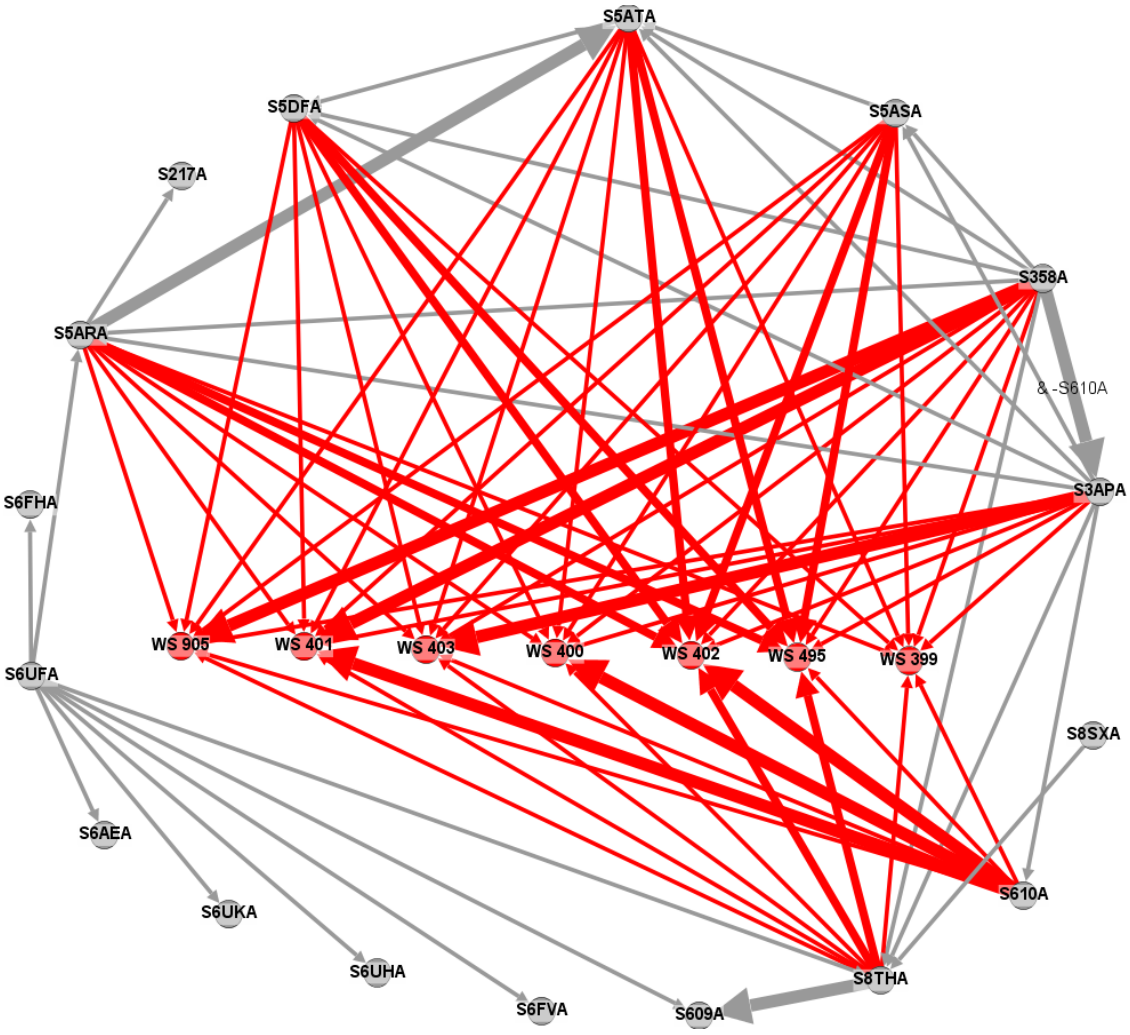


Figure A.18: Graph for European models with circular layout and coloring based on parts

