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DEVELOPMENT OF A DESIGN METHOD TO REDUCE CHANGE PROPAGATION EFFECTS

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ABSTRACT

This dissertation presents a design method to reduce engineering changes caused due to change propagation effect. The method helps designers to systematically plan a verification, validation, and test (VV&T) plan. The rationale behind such a method is founded on a well-accepted principle that a robust validation plan can reduce engineering changes. However, such method has not yet been developed in mechanical engineering domain for supporting incremental product design, so a method from software engineering has been adopted and extended to address the limitations in the existing design evaluation tools.

Tools extensively used in industry, such as FMEA, and in academia have been reviewed to determine if they can identify different propagation pathways including variant, behavior, organization, and geometric pathways. As a result, it is found that variant and organizational pathways are not identified in any of the reviewed tools — propagation in these pathways have caused a major product failure in a commercial vehicle and an automatic fire sprinkler manufacturing industries.

A seven-step VV&T method is proposed to address the aforementioned gap in which each step is tailored to suit mechanical engineering needs. The major contribution is developing the construct to identify variant and organization pathways and a prescriptive method. It has been validated in a leading commercial vehicle manufacturer, one of the passenger car manufacturing giants, a rolling mill manufacturer, and an automatic fire sprinkler manufacturer using case study and Delphi validation technique. The results from these studies indicate the proposed VV&T method enables designers to

identify variant and organizational pathways and evaluate them, which in turn can reduce engineering changes due to propagation effects. Objective evidence obtained from the fire sprinkler manufacturing company supports this claim explicitly.

> *"The time saved in finding the issue (using this method) during testing is likely between one and three months….I would estimate the cost savings to be somewhere between $2000-$4000…assuming it would have been caught before the valve was released (for customer use)."*

- Project engineer, Automatic Fire Sprinkler manufacturer, September 2011

"I understand it to be a work to validate a product family of slightly different variants... Then thinking about worst case amongst the set indicates the actual set of variants to test. Very cool!... I like how you created and laid it out as standard work that people can repeat and follow."

- Dr. Kevin Otto, October 2011

DEDICATION

Dedicated to my parents, my sister, my wife, and my in-laws.

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NOMENCLATURE

3D	:	3-Dimensional
Ab	:	Abstract
AFMEA	:	Advanced failure mode and effect analysis
ANSI	:	American national standards institute
AVA	:	Air ventilation area
B.S.	:	Bachelor of science
BOM	:	Bills of material
BP	:	Basic product
C	:	Components
C&CM	:	Channel and contact model
CAD	:	Computer aided design
CAE	:	Computer aided engineering
CBD	:	Component block diagram
CDR	:	Critical design review
CF	:	Components-failures
CFG	:	Configuration flow graph
CFMA	:	Conceptual failure mode analysis
CIM	:	Change interaction model
CM	:	Configuration management
CMMI	:	Capability maturity model-integration
Cn	:	Number of combination vectors
CPM	:	Change prediction method
CSS	:	Channel and support structure
CV	:	Concept variants
D	:	Detection
DFMEA	:	Design failure mode and effect analysis
DFSS	:	Design for six sigma
DMM	:	Domain mapping matrix
DP	:	Design parameters
DR	:	Design review
DSM	:	Design Structure Method
DVP	:	Design verification/validation plan
E	:	Element
E-S-V	:	Element- Supplier-Variant
EC	:	Functions – components
ED	:	Elasto-dynamics
EF	:	Function-failure
Ex	:	External
ECM	:	Engineering change management
ECN	:	Engineering change note
ECO	:	Engineering change order
ECP	:	Engineering change process

ECR	:	Engineering change request
ECs	:	Engineering changes
EFD	:	Elasto fluid dynamics
EIA	:	Electronic industries alliance
ERN	:	Engineering release note
ES	:	Elasto-statics
ETA	:	Event tree analysis
F	:	Failure
F-B-S	:	Function-behavior-structure
FAST	:	Function analysis system technique
FBD	:	Functional block diagram
FEA	:	Finite element analysis
FFDM	:	Function failure design method
FFIP	:	Function failure identification and propagation
FMEA	:	Failure mode and effect analysis
FMECA	:	Failure mode and effect criticality analysis
FMVSS	:	Federal motor vehicle safety standards
Fn	:	Functions
FRs	:	Functional requirements
FTA	:	Failure tree analysis
G	:	Geometric
GE	:	General Electric
GEIA	:	Government electronics and information technology association
HOQ	:	House of quality
I	:	Internal
IEC	:	International electro-technical commission
IEEE	:	Institute of electrical and electronics engineers
ISO	:	International organization for standardization
LTM	:	Long term memory
M.S.	:	Masters of science
ME	:	Mechanical energy
MS	:	Microsoft
N.A.	:	Not applicable
NE	:	Number of elements
NFRs	:	Non-Functional Requirements
NSTSP	:	National school transportation specifications and procedures
O	:	Occurrence
OEM	:	Original equipment manufacturer
P.E.	:	Professional engineer
PDM	:	Product data management
Ph.D.	:	Doctor of philosophy
PR	:	Prototypes
Pr.E	:	Project engineer
PRA	:	Probabilistic risk assessment

Q	:	Question
QFD	:	Quality function deployment
R	:	Requirement
RAND	:	Research and development
RMS	:	Requirement modeling scheme
RPN	:	Risk priority number
RQ	:	Research question
S	:	Supplier
SAE	:	Society of automotive engineers
SD	:	System dynamics
Se	:	Severity
SFMEA	:	Scenario based failure mode and effect analysis
SP	:	Spatial relationship
SRR	:	System requirements review
STM	:	Short term memory
Su	:	Success
T	:	Test
TGR	:	Things gone right
TGW	:	Things gone wrong
TM	:	Test measures
To	:	Tolerance relationship
TS	:	Technical specification
USA	:	United States of America
V	:	Variant
VCI	:	Verification complexity index
VP	:	Variant product
VV&T	:	Verification, validation, and test
WIFA	:	German acronym for FMEA
WIP	:	Work in process
WM	:	Working memory
WP	:	Working principles
WS	:	Working structure
WSP	:	Working surface pair

CHAPTER ONE : INTRODUCTION TO ENGINEERING CHANGES

The objective of this research is to develop a control to reduce engineering changes caused due to change propagation effects. As soon as new products are launched in the market, competitors launch products with better performance characteristics. Such global competition in the market place motivates technology driven firms to develop products with improved performance and quality at lower costs (Otto and Wood 1998). As a result, product development involves a steady evolution of the designed artifact as the components and the sub systems are continuously changed <u>during the course of production</u> (Duhovnik and Tavcar 2002; Eckert et al. 2003; Clarkson et al. 2004; Tavcar and Duhovnik 2005). These in production changes are termed engineering changes (ECs) based on refinements of definitions offered by various authors. In section 1.1, these different definitions are reviewed and the definition that is used in this research is described.

1.1 Definition For Engineering Change

Several authors have defined engineering changes with subtle differences, including:

- *Engineering changes are changes to parts or drawings that have already been released* (Clark and Fujimoto 1991)
- *Engineering changes refer to modifications in forms, fits, functions, etc. in product design* (Huang and Mak 1997)
- *An engineering change is a modification to a component of a product, after*

that product has entered production (Wright 1997)

The last definition (Wright 1997) is restricted to the production phase of the product life cycle whereas the other two does not specify any particular phase in the product life cycle. Subsequently, the software design issues that are important for mechatronic design are addressed by (Terwiesch and Loch 1999). They state:

- *Engineering change orders are changes to parts, drawings or software that have already been released* (Terwiesch and Loch 1999)

In this definition, the term engineering change orders is synonymous to the term engineering changes. This definition is further enhanced to include the size and scope of the change as they can range from a simple correction of a drawing error taking an engineer few hours to a major cost reduction project extended over several months involving a large team of engineers. Thus, a modified definition states:

- *An engineering change is an alteration made to parts, drawings, or software that has already been released during the design process. The change can be of any size or type, can involve any number of people, and can take any length of time* (Jarratt et al. 2005).

This definition focuses on engineering changes only during the design process whereas changes can be initiated even after it is introduced in to the production as indicated by (Wright 1997). The definitions listed above implicitly refer to parts that have an embodiment; neglecting changes that occur during the conceptual design phase.

Therefore, in this research, engineering change is defined in a comprehensive manner to encompass the content of other definitions by other researchers and explicitly including the phase of the product life cycle.

An engineering change is an alteration made to parts in its form or fit or function, drawings or software that has already been released <u>from embodiment design through production stage of the product life cycle</u>. The change can be of any size or type, can involve any number of people, and can take any length of time.

ECs are also described using different terms such as 'design changes' (Ollinger and Stahovich 2001; Rouibah and Kevin 2003), 'product design changes' (Huang and Johnstone 1995), and 'product change' (Innes 1994). Nevertheless, all these terms refer to the same general concept (Jarratt et al. 2005). In this research, the term engineering change (EC) or design change is used for simplicity.

1.2 Requirement Changes Versus Engineering Changes

ECs may have multitude causes: requirement change, design corrections, decision indiscipline, technological innovations, and communication and co-ordination issues within the supply chain of the organization (Fricke et al. 2000). Nonetheless, ECs are generally perceived as being initiated due to requirement changes (Morkos and Summers 2010), but they may not necessarily lead to engineering changes. For instance, a truck with a rated payload of 4.5 ton may be used by the customers with 5 ton; typically such scenarios are observed in the South-East Asia automotive market. The marketing executives, after observing the field practice, may request the engineering design department to formally upgrade the vehicle specification from 4.5 to 5 ton, which will provide them with an opportunity to boost sales. The engineering design department, after assessing the effects of the increased load, may conclude not to conduct any design change in the vehicle because the existing design possess sufficient safety margins on both strength and performance limits. Thus, a requirement change can be, but not always, the reason for ECs.

1.3 Overview of Engineering Change Management (ECM)

Engineering change management (ECM) is a special business process that deals with managing engineering changes to deliver the right products to the customers at the right time (Huang et al. 2000). Inefficient and ineffective management of ECs will lead to perturbed manufacturing resulting in an increased product delivery time to the customers and the cost (Pikosz and Malmqvist 1998; Huang et al. 2000; Huang et al. 2003), eventually leading to customer dissatisfaction. In order to be able to manage these ECs in an effective and efficient manner, ECM essentially describes a seven step process, as shown in Figure 1, to conduct an EC and establishing a communication channel to coordinate the change within and between various departments across the manufacturing firm (Jarratt et al. 2006).

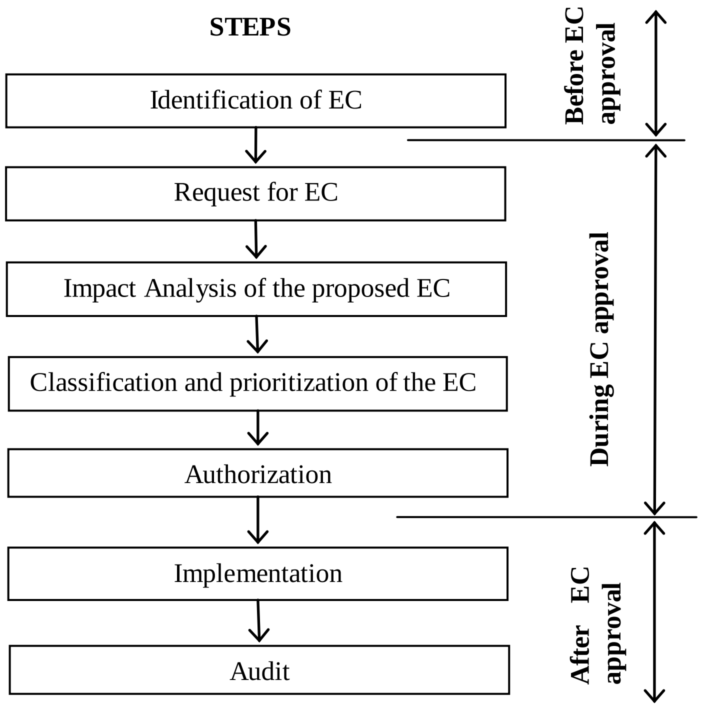


Figure 1.1 Engineering Change Process (Jarratt et al. 2006)

1.3.1 Brief Description of the Engineering Change Process (ECP)

The engineering change process (ECP), as shown in Figure 1.1, is divided into three stages: before EC approval, during EC approval, and after EC approval. In the first stage, an engineering change is identified, which will be triggered by a reason for change such as design error or product redesign. In the second stage during EC approval, the person who identifies the change prepares a change request, termed as engineering change request (ECR), in a standardized document as per the company's best practices and communicates this to the engineering design department. Subsequently, the requested change is analyzed for its impact on the product and its manufacturing. Analyses could include, but not limited to, effect of the change on the performance, the strength aspects of the design, and the manufacturability of the modified design. After the impact analysis, the proposed change is classified and prioritized based on the impact level. In the last step of the second stage, the proposed change is either approved or rejected by a change committee comprised of members from different departments who are responsible for smooth product transitions in the production. If the committee approves the change, the EC enters the last and final stage in the ECP, then the different departments in the manufacturing firm gear up to implement the change. Finally, after implementing the change, the entire process is audited to evaluate the effectiveness of the change and the lessons learnt are documented.

In this process, a request for change can be declined at three different steps. First, a request for change can be declined after it is initiated. A preliminary review of this request may be sufficient to decline the proposal if it is impractical. This is in line with the suggested filtering criteria (Maull et al. 1992; Boznak and Decker 1993). Second, there could be no possible solutions for the proposed request. Third, the results of the impact analysis might reveal that the proposed change is too risky to be implemented. Thus, the engineering change committee may not authorize considering the results of the impact analysis and the phase of the product life cycle in which the change is proposed. Therefore, not every change request is successfully realized in the product. Nevertheless, companies that follow the ECM system adhere to a process that is by and large similar to the one described here (Jarratt et al. 2006).

ECP encompasses the features of configuration management (CM), which deals with developing product documentation controls for identifying, controlling, and accounting the status of changes (Monahan 1995). CM is also necessitated by the quality standards such as ISO/TS 16949 (Kymal 2004) requirements to document all the business process activities. Thus, analysis on ECs is made possible by referring to the documents as prescribed in the CM.

1.3.2 Association Of The ECP In The Product Life Cycle

By definition of the EC (see section1.1), the design iterations that take place in the conceptual design stage is not considered as an EC. However, any changes that are initiated from the embodiment design stage through the production phase of the product life cycle is considered as an EC. These changes are managed by the ECP, and hence, it is a closely associated process with the product life cycle, as shown in Figure 1.2. The activities associated with ECP in each phase of the product life cycle are different. For example, an EC in the embodiment design stage may not require communication to the logistics-planning department whereas it is required during the production ramp up stage. A different set of communication channels is required for implementing an EC at different stages of the product life cycle. This research focuses only on the production phase of the life cycle, the reason for which is described in the next section.

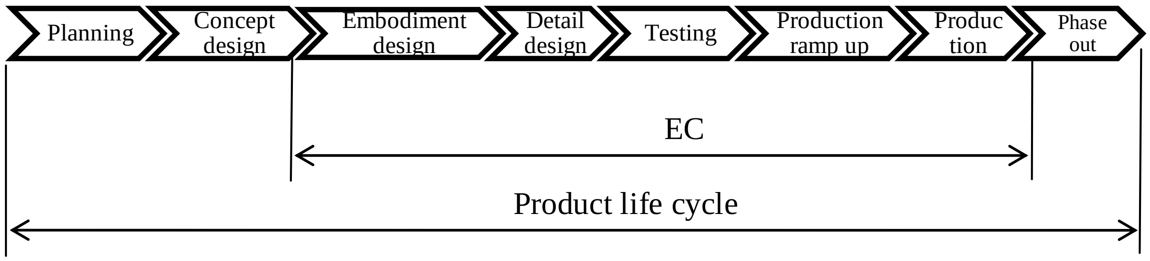


Figure 1.2 Association of ECP In the Product Life Cycle (Jarratt et al. 2005)

1.4 Detrimental Effects of ECs

The detrimental effects of ECs to a company can be divided into two factors: lead-time and cost. Industrial case studies conducted in the manufacturing companies reveals that the average throughput time of an EC from its identification to implementation is unduly long (Loch and Terwiesch 1999). For example, the average time taken to implement an EC is 120 days; forty days to design and develop, forty days to process and forty days to implement in production (Watts 1984; Rouibah and Kevin 2003). In certain cases, the implementation time has extended well over a year (Loch and Terwiesch 1999). This long duration for implementation is mainly attributed to the non-value added activities in the administrative offices. The major reasons for delay are batching and delayed information and project congestion. Batching often results from a tendency to avoid intellectual or mental effort leading to stack up of ECR in one's account. As a result, this leads to delayed processing of the information leading to work in process (WIP) and inventories of ECs in the administrative office. The processing lead times for ECRs are studied in an automotive industry during a new product development process, and it has been identified that the time consumed to process ranged from weeks to months and, in certain cases, over a year (Loch and Terwiesch 1999). Engineers work simultaneously in multiple projects due to resource scarcity. They are also switched between projects based on project's priorities. This leads to further time loss because the engineers have to remind themselves of their earlier work in the project. The use of internet based engineering change management (Huang et al. 2001) can reduce such long implementation time, which is forty days, needed to process an EC. This is possible because internet based ECM is transparent about who is working on the ECR, and how long has it been pending on one's ownership. However, the forty days in the design department and the forty days in the production department can significantly affect the product lead time.