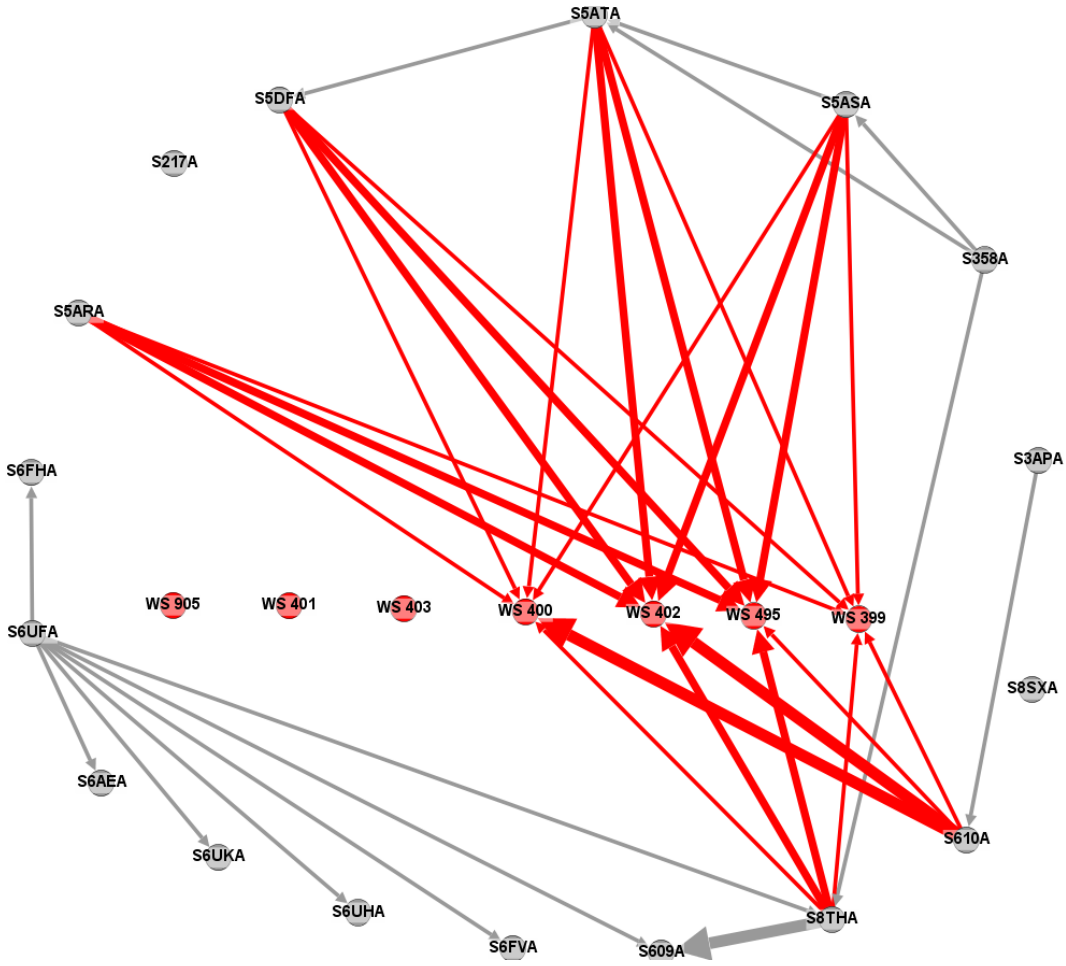


Figure A.19: Graph for US models with circular layout and coloring based on parts