A change early in the development process is associated with minimal investments in tooling, validation, manufacturing processes, and equipment. These investments increase successively as the design moves towards maturity for full-scale production. The cost of an EC in each successive phase within the product life cycle is ten times more than the previous phase (Hoover and Jones 1991; Jarratt et al. 2006). Another reason for the increased cost is the requirement of nearly one-third to one-half of the engineering human resource to manage the ECs (Soderberg 1989; Terwiesch and Loch 1999). These detrimental effects of ECs will proliferate with the change propagation phenomenon, which can further reduce the profitability of the firm and can have greater impact during the production phase, for ECs in this phase are the most expensive. Motivated by the detrimental factors, product lead-time and cost factors, this research aims to reduce the engineering changes caused due to change propagation effects by developing suitable controls. With this overarching goal in this research, the phenomenon of change propagation and the requirements for a change propagation tool are described in the next chapter.

CHAPTER TWO : CHANGE PROPAGATION

2.1 What is Change Propagation?

Complex engineering products are built with highly interconnected elements within a sub-system and between systems (Suh 1998; Clarkson et al. 2004; Giffin 2007). Higher-order functions, beyond those of individual elements, are achieved in such systems through interactions between the system elements (Summers and Shah 2010). The interconnections within the system establish pathways between different portions of the design, which form the backbone for propagating the effects of an engineering change (EC).

Introducing an EC in a complex system can initiate a propagation chain, thereby affecting numerous elements. When this propagation causes a degrading effect in one or more of the system requirements, product failures can result thereby requiring further change. This phenomenon of one change leading to another is termed "change propagation". It is formally defined as:

> *"Change propagation is the process by which a change to one part or element of an existing system configuration or design results in one or more additional changes to the system, when those changes would not have otherwise been required* (Giffin 2007)*."*

Change propagation appears as cause-effect-cause-effect patterns, whereby the dependent variable, or effect, at an earlier stage becomes the independent variable, or cause, for the subsequent stage. A concern identified in the product because of an engineering change, EC1 in Figure 2.1, manifests itself into a cause for a propagated change (EC2), which can result in a series of other changes.

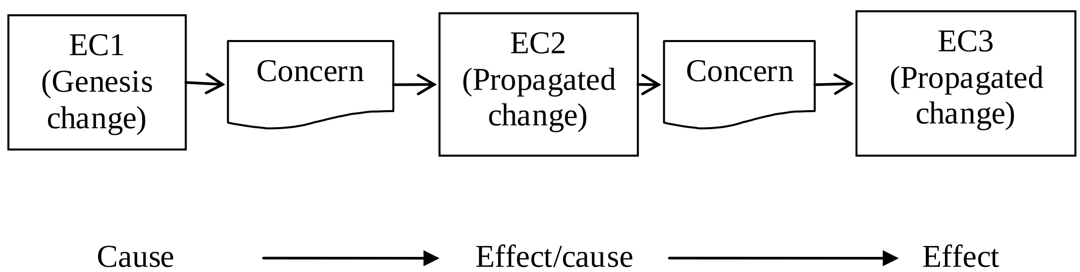


Figure 2.1 Concept of Change Propagation

Changes can propagate to different systems, including seemingly indirectly through the connected systems. Such cascading effects of the change can transform a simple cost effective change to a cost significant change due to the associated expenses in addressing the problems occurred elsewhere in the system. It is the secondary, or indirect relations that seem to be the most difficult for engineers to assess and predict (Morkos and Summers 2010). As ECs in themselves are expensive, as indicated in Section 1.4, change propagation will further augment the expenses. Hence, reducing design changes rooting from the change propagation phenomena is critical for an organization to meet the product delivery time and remain within the budget. Thus, the goal of this research is not to eliminate the need for engineering changes, but to create a containment strategy to reduce the unforeseen change propagation effects from the requisite change.

2.2 Propagation Pathway and Its Dependency on Change Modes

The different pathways through which the propagation effects cascade must be identified and evaluated during an EC, for an overarching goal of developing controls to reduce changes stemming from change propagation. This phenomenon of propagation and its associated pathways are dependent on change modes; that is, what type of change is implemented in the product. This concept of change modes is explained further.

2.2.1 Change Modes

A change mode could be an alteration in a part property or the addition and/or removal of a part to the product. These change modes can be classified into two types: (i) an active change mode is one that initiates propagation and (ii) an inactive change mode is one that does not. A change in the color of the hand drill's battery, for example, from black to blue may not initiate propagation - *an inactive change mode* - although a change in the battery's voltage will initiate - *an active change mode*.

In the event of an active change mode, the effect can travel through several different pathways. This can be visualized as arcs connecting nodes in a graph, as shown in Figure 2.2. A series of these arcs forms the propagation chain. Recent industrial case studies have suggested that propagation pathways are formed not only between interconnected system elements but between two different interconnected departments of the organization (Giffin 2007; Morkos and Summers 2010). This concept is illustrated using Figure 2.2 in which the nodes *A*, *B1*, and *B2* represent system elements, *B1* and *B2* being product variants, while node *C* represents a department in the organization. A change in the element *A* can propagate to node *C* through *α*, *β*, and *γ* pathways for one system configuration whereas in another node *C* can be affected via *α1*, *β1*, and *δ* pathways. Thus, the propagation chain in one configuration could be *A- α-B1- γ – C, A-*

β-B1- γ-C or *A- α* and *β-B1- γ -C*. However, there are three possible pathways between two nodes unlike the two shown in the illustration: (i) ambient pathway such as liquid and air, (ii) connected structural pathway such as energy, material, information, geometry, and variant, and (iii) interconnected organizational pathway such as design affecting manufacturing and design affecting logistics.

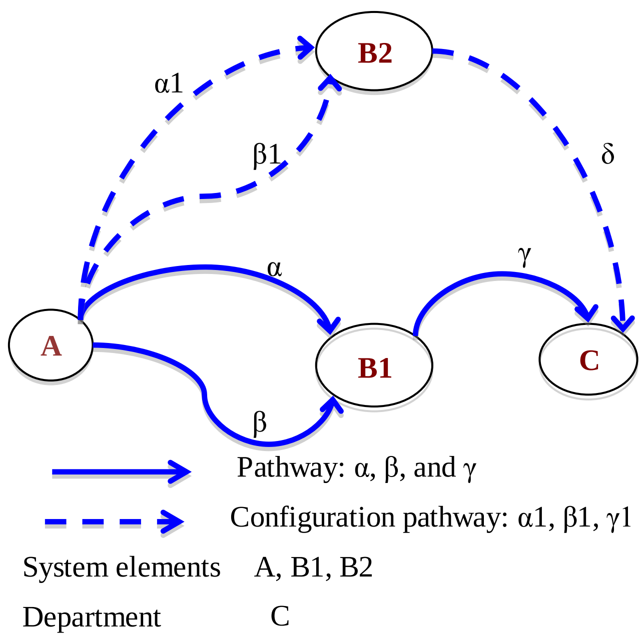


Figure 2.2 Schematics of Propagation Pathway

The identification of these pathways, in turn, also depends on the change mode. An alteration of the electrical energy in a hand drill's battery, for example, can change the quantity of the input current to the motor via interconnected system elements. This different physical quantity, due to change, may necessitate a change in the motor. Thus, this change mode has initiated propagation through a structural pathway. In another instance, the exterior color of the hand drill's box may be changed from black to green for ease of identification in the assembly line, which may cause corrosion due to environment interaction in the different types of colorings used. In this case, the change initiates propagation through an ambient pathway.

In addition, an active change mode can invoke single or multiple pathways at the onset of propagation such as *A-* α *-B1* or *A-* β *-B1*. Hence, design tools used for predicting change propagation must

- enable designers to model *change modes*,
- identify their associated *propagation pathways*,
- identify the *propagation chain*, and
- *evaluate* the propagation effects in order to determine if the change would cause any performance degradation or product failures.

In summary, the requirements for a change propagation tool are presented in Table 2.1.

Table 2.1 Requirement for a Change Propagation Tool

Index	Requirement description
1	Must enable designers to model change modes
2	Identify pathways (structural, ambient, configuration, and organizational)
3	Identify propagation chain
4	Evaluate the effects of propagation in the chain
5	Should be suitable for use in the production phase

2.3 Examples of Different Propagation Pathway

The concept of propagation pathway is further illustrated with examples from a wheel end layout of a heavy commercial vehicle. These examples are based on author's six years of industrial experience in the automotive industry. Three different pathways are illustrated in this section: (i) ambient pathway in section 2.3.1; (ii) variant or configuration pathway in section 2.3.2; and (iii) organizational pathway in section 2.3.3.