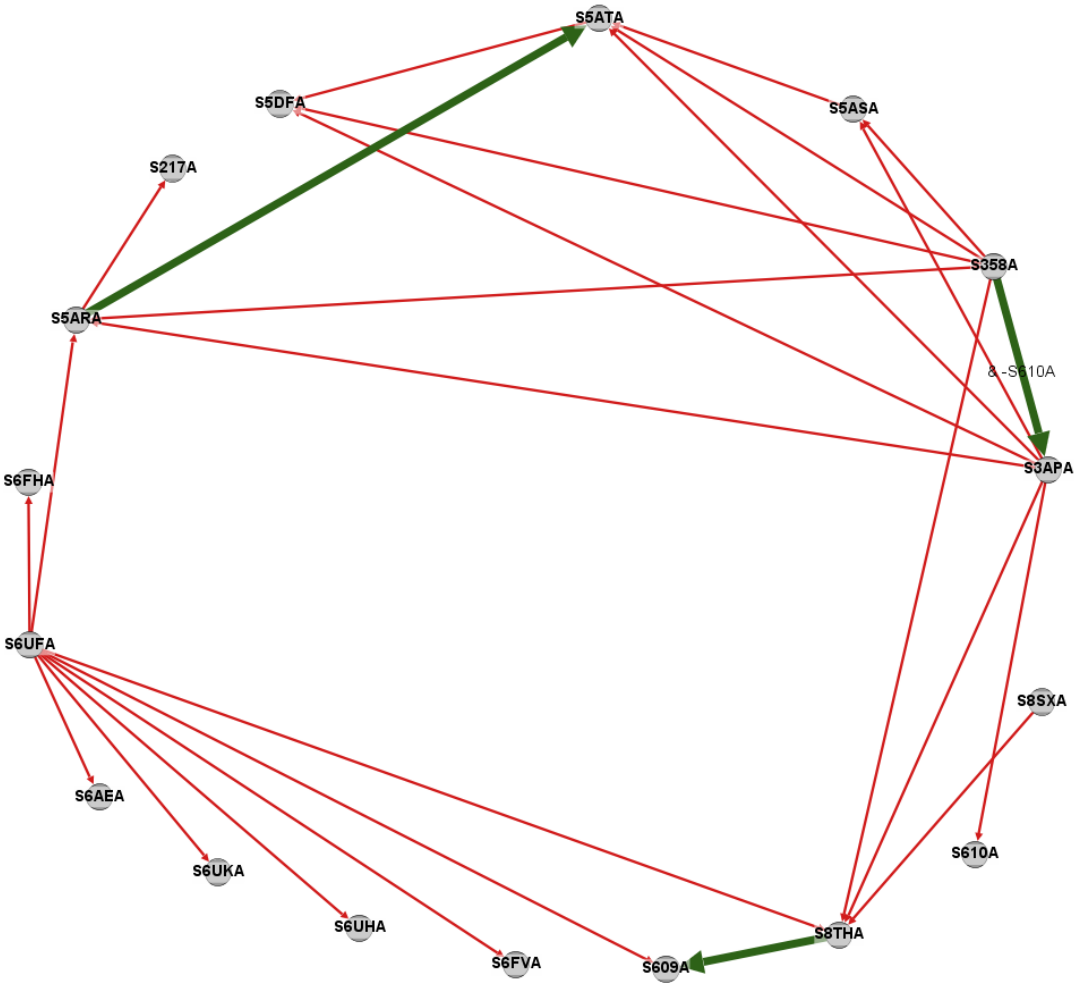


Figure A.20: Graph for European models with circular layout and coloring based on interactions (options only)

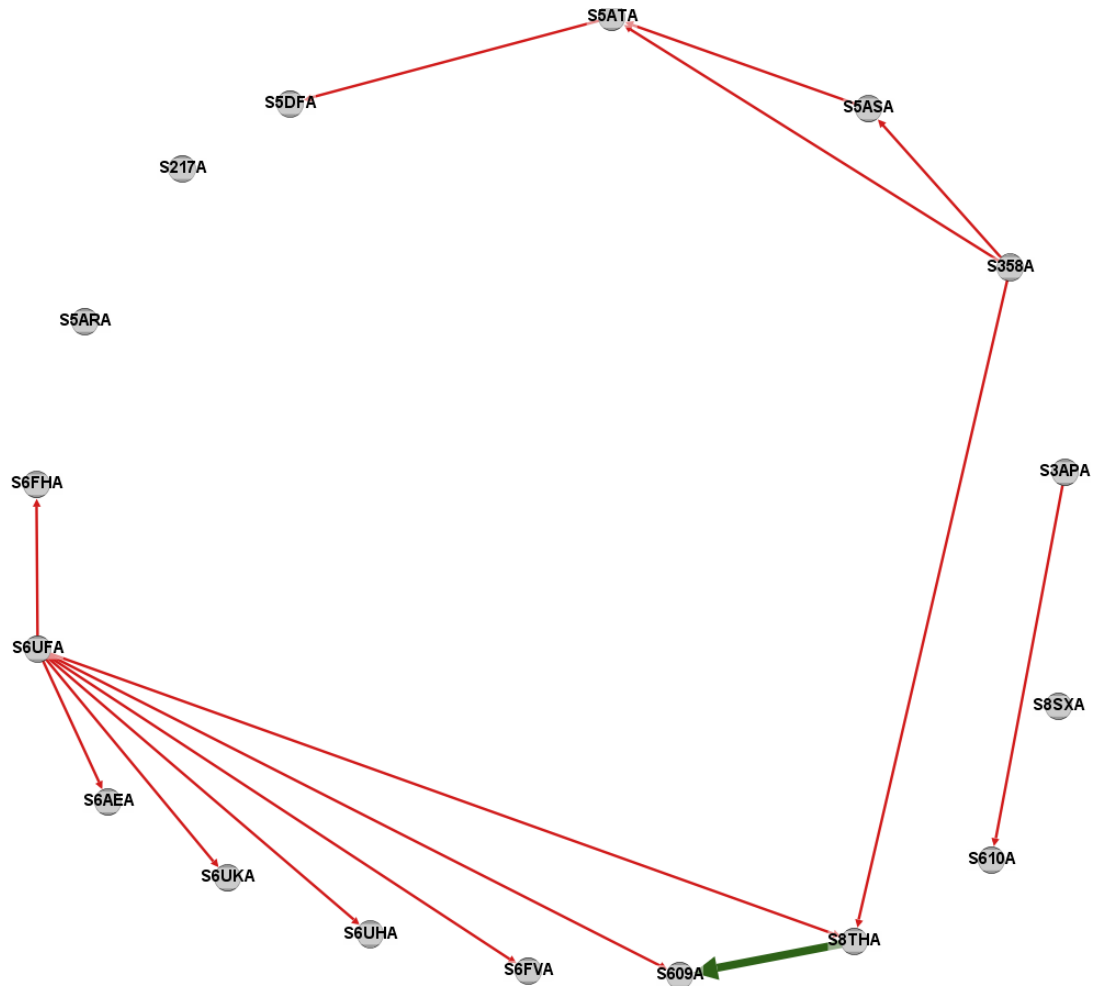


Figure A.21: Graph for US models with circular layout and coloring based on interactions (options only)