2.3.1 Propagation through Ambient Pathway

Ambient pathway of propagation effects is illustrated using a cross sectional view of a wheel-end layout of a heavy commercial vehicle, as shown in Figure 2.3. The surface between the brake drum and the brake shoe is where the frictional heat is generated during braking operation. This heat is transferred to the tire's tube (see green color dotted arrow in Figure 2.3 for heat flow direction) through the brake drum's wall thickness, the gap between the brake drum and the wheel rim, across the wheel rim and finally, to the tube. Thus, the transfer of heat through an air medium is an ambient propagation pathway. An increase in the brake drum thickness due to a new requirement change leads to problems including, but not limited to, tire-tube puncture (Kumar et al. 2006) and hub grease melting (Lee 2000). Thus, the effects of design change have initiated ambient pathways of propagation and lead to subsequent design changes.

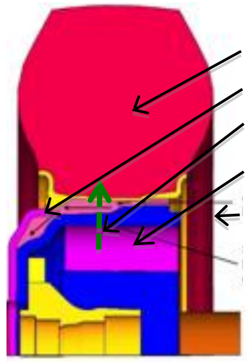


Figure 2.3 Wheel End Layout (Kumar et al. 2006)

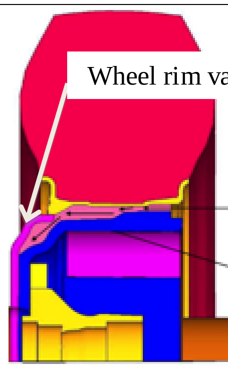
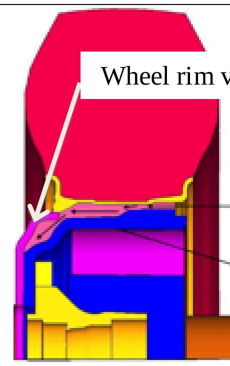
2.3.2 Propagation through Variant Pathway

The development of product families is in the increasing trend among industries because of their enhanced ability to provide a variety of products, with economies of scale, which satisfies customer requirement in different market niches (Jiao et al. 2007; Wie et al. 2007; Alizon et al. 2009). A product family is a set of similar products, where the individual products possess specific features or functionality to satisfy distinct customer needs. Each product within the product family is a product variant or an instance (Meyer and Lehnerd 1997; Sundgren 1999). Product families are interpreted from marketing, sales, and engineering standpoints (Jiao et al. 2007). This research adheres to the engineering view, which takes the view of embodying different product technologies that are characterized by different design parameters, components, and assembly structures (Simpson 2005). The concept of product variants have widely used in diverse fields, such as automotive, aerospace, electronic goods, personal computers, microprocessors, automatic teller machines, and power tools (Sundgren 1999; Simpson 2005).

As variants are designed with common interfaces, changing the design of the interfacing element can have adverse affects in any one of the interacting variants. Propagation effects travelling through such medium are termed as variant pathway propagations, which is illustrated using the wheel-end layout described earlier. In this case, let it be assumed that the brake drum is released for a new customer requirement with appropriate gap between the brake drum and the wheel rim, and it interacts with two different variants of the wheel-rim – one with lower air ventilation area than the other. When the brake drum interacts with the wheel rim possessing lower air ventilation area (AVA) (see Figure 2.4), it will retain the heat during each braking application and eventually cause tire-tube puncture through an ambient pathway. Thus, interaction of the variants with the change component can result in adverse propagation effects in any one of the resulting assembly configurations (see Table 2.2).

Figure 2.4 Wheel Rim

Table 2.2 Multiple Assembly Combinations due to Variants

Assembly description	Assembly combination ‘A’: (wheel rim variant 1, brake drum)	Assembly combination ‘B’: (Wheel rim variant 2, brake drum)
Picture		
Difference in variant’s design parameter	High air ventilation area	Low air ventilation area
Effect of design change	No adverse affect	Adverse effect: tire-tube puncture

2.3.3 Propagation through Variant and Organization Pathway

In addition to the structure and ambient pathways, a third pathway is identified here – the variant and organizational pathway. Products are purchased from multiple suppliers in order to achieve cost competitiveness in the marketplace (Rossetti 2005; Wei and Chen 2008). The idea behind this strategy is three fold (Seshadri et al. 1991):

(1) To create a competition between the suppliers, thereby leveraging cost benefits. In addition the supplier behaviour can also be controlled after awarding the business.

(2) From the supply chain standpoint, to avoid a "lock-in" situation with an individual supplier and to prevent inventory loss, should one of the suppliers go on strike or face a natural disaster such as Tsunami.

(3) Alternate suppliers can help mass customization should the other supplier do not possess the required variant in their product portfolio (Balakrishnan and Chakravarty 2008).

A scenario with multiple suppliers for the wheel rim is used to illustrate the propagation effects through an organization pathway. Two suppliers, 'S1' and 'S2', are supplying the wheel rim while 'S1' is supplying with large air ventilation area while the supplier 'S2' is supplying with a low air ventilation area. The reason for choosing supplier 'S2' is that they had the unique feature that is required to satisfy the specific customer need. Again, let the brake drum be modified due to a requirement change in which case the adverse propagation effects will be resulted when the brake drum interacts with supplier 'S2's wheel rim as it has a low ventilation area. Such instances can occur if the effects of interaction of the change component with elements from multiple suppliers are not considered during the release of design changes. Hence, the outsourcing variable is considered in this pathway though it is an extension of the variant pathway.

Organizational pathway of propagation does not limit itself to the multiple suppliers' paradigm; it can be also be interdepartmental. The following examples illustrate this scenario:

1. A change of material in a part can lead to breakage of the cutting tool during manufacturing;
2. A change in the length of the part can lead to a change in the dimensions of the packaging box;
3. A change from the drum brake to a disc brake in a heavy commercial vehicle can render the hydraulic lift in the manufacturing with insufficient grab force.

In these examples, if the respective affected departments are not considered during change, it can potentially lead to another change, which is also change propagation. Traditionally, it has been studied with an assumption that the interaction between the parts through linking design parameters is the fundamental cause of propagation (Eckert et al. 2004). As earlier research has indicated, this assumption is not necessarily the case because change propagation has been experienced due to the inter-connection between various departments in the organization (Giffin 2007; Morkos and Summers 2010); even as the reasons for such propagation has not yet been studied in detail. Nonetheless, using the knowledge of these reasons, the new design tool, which will be proposed later in this dissertation, can be designed to address them.

The identification of these different propagation pathways causing change propagation, and the goal of developing a design tool to reduce engineering changes rooting from them, has paved way for different research questions, which are discussed in the next chapter.

CHAPTER THREE : RESEARCH QUESTIONS

The overarching goal of this research to develop a design method for reducing the engineering changes caused due to change propagation motivated the following key research question:

RQ1 :	*How can the engineering changes caused due to change propagation be reduced?*

It is hypothesized that a systematic verification, validation, and test planning method can help engineers to conduct the necessary verification and validation tests, thereby identifying the design flaws and necessary suitable actions. Thus, the hypothesis for the research question, RQ1, is:

Hypothesis1 :	*A systematic planning of verification, validation, and test method can reduce engineering changes due to change propagation*

Tests conducted based on the systematic planning method should enable designers to identify the change propagation effects due to different propagation pathways. In order to address this question, the propagation pathways that are not currently identified by the different existing design evaluation tools should be discovered. With this knowledge, the systematic planning of verification, validation, and test (VV&T) method can be designed to address the identified gap. Thus, a sub research question to RQ1 is:

RQ1.1 : *What are the limitations of the existing design evaluation tools that are used to evaluate engineering changes?*

It is hypothesized that the existing design evaluation tools cannot identify organization or variant pathways. Several tools are examined against the requirements of the change propagation tools, as indicated in section 2.2.1. Thus, the hypothesis for this research question, RQ1.1, is:

Hypothesis1.1: *Organizational and variant pathways are not evaluated by the existing design evaluation tools*

As explained in section 2.3.3, the organizational pathway of propagation is not well understood. In order to answer the research question, RQ1.1, it is essential to develop further understanding in terms of what are the reasons for ECs that cause organizational pathway with which it will be possible to evaluate whether or not each design tool evaluates such pathway. This leads to another sub research question, RQ1.2:

RQ1.2 : *What are the reasons for change propagation due to non-part interconnectedness?*

It is hypothesized that information relevant to the engineering change documents, such as bills of material (BOM) and introduction dates of the change, can lead to change propagation across the organization.