Appendix G: Visualization Tool Validation User Study Packets

A

Provided

- 1x rule database
- 3x rule graphs
- 3x example configuration changes

Instructions

- Based on the information provided in each configuration change, make edits to the provided rule graph.
- Configuration changes are independent – Configuration Change 1 should not be considered when evaluating Configuration Change 2.
- Use a fresh rule graph for each Configuration Change.
- No changes need to be made to the rule database, it is for reference only.
- If removing a rule is required, make sure it is clear which rule is to be removed and how the removal is shown.

Rule Grammar

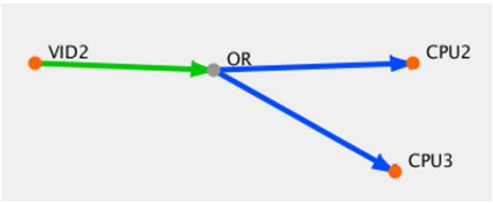
Rule type	If-Part of rule	Then-part of rule
+	VID3	CPU3

"+" for positive relationship

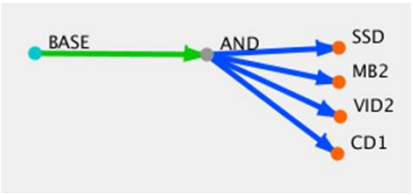
Rule type	If-Part of rule	Then-part of rule
-	MB1	MB2

"-" for negative relationship

Rule type	If-Part of rule	Then-part of rule
+	VID2	CPU2 / CPU3



Rule type	If-Part of rule	Then-part of rule
PK	BASE	VID2 & MB2 & SSD & CD1



-Green lines indicate positive
-Red lines indicate negative
-Blue lines indicate multiple, positive