Hypothesis1.2 : *Incorrect BOM and introduction dates are the reasons for change propagation due to non part interconnectedness*

This research question, RQ1.2, cannot be answered directly without the knowledge of reasons for change propagation. As this research is focused only to the production phase of the product life cycle, the reasons for engineering change in this phase should be known. Only limited studies have been undertaken so far to determine the reasons for changes in this phase (Ahmed and Kanike 2007; Vianello and Ahmed 2008). However, these researchers did not explore how an EC could affect different functional silos in the manufacturing firm, which is organizational pathway, thereby leading to subsequent changes. Therefore, the following sub research question, RQ1.2.1, is formulated:

RQ1.2.1 :	*What are the reasons for engineering changes in the production phase of the product life cycle?*

It is hypothesized that new customer needs, design errors, and clerical errors are the reasons for changes in the production phase of the product life cycle.

Hypothesis1.2.1 :	*New design needs, design errors, and clerical errors are the reasons for changes in the production phase of the product life cycle*

Thus, three sub research questions are formulated to identify the gap that has to be addressed in the primary research question RQ1. In the process of designing the systematic VV&T planning method, a requirements modeling tool is used to identify the system level requirements. Results from research question RQ1.2.1 indicated the need for including manufacturing requirements in the modeling scheme, which is a limitation of the existing modeling scheme. This motivated further investigation to understand why the non-behavioral type of requirements is excluded from the existing scheme. Hence, the following research questions are formulated to advance the state of the art of the requirement-modeling scheme:

RQ 2.1 : *How do non-functional requirements (NFRs) contribute to the design process in mechanical system?*

RQ 2.2 : *Where in the sequence of domains, as presented in the existing modeling scheme, should the NFRs domain be incorporated?*

The following two hypotheses are investigated for the two research questions identified above. There is a one to one correspondence between the research questions and the hypothesis.

Hypothesis 2.1 : *NFRs drive design change decisions*

Hypothesis 2.2 :*NFRs can be sequenced after working principle domain*

Thus, the key research question investigated in this dissertation is answered by five sub research questions, as shown pictorially in Figure 3.1.

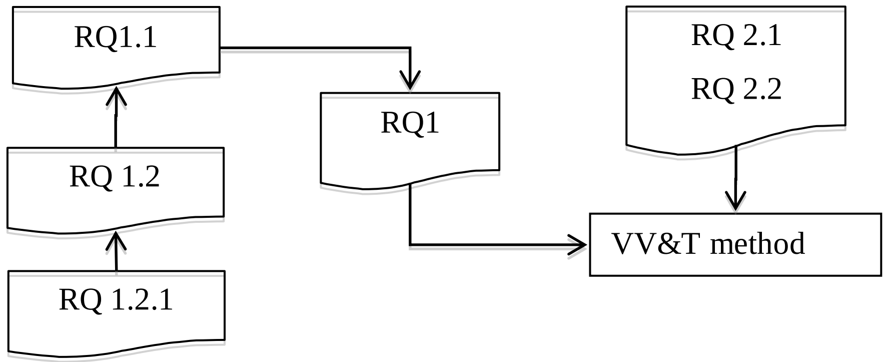


Figure 3.1 Interconnections Between Research Questions

3.1 Overview of the Dissertation

This section presents an overview of the dissertation directing the readers about which chapter addresses which research question. This is presented in a form of flowchart (Figure 3.1). In the first chapter, the research motivation is presented after presenting the foundations for engineering change and its process. In the second and third chapter, the problem is defined and the research questions along with the formulated hypothesis are presented.

Chapter Four begins to address the first research question, RQ1, which consists of three sub research questions that build upon each other. In this chapter, the different reasons that can cause change propagation in organizational pathway are investigated. Subsequently, this understanding is used to explore research question RQ 1.1 in Chapter Five where the existing design evaluation tools are reviewed for their ability to identify different propagation pathways.

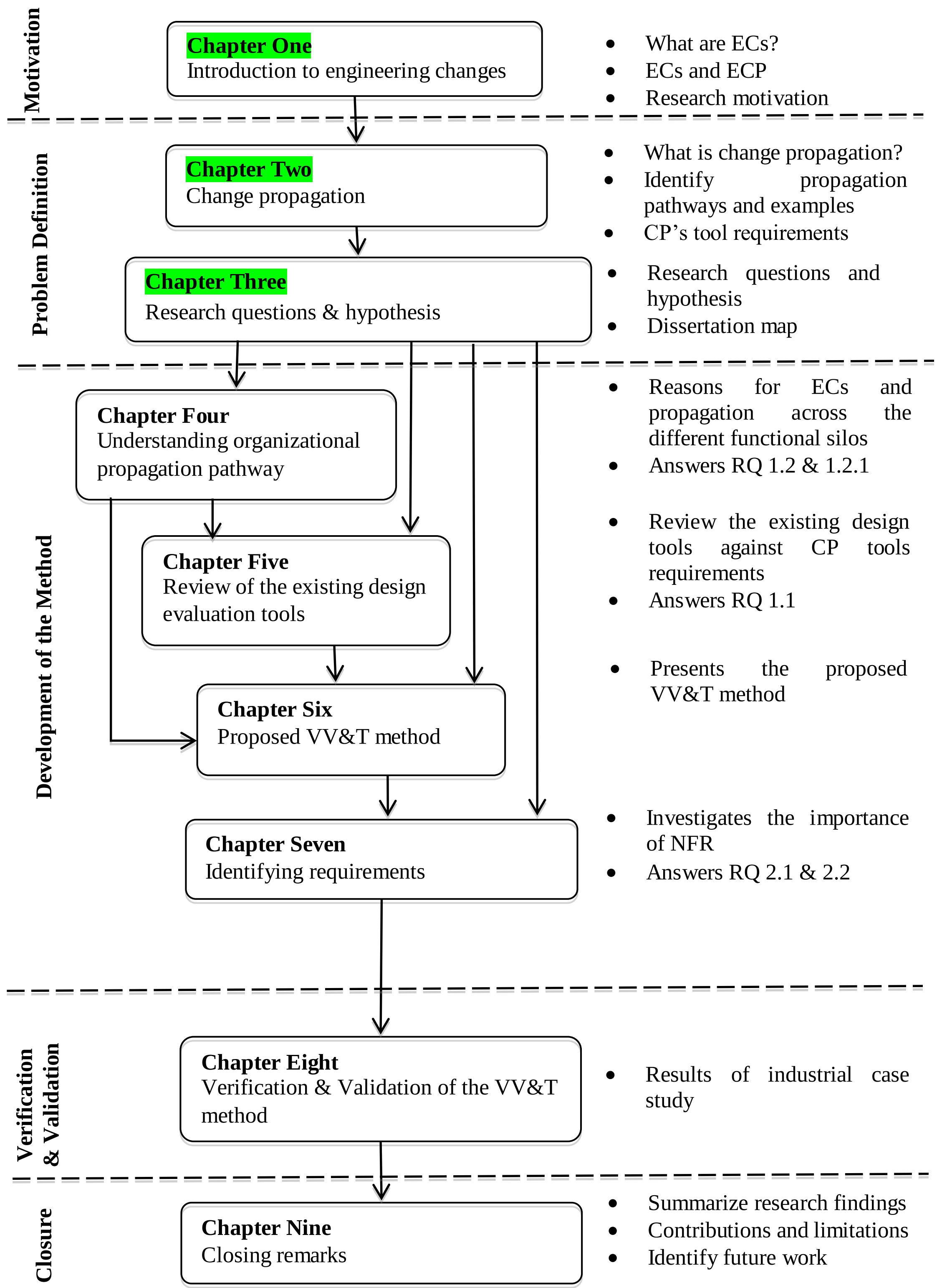


Figure 3.1 Dissertation Overview

The propagation pathway type that cannot be identified by the existing design method is identified and used as a basis for developing the systematic VV&T planning method in Chapter Six. This method is a seven-step method starting from identifying design requirements. In order to facilitate this step in the method, an existing requirements modeling scheme is explored as to whether or not it can be used as presented in the literature. Limitations in this scheme are identified and its state of the art is advanced (Chapter Seven).

Chapter Eight presents the results of the industrial case study conducted at multiple companies with different product types in order to verify and validate the different elements of the proposed method in addition to the theoretical validation. Finally, in Chapter Nine, the research findings are summarized, the contributions from this dissertation that advances the knowledge in this field are discussed, the limitations of the proposed method are identified, and the future directions of this work are presented.