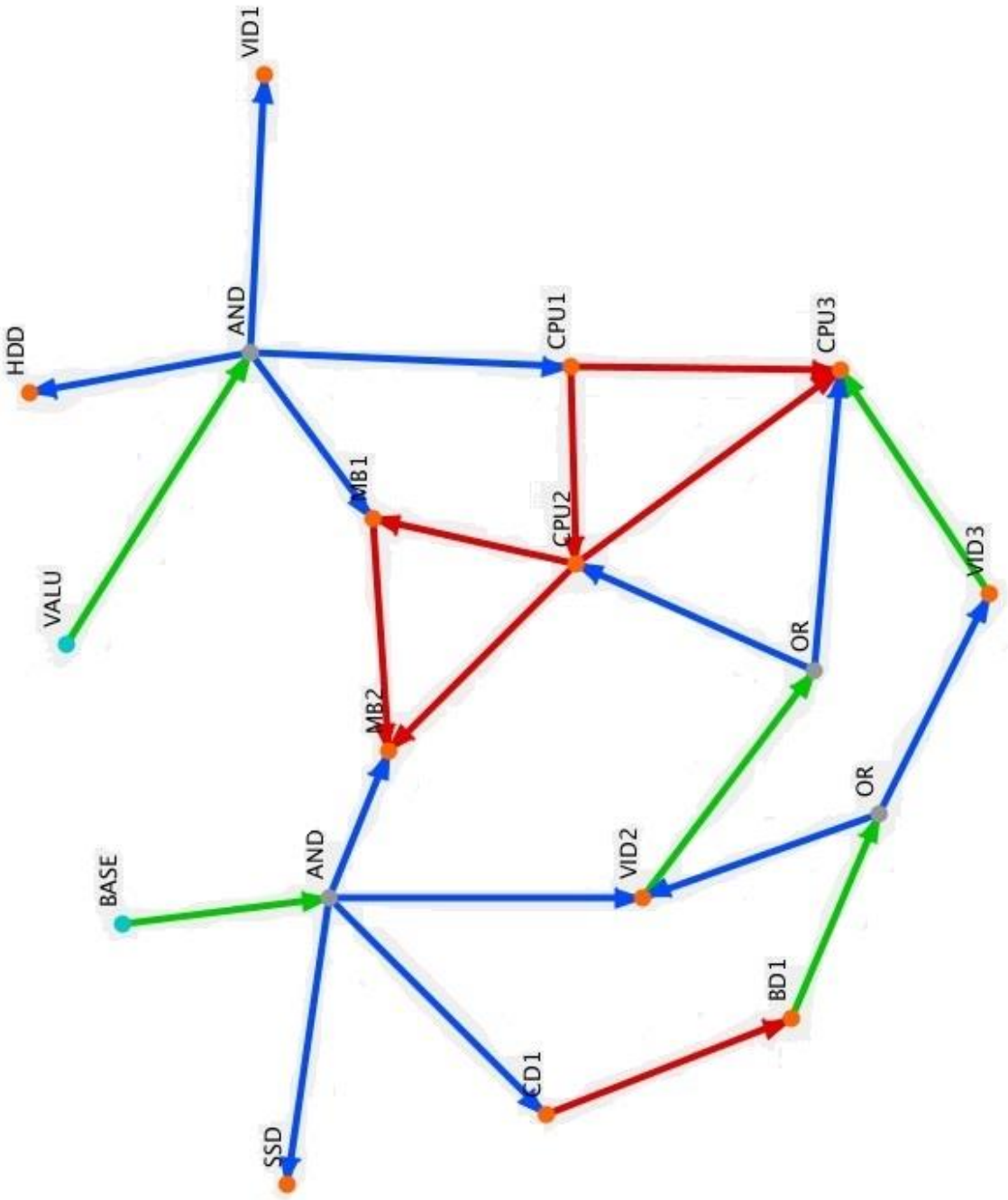
Rule Database

Option typ	Name	Description
Option	MB1	VALUE MOTHERBOARD
Option	MB2	HIGH-END MOTHERBOARD
Option	CPU1	VALUE PROCESSOR UNIT
Option	CPU2	MID-RANGE PROCESSOR UNIT
Option	CPU3	HIGH-END PROCESSOR UNIT
Option	VID1	VALUE VIDEO CARD
Option	VID2	MID-RANGE VIDEO CARD
Option	VID3	HIGH-END VIDEO CARD
Option	HDD	HARD DISK DRIVE
Option	SSD	SOLID STATE DRIVE
Option	CD1	CD-ROM DISK DRIVE
Option	BD1	BLURAY DISK DRIVE
Package	VALU	VALUE PACKAGE
Package	BASE	MID-RANGE PACKAGE
Rule type	If-Part of rule	Then-part of rule
-	MB1	MB2
-	CPU2	MB1
-	CPU2	MB2
-	CPU1	CPU2
-	CPU1	CPU3
-	CPU2	CPU3
-	CD1	BD1
+	VID3	CPU3
+	VID2	CPU2 / CPU3
+	BD1	VID2 / VID3
PK	VALU	VID1 & CPU1 & MB1 & HDD
PK	BASE	VID2 & MB2 & SSD & CD1

Configuration change 1

Problem:
A previous change in the CPU (CPU2) from Supplier Y resulted in an incompatibility with all of the existing motherboards that are available for all laptops.
Solution:
A new motherboard (MB3) has been identified from Supplier X that meets the performance criteria for all of the CPUs currently being manufactured. Make the motherboard available for all laptops and ensure the correct CPUs are associated with the newly added motherboard.
Rule changes:
-Add new motherboard (MB3 – “High-end motherboard”) to the rule database -Add inclusion between CPU2 and MB3 -Add exclusion between MB3 and MB1 -Add exclusion between MB3 and MB2