CHAPTER FOUR : UNDERSTANDING ORGANIZATIONAL PROPAGATION PATHWAY

This chapter explores the reasons for change propagation between the different departments in a manufacturing firm, thereby developing a deeper understanding of organizational pathway of propagation. The research questions that are investigated in this chapter are:

RQ1.2	**:**	*What are the reasons for change propagation due to non-part interconnectedness?*
RQ1.2.1	**:**	*What are the reasons for engineering changes in the production phase of the product life cycle?*

RQ1.2.1 is first investigated before exploring RQ1.2, as it is a pre-requisite for the latter. A case study research method is used for investigating this research question in an automotive original equipment manufacturer (OEM). The research question, RQ1, presented here explores a complex phenomenon in a real life context. This phenomenon drives the choice of research technique to be qualitative because it allows the investigator to develop an interpretation and identification of the variables that describe the phenomenon under study (Lincoln and Guba 1985). When considering the different types of qualitative research strategies, such as case study, grounded theory, phenomenology, critical qualitative research, and postmodern research, the choice of research strategy depends on the answers to the following questions as described in (Yin 2003):

1. Form of the research question – 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?

A state of the art of research relevant to these research questions is presented in the next section prior to the description of the research method and the results of the investigation.

4.1 State of the Art of Research in Change Propagation

As this field is explored for its state of the art, it is realized quickly that there is a scarcity of published research papers. It is not surprising as the earliest significant research conducted in the field of engineering changes finds its roots in a journal paper published in the 1990s by (Wright 1997) in which an extensive literature survey about the design tools and methods to manage engineering changes is conducted. The tools that are identified in that paper view engineering changes as a manufacturing issue and developed method to control them. However, the importance of studying ECs in the incremental product design is emphasized, as it presents both risk and opportunities to the company.

Subsequent studies are focused on understanding and improving the engineering change management strategies and the engineering change process itself (Pikosz and Malmqvist 1998; Huang et al. 2003; Tavcar and Duhovnik 2005). These researchers indicated the phenomenon of change propagation implicitly. However, the first explicit reference to this phenomenon is by (Fricke et al. 2000) where the reasons for changes are studied at a managerial level in an effort to develop strategies to cope up with those changes. In this referenced paper, change propagation is mentioned as one of the major reasons for design changes.

An extensive study in a helicopter company provided compelling evidence of change propagation phenomenon and their detrimental effects in the product design and development (Eckert et al. 2004). Motivated by the need to address this phenomenon, reasons for such propagation are investigated, four reasons are identified, of which three are due to human limitations while the other is due to the system's behavioral properties (Jarratt et al. 2006). Specifically, they are:

1. Forgetfulness and/or oversight
2. Lack of systems knowledge
3. Communication breakdown between the functional groups in an organization
4. Emergent properties of the complex system

These high level reasons for propagation are necessary to develop a preliminary understanding of this complex change propagation phenomenon. However, these are not sufficient to understand the organizational pathway, which is the goal of this chapter. A later study (Giffin 2007) included a massive set of EC data (around 41,000) to understand change propagation. In the process, metrics are developed to measure change propagation and the order of propagation to be considered while developing a change prediction tool is identified. Another important outcome is the indicated existence of organizational pathway of propagation, yet understanding it was not their focus of study. Thus, only limited studies have been conducted to specifically investigate the reasons for change propagation to understand organizational pathway. This chapter aims to address this gap, which is why RQ1.2 is formulated.

The nature of propagation, as shown in section 2.1, necessitates to contain the genesis and propagated changes. To this point, it is necessary to obtain the reasons for engineering changes in the production phase, as this phase is the focus of this dissertation. Limited studies have been conducted to generalize the change reasons and use it for this research (Huang. G and Mak. K 1997; Ahmed and Kanike 2007; Vianello and Ahmed 2008), which lead to the formulation of the sub research question RQ1.2.1 to address this limitation.

4.2 Research Method

The research reported in this paper uses case study research method applied in an automotive original equipment manufacturer (OEM) to address these research questions. It was selected using the criteria of the specific product manufactured, which are complex large road vehicles requiring a great degree of product customization.

The case study research method is selected as it is widely employed in engineering design research to investigate contemporary phenomena in uncontrolled environments to study complex topics and interactions between them (Frost 1999; Roth 1999; George and Bennett. 2005; Flyvbjerg 2006; Sheldon 2006; Stowe 2008; Teegavarapu et al. 2008).

The author of this dissertation worked as a graduate design intern for eight months in the engineering design department of this OEM. This department has the sole authority to control all decisions regarding engineering changes. The product development and support groups work collaboratively to ensure the smooth production of these large road vehicles. The change requests are received by the support group and processed subsequently in consultation with the development group on an as-need basis.

In order to explore the research question RQ1.2.1, archival records are used for data collection. This result is used to differentiate the changes into genesis and propagated changes with which the research question RQ1.2 is answered. The potential reasons for propagated changes are subsequently identified through the development of an interaction model of the cause-effect pattern of ECs from the data obtained through focused interviews. Prior to the discussion of data collection, an overview of the investigation site and their engineering change process to handle changes in the production phase is presented in the following section.

4.2.1 Overview of the Investigation Site

The OEM, located in the central part of the United States, manufactures large road vehicles by making use of both in-house manufactured parts and parts from its large network of suppliers. The manufacturing plant is a non-automated factory that produces typically sixty vehicles daily using such conventional manufacturing process as arc welding, spot welding, simple tube bending process, and manual assembly process. This OEM offers its dealer-customers a wide variety of sub-systems to an extent that no two vehicles in the production line are similar.

This firm has a custom-built engineering change management system to manage all engineering changes. This system is common to other divisions of the OEM located in different geographical locations within and outside the United States. Users from any department in any location, such as manufacturing engineers, quality engineers, production planners, purchasing professionals, or senior management, may access the distributed engineering change management system to archive and retrieve information from the system. For instance, production planners may search for the introduction date of a product to initiate necessary actions at their end to ensure smooth production while managers may search for information related to the time elapsed between the initiation and closure of an EC.

The communication of an EC between departments in the manufacturing firm is through different online forms, such as the engineering change note (ECN), the engineering release note (ERN), substitutions, and deviations. The sole authority to issue these forms is within the engineering department. An ERN is used to communicate the release of a new product, whereas an ECN is used to communicate any modification in the product. However, an alternate approach is used to address the concerns or issues identified during production where the formal ECN document is bypassed to minimize the product delivery lead-time. This approach is known as a containment action with its associated forms known as deviations and substitutions. Deviations are short-term departures from compliance with engineering drawing specifications for a specific number of parts after manufacture. Substitutions are a subset of deviations in which a part ‘x’ is replaced with a part ‘y’ before manufacturing based on written authorization. These deviations are later formalized with an ECN.

All employees, as identified by the management, attend two-week training sessions to learn the software that supports the engineering change process and are examined and graded at the end of these sessions. Upon achieving satisfactory performance, the employee is then provided a password so they may engage in daily system operation activities. The degree of access to specific components in the software, such as approval of deviation, is defined by the system administrator based upon the department, the job description, and the degree of responsibility held by the executive.

The online system allows any authorized user from the manufacturing, the production planning, the inventory, and the design department to request a substitution or deviation in two separate forms. Each of these forms contains the following data to be entered by the user in the system: (i) the reason for substitutions or deviations, (ii) a short description of the problem, (iii) the associated part numbers, (v) the number of parts for which the deviation/ substitution is requested, (vi) and duration of the deviation/substitution. The name and department of the requestor, approver, and manager are also required. Files such as Microsoft (MS) PowerPoint, MS Excel, or MS Word files, may also be attached describing the changes; the handling of which is described in the next section.

4.2.2 The EC Process

A flow chart (Figure 4.1) is used to describe this change process followed in the OEM. The process begins with the identification of a concern identified by any department in the manufacturing firm. These problems are reported to the engineering department through the online system described above using the deviation/substitution request form. Depending on the situation, concerns are classified as either a substitution or a deviation. The engineer from the product support group discusses the issue with other associates in the department concerned and the engineer develops a feasible interim solution to ensure uninterrupted production. This solution is then reviewed and approved by the product support manager, which is then communicated to the manufacturing and quality department. The time elapsed between concern initiation and approval of deviation varies between one to three days, though there are exceptions.

Subsequently, if the approved deviation/substitution requires design document changes, an appropriate work authorization is issued with which an engineering release number is obtained from the system. A permanent engineering solution is then developed either by the product support engineer or in collaboration with the product development engineers within the engineering department. The necessary design documents such as drawings or bills of material (BOM) are updated in the information management system such as a product data management (PDM) system and reviewed by focus groups before it is made available to manufacturing. At the end of this process, the product support engineer closes the concern. The time elapsed between the work authorizations and closing the concern varies between thirty and sixty days.