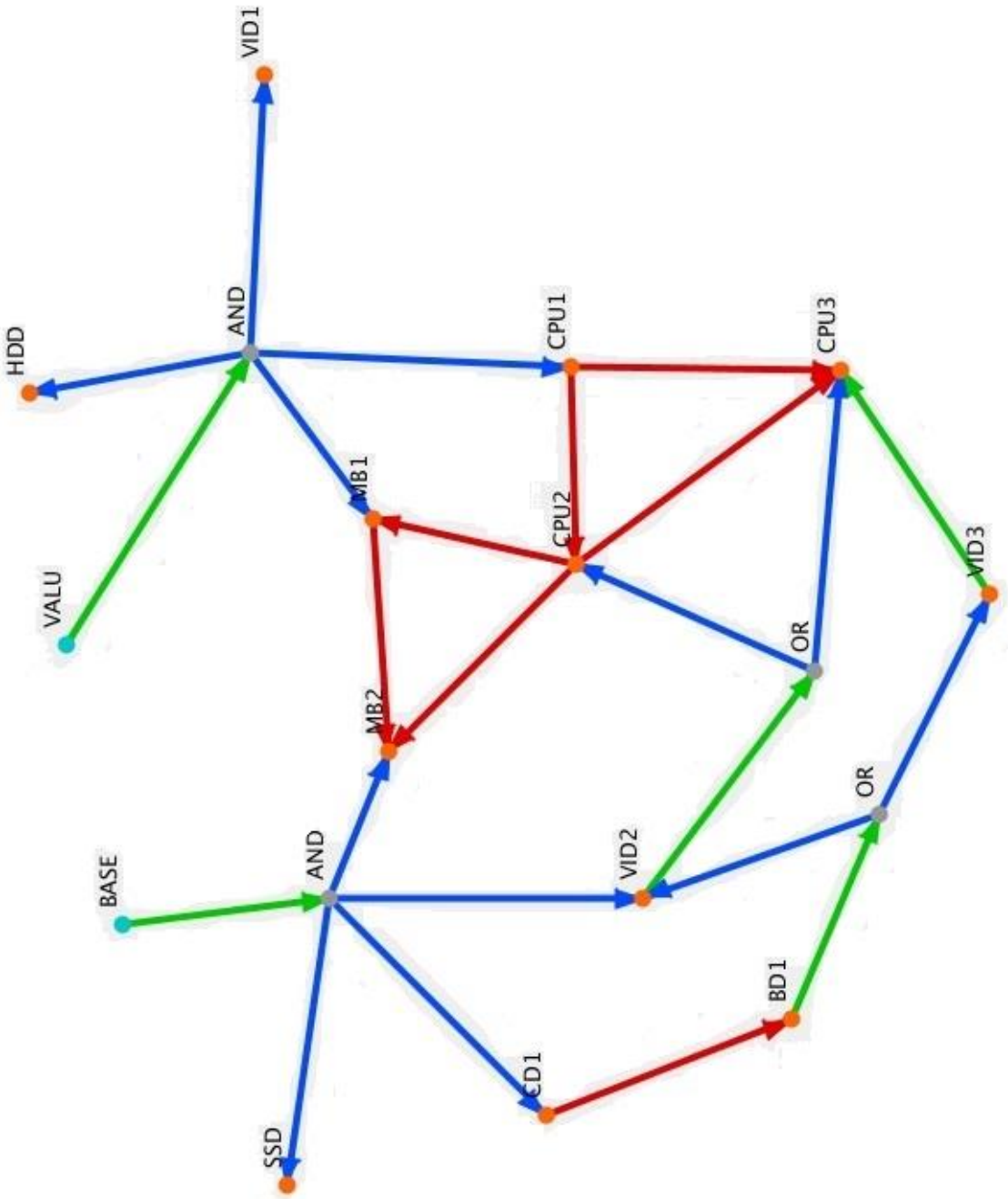
Change 1


VID1
AND
HDD
CPU1
CPU3
MB1
CPU2
VID3
VALU
OR
MB2
OR
BASE
AND
VID2
BD1
CD1
SSD

Configuration change 2

Problem:
The supplier that manufacturers the parts for CPU1 has gone out of business, resulting in the potential loss of that option.
Solution:
A new supplier has been found that can produce a similar processor unit to the previous one used in CPU1. As a result, CPU1 remains a viable option. Video card rules must be changed due to new part compatibilities.
Rule changes:
-Add exclusion between CPU1 and VID1 -Remove inclusion between VID2 and CPU2 / CPU3 -Change package declaration for VALU from VID1 & CPU1 & MB1 & HDD to VID1 & MB1 & HDD
Bonus:
Why is the third rule change necessary?

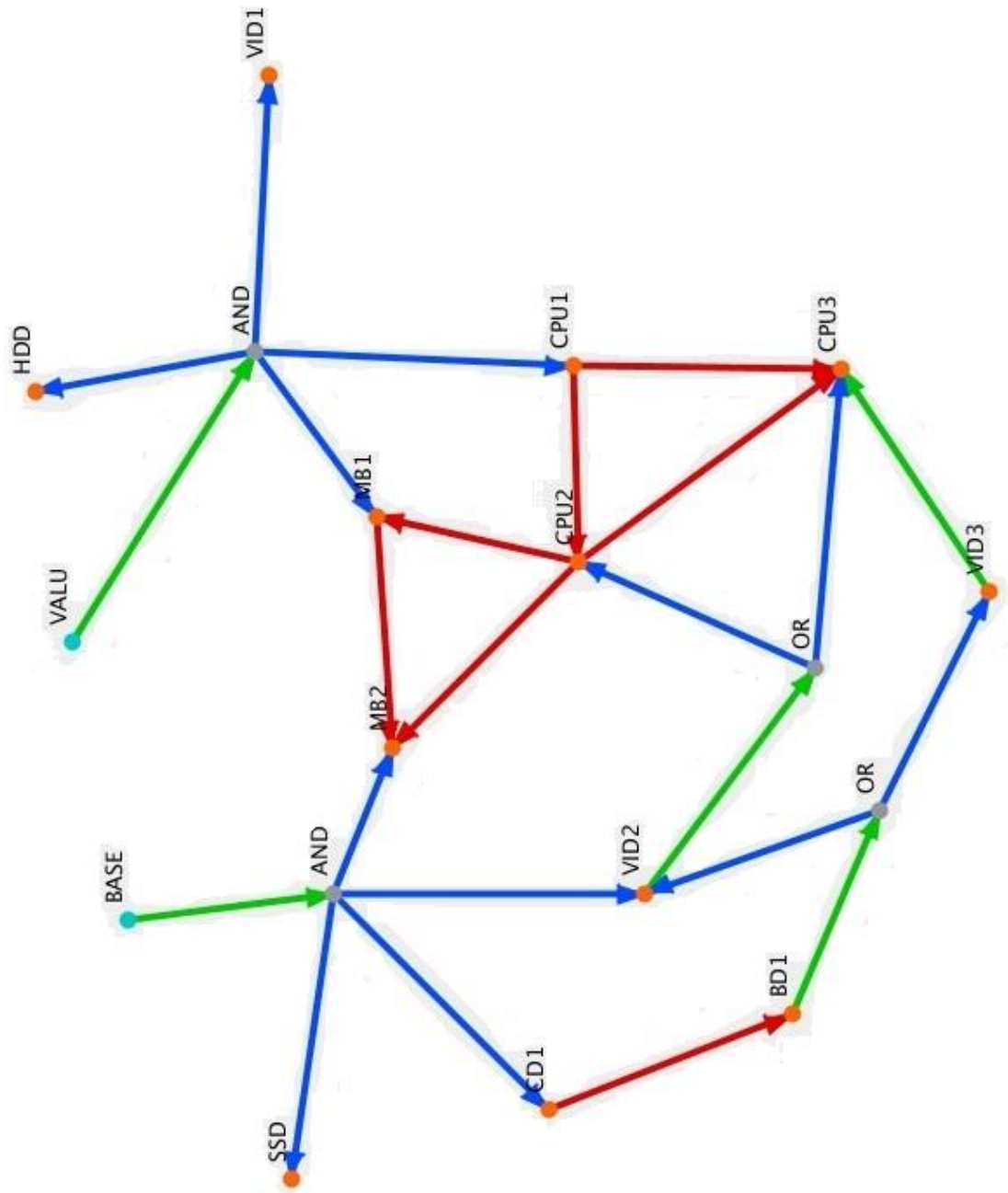
Change 2


VID1
AND
HDD
CPU1
CPU3
MB1
CPU2
VID3
VALU
OR
MB2
OR
AND
VID2
BASE
BD1
CD1
SSD

Configuration change 3

Problem:
Order history has shown that the customers are ordering the high-end video card (VID3) with the high-end CPU (CPU3), but have been settling for the less expensive motherboard (MB1). As MB1 is compatible with both options and has not been shown to hinder the performance of either higher-end option, many customers have ordered these together, resulting in a decrease in sales for laptops with the more expensive motherboard (MB2).
Solution:
Implement a new package (XPNS) that includes the high-end eversion of the motherboard (MB2), CPU (CPU3), and video card (VID3). In order for the customers to order either the high-end CPU or video card, they must include the XPNS package.
Rule changes:
-Add new package (XPNS – “High-end package”) to the ruleset -Add package declaration for XPNS of SSD & BD1 & VID3 & MB2 & CPU3 -Add inclusion between VID3 and XPNS -Add inclusion between CPU3 and XPNS

Change 3


VID1
AND
HDD
CPU1
CPU3
MB1
CPU2
VID3
VALU
OR
MB2
OR
AND
VID2
BASE
BD1
CD1
SSD

B

Provided

- 3x rule database
- 3x example configuration changes

Instructions

- Based on the information provided in each configuration change, make edits to the provided rule database.
- Configuration changes are independent – Configuration Change 1 should not be considered when evaluating Configuration Change 2.
- Use a fresh rule database for each Configuration Change.
- If removing a rule is required, make sure it is clear which rule is to be removed and how the removal is shown.

Rule Grammar

- "-" indicates mandatory exclusion (negative relationship)
- "+" indicates mandatory inclusion (positive relationship)
- "PK" indicates a package declaration rule (elements are included in the package)
- "/" indicates "either/or" relationship (only one of them is required)
- "&" indicates "and" relationships (both are required)

Configuration change 1

Problem:
A previous change in the CPU (CPU2) from Supplier Y resulted in an incompatibility with all of the existing motherboards that are available for all laptops.
Solution:
A new motherboard (MB3) has been identified from Supplier X that meets the performance criteria for all of the CPUs currently being manufactured. Make the motherboard available for all laptops and ensure the correct CPUs are associated with the newly added motherboard.
Rule changes:
-Add new motherboard (MB3 – "High-end motherboard") to the rule database -Add inclusion between CPU2 and MB3 -Add exclusion between MB3 and MB1 -Add exclusion between MB3 and MB2