The use of the deviation and substitution approach to manage the ECs is a simplified approval and documentation method of an EC that does not require design document updates. As ECs identified during the production must be resolved quickly, necessary documents are also created quickly for quality purposes to ensure timely vehicle delivery. However, at a later stage, the design documents are updated through a formal ECN by raising a work authorization. Therefore, because of the likelihood that the propagation causes substitution and deviation in the production process, data related to these changes including substitutions and deviations are retrieved from the archival record. This document analysis protocol is described next.

4.3 Data Collection from the Archival Records

The reasons for the emergent changes are identified from a large set of EC's (1241) from the OEM's online ECM system. These data covered a time frame of nearly three years (between September 2006 and June 2009). The collected large number of ECs is significant for establishing a trend and identifying the reasons behind a greater percentage of occurrences. These reasons are classified into internal and external changes based upon who initiated the change (Jarratt et al. 2006; Ahmed and Kanike 2007) and based upon the nature of the change (Ahmed and Kanike 2007) such as time of change, motivation of change, result of change, type of problem, drawing and design error rectification, manufacturing and assembly problems.

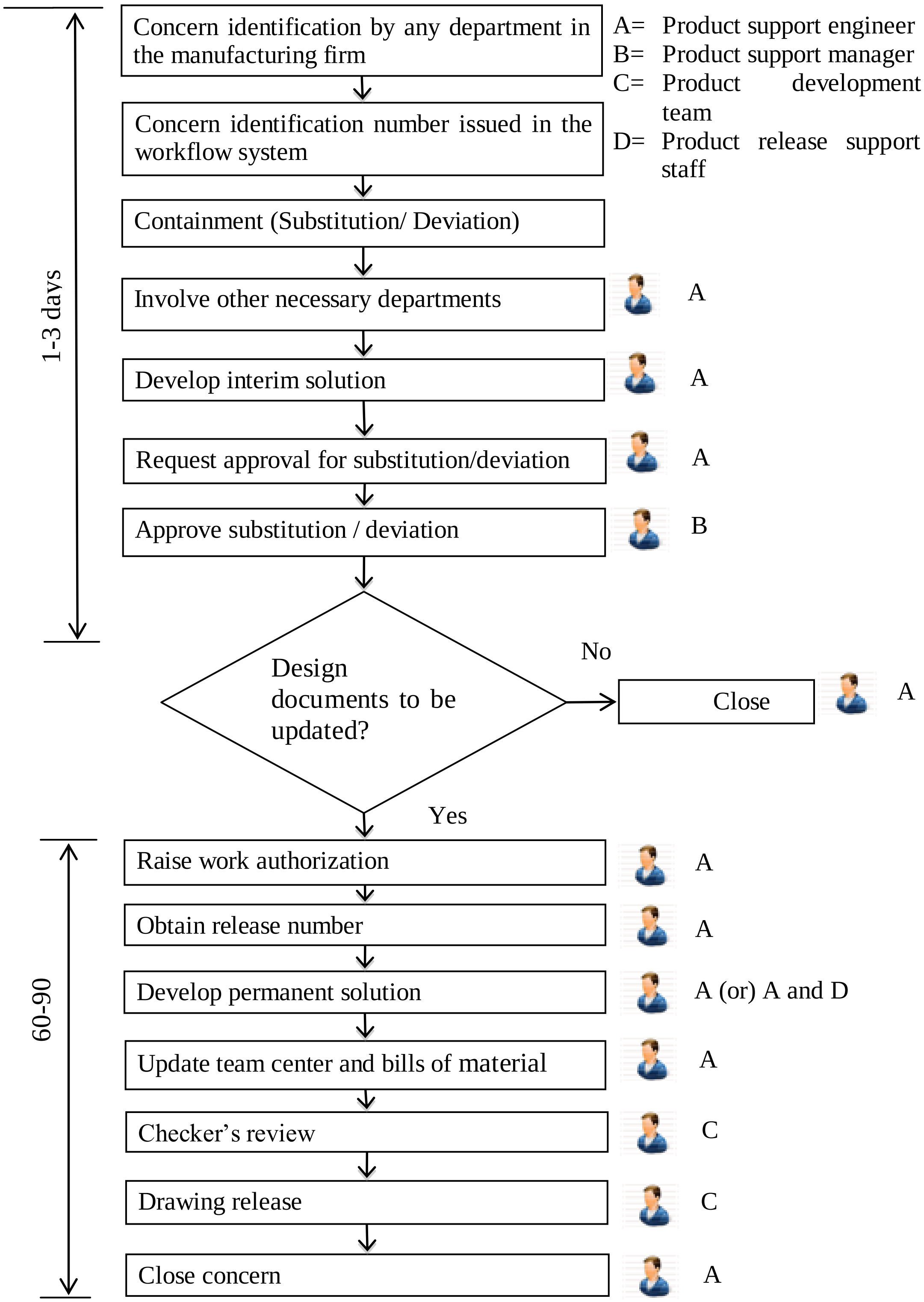


Figure 4.1 EC Process at the Investigation Site

4.4 Reasons for Engineering Changes

The large set of EC records (1,241) analyzed to determine the rational for the change were classified based upon the nature and initiation of the change. It was found that 77.0% of the reports were initiated internally with the remaining 23.0% initiated externally, as shown in **Error! Reference source not found.**.

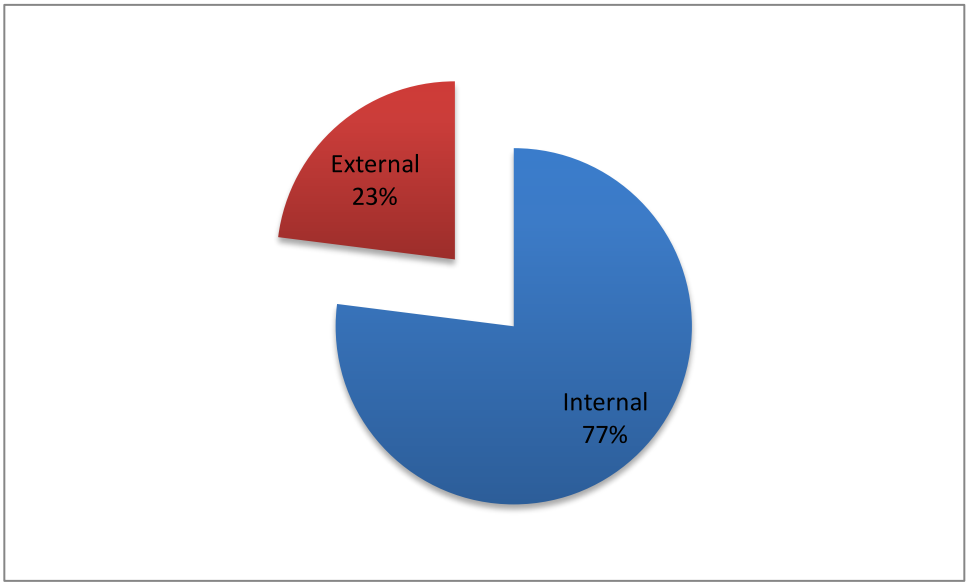


Figure 4.2 Distribution of Changes based on Initiation

Within the 77.0% of internal changes, as shown in Figure 4.3, 28.9% were document error corrections such as BOM error (9.7%), drawing error (16.6%), and introduction date error in ECN (2.0%). Cost reduction exercises accounted for 15.7%, the second highest, closely followed by manufacturing issues, which accounted for 14.3%. Design corrections, such as addressing field problems, parts that did not fit into the vehicle, and other design limitations, accounted for 9.1% of errors, while inventory issues such as material shortages necessary to produce the vehicles and obsolete materials accounted for 9.0%. It should be noted that management attempted to use these materials in any future vehicles when feasible. Finally, regarding external changes, 21.3% were due to cost reduction exercises initiated by the vendor while changes due to requirement change accounts for a scant 0.7%. Such changes, though small, cannot be dismissed, as other researchers have studied change propagation based upon such requirement changes (Morkos and Summers 2010).