Change 1

Option typ	Name	Description
Option	MB1	VALUE MOTHERBOARD
Option	MB2	HIGH-END MOTHERBOARD
Option	CPU1	VALUE PROCESSOR UNIT
Option	CPU2	MID-RANGE PROCESSOR UNIT
Option	CPU3	HIGH-END PROCESSOR UNIT
Option	VID1	VALUE VIDEO CARD
Option	VID2	MID-RANGE VIDEO CARD
Option	VID3	HIGH-END VIDEO CARD
Option	HDD	HARD DISK DRIVE
Option	SSD	SOLID STATE DRIVE
Option	CD1	CD-ROM DISK DRIVE
Option	BD1	BLURAY DISK DRIVE
Package	VALU	VALUE PACKAGE
Package	BASE	MID-RANGE PACKAGE
Rule type	If-Part of rule	Then-part of rule
-	MB1	MB2
-	CPU2	MB1
-	CPU2	MB2
-	CPU1	CPU2
-	CPU1	CPU3
-	CPU2	CPU3
-	CD1	BD1
+	VID3	CPU3
+	VID2	CPU2 / CPU3
+	BD1	VID2 / VID3
PK	VALU	VID1 & CPU1 & MB1 & HDD
PK	BASE	VID2 & MB2 & SSD & CD1

Configuration change 2

Problem:
The supplier that manufacturers the parts for CPU1 has gone out of business, resulting in the potential loss of that option.
Solution:
A new supplier has been found that can produce a similar processor unit to the previous one used in CPU1. As a result, CPU1 remains a viable option. Video card rules must be changed due to new part compatibilities.
Rule changes:
-Add exclusion between CPU1 and VID1 -Remove inclusion between VID2 and CPU2 / CPU3 -Change package declaration for VALU from VID1 & CPU1 & MB1 & HDD to VID1 & MB1 & HDD
Bonus:
Why is the third rule change necessary?

Change 2

Option typ	Name	Description
Option	MB1	VALUE MOTHERBOARD
Option	MB2	HIGH-END MOTHERBOARD
Option	CPU1	VALUE PROCESSOR UNIT
Option	CPU2	MID-RANGE PROCESSOR UNIT
Option	CPU3	HIGH-END PROCESSOR UNIT
Option	VID1	VALUE VIDEO CARD
Option	VID2	MID-RANGE VIDEO CARD
Option	VID3	HIGH-END VIDEO CARD
Option	HDD	HARD DISK DRIVE
Option	SSD	SOLID STATE DRIVE
Option	CD1	CD-ROM DISK DRIVE
Option	BD1	BLURAY DISK DRIVE
Package	VALU	VALUE PACKAGE
Package	BASE	MID-RANGE PACKAGE
Rule type	If-Part of rule	Then-part of rule
-	MB1	MB2
-	CPU2	MB1
-	CPU2	MB2
-	CPU1	CPU2
-	CPU1	CPU3
-	CPU2	CPU3
-	CD1	BD1
+	VID3	CPU3
+	VID2	CPU2 / CPU3
+	BD1	VID2 / VID3
PK	VALU	VID1 & CPU1 & MB1 & HDD
PK	BASE	VID2 & MB2 & SSD & CD1

Configuration change 3

Problem:
Order history has shown that the customers are ordering the high-end video card (VID3) with the high-end CPU (CPU3), but have been settling for the less expensive motherboard (MB1). As MB1 is compatible with both options and has not been shown to hinder the performance of either higher-end option, many customers have ordered these together, resulting in a decrease in sales for laptops with the more expensive motherboard (MB2).
Solution:
Implement a new package (XPNS) that includes the high-end eversion of the motherboard (MB2), CPU (CPU3), and video card (VID3). In order for the customers to order either the high-end CPU or video card, they must include the XPNS package.
Rule changes:
-Add new package (XPNS – "High-end package") to the ruleset -Add package declaration for XPNS of SSD & BD1 & VID3 & MB2 & CPU3 -Add inclusion between VID3 and XPNS -Add inclusion between CPU3 and XPNS

Change 3

Option typ	Name	Description
Option	MB1	VALUE MOTHERBOARD
Option	MB2	HIGH-END MOTHERBOARD
Option	CPU1	VALUE PROCESSOR UNIT
Option	CPU2	MID-RANGE PROCESSOR UNIT
Option	CPU3	HIGH-END PROCESSOR UNIT
Option	VID1	VALUE VIDEO CARD
Option	VID2	MID-RANGE VIDEO CARD
Option	VID3	HIGH-END VIDEO CARD
Option	HDD	HARD DISK DRIVE
Option	SSD	SOLID STATE DRIVE
Option	CD1	CD-ROM DISK DRIVE
Option	BD1	BLURAY DISK DRIVE
Package	VALU	VALUE PACKAGE
Package	BASE	MID-RANGE PACKAGE

Rule type	If-Part of rule	Then-part of rule
-	MB1	MB2
-	CPU2	MB1
-	CPU2	MB2
-	CPU1	CPU2
-	CPU1	CPU3
-	CPU2	CPU3
-	CD1	BD1
+	VID3	CPU3
+	VID2	CPU2 / CPU3
+	BD1	VID2 / VID3
PK	VALU	VID1 & CPU1 & MB1 & HDD
PK	BASE	VID2 & MB2 & SSD & CD1