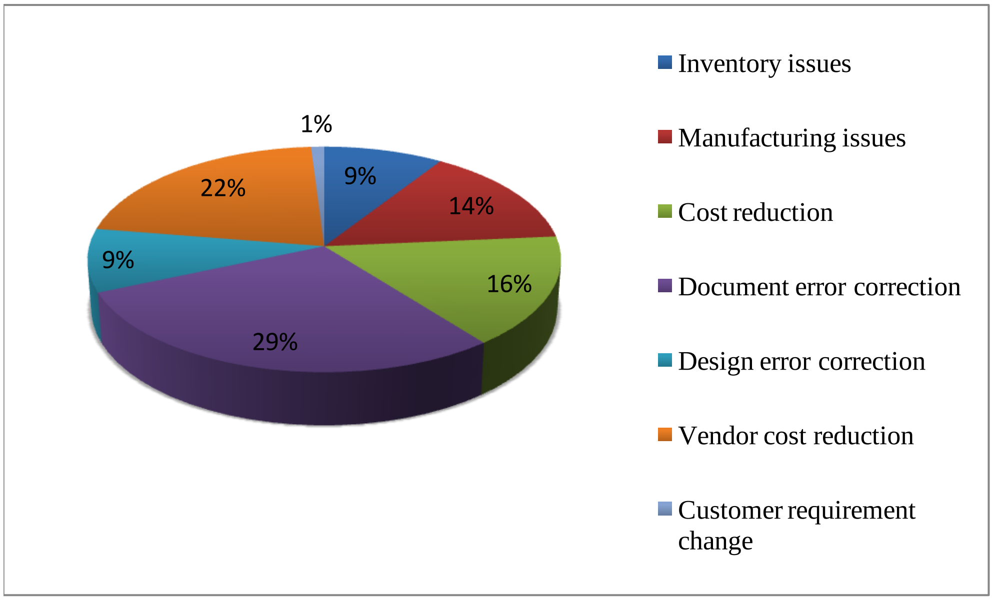


Figure 4.3 Distribution of Changes based on Nature

From Figure 4.3, it can be inferred that this OEM spends a significant effort in correcting drawing errors. To avoid overlaps between design and drawing errors, each of these drawings were reviewed individually. It was found that such errors are typically due to the reuse of drawings such as modifying older versions to update missing sections and CAD software errors such as incorrect placement of dimensions. It was also determined that this OEM should develop a quality assurance method in the release of BOM which, from the researcher's perspective, is extremely complex to understand and use.

It is also observed during the internship, as a participant, that the release of BOM with errors such as incorrect part quantity or missing required assembly part numbers may lead to disruption in production such as shortage of materials to build the vehicle. This effect, in turn, must be addressed by the design department by providing an equivalent alternate part, if technically feasible, to ensure continuous productivity. Though this EC's cause-effect-cause-effect pattern is analogous to the definition of change propagation, *it is due to the interlinked functional groups within an organization and not due to either the direct or the indirect links within a product*. Thus, to understand the reasons of propagation across the functional domain within an organization, it is essential to further classify these ECs into genesis and propagated changes. Subsequently, it is important to identify the reasons for propagated changes to address RQ1.2, which is investigated in section 4.5 after a brief discussion on the status of the hypothesis H1.2.1 and culminating in the generalization of the results.

4.4.1 Results for the Research Question RQ 1.2.1

Thus, from archival records, research question RQ1.2.1 is investigated where its associated hypothesis H1.2.1. "New design needs, design errors, and clerical errors are the reasons for changes in the production phase of the product life cycle", is tested using the case study research method. The results from this study **did not confirm** the hypothesis, as there are additional reasons for change in the production phase of the product life cycle than what were hypothesized.

4.4.2 Generalization of the Results for the Research Question RQ1.2.1

Research results regarding the presence of ECs in the production phase are generalized by comparing the results from similar research. The ratio of internal-to-external changes, 77:23, identified from the archival records directly aligns with the previous case study conducted in an aero-engine product (Ahmed and Kanike 2007) and in a large sized compressor-and-pumps manufacturing company (Harhalakis 1986). Based upon these results, it can be generalized that the ratio of internal-to-external changes exhibits a similar trend between different mechanical systems with varying degrees of complexity. The reasons for the presence were also similar but with varying proportions. Moreover, the fact that the trends are similar to others found in the literature suggests that this is a sound case to study.

4.5 Investigation of Research Question RQ1.2

Investigation of the change reasons through the research question RQ1.2.1 sets the foundation for exploring the specific reasons for propagation. In the earlier section, as archived reports do not explicitly show the causal relationships between the changes, a matrix-based approach is used to capture these cause-effect patterns of various reasons for changes at a detailed level based on the engineers' experience. The hypothesis for this research question RQ1.2 is: *Incorrect BOM and introduction dates are the reasons for change propagation due to non-part interconnectedness*. The case study research strategy is used to test this hypothesis based on the answers to the following questions, as shown in Table 4.1.

Table 4.1 Justification for Case Study Research Method to Explore RQ1.2

Research Question	Question	Answer	Justification
RQ2	Form of the research question – is it exploratory or explanatory?	Exploratory	The research question ***explores*** the identified change reason and cordons off the propagation changes from the genesis changes
	Does the researcher require control over the events?	No	The goal is to learn the cause of an occurred event. Hence, no control over the events is required
	Is the phenomenon under study a contemporary or a historical event?	Historical event	Though propagated changes can be both contemporary or historical, the event leading to a propagated change is always historical

First, the form of the research question is exploratory as it intends to isolate the propagated from the genesis changes. Second, the goal is to learn the cause of an occurred event; hence, no control over the events is required. Third, propagated changes are both historical and contemporary while the initiated is essentially historical. Thus, based on the answers to the justification questions, and the necessity to understand the context of what lead to a propagated change, case study analysis is identified as an appropriate research strategy to address this research question. The next section describes the interviews with engineers, the protocol of analysis, and interpretation of these interviews.

4.5.1 Data Collection and Analysis from the Focused Interview

The product support engineers in the engineering department are those who directly deal with sustaining the production line. Therefore, six-product support engineers, located at the investigation site, as well as the product support manager were interviewed. The qualifications of the engineers, their years of experience at the investigation site and in different automotive companies, and their job titles are presented in Table 4.2.

Table 4.2 Background Information of the Interviewee

Interviewee ID #	Years of experience at investigation site	Experience in a different auto company	Qualification	Job title
1	1	0	B.S	Product support engineer –body
2	8	0	B.S	Product engineering manager –body and chassis
3	2	0	B.S	Product support engineer –body Product support and development engineer –body
4	15	2	B.S	Product support and development engineer - Chassis
5	8	0	B.S	Product support engineer –body
6	11	0	B.S	Product support engineer –body

The interviewee was informed about the theme of the interview a week in advance to provide them with many opportunities to formulate their responses and provide examples of production changes from their own experience. It was the first time that several of the interviewees had explicitly considered the events that led to a change, the implication being that no explicit answers were forthcoming. Thus, follow-up questions were posed to interviewees to collect this relevant information.

Additionally, the interaction between ECs, known as the change interaction model (CIM) for simplicity, was modeled using a domain mapping matrix (DMM) (Danilovic and Browning 2007) and was based on the reasons for ECs with the investigator's prior work experience and previous literature (Watts 1984; Huang and Mak 1997; Fricke et al. 2000; Huang et al. 2003; Jarratt et al. 2005; Jarratt et al. 2006; Ahmed and Kanike 2007). This matrix is used as a guiding instrument to enable interviewees to remind them of previous similar occurrences should they be at a loss for such examples. The sources and the reasons used in CIM are presented in Table 4.3. It should be noted that manufacturing and assembly are regarded as two individual sources because an OEM can internally manufacture parts such as front axle for a heavy commercial vehicle for subsequent assembly with parts bought from various suppliers. The process of developing such a CIM is presented in section 4.5.2.

Table 4.3 Sources and Reasons for Emergent Changes from Experiential Analysis

Sources	**Reasons**	**Remarks**
Design	Cost reduction	
	Thickness change	
	Material change	
	Part consolidation	
	Material reduction through topology change	
	Part redesign	
	Design error	
	Incorrect Installation layout	
	Incorrect BOM	
Manufacturing	Operator error	
	Tool failure	
	Improper tool maintenance	
	Tool availability	
	Machine breakdown	
	Process change	
	Material shortage	
Assembly	Material shortage	
	Interference	
	Operator error	

Sources	Reasons	Remarks
	Wrong assembly	
Materials & Purchase	Logistics issues	
	Shipping damage	
	Process change in material handling	
	Failure to order parts by purchase department	
Supplier	Supplier initiated design changes	
	Alternate supplier	Switching between two approved suppliers for a given part
	Change of supplier	Switching to a new supplier for a given part
	Drawing not to specifications	
	Design error	
Marketing	Aesthetic improvement suggestions	
Service	Poor accessibility	
	Warranty	
	Field failures	
	Customer dissatisfaction	
Quality	Non conformance - internal	
Inventory	Obsolete parts	
	Excess inventory	

4.5.2 Process Of Constructing a CIM

The entries presented in Table 4.3 are represented as rows and columns of the DMM. The scenarios from prior experience are reconstructed and modeled in the CIM as causal relation. These relationships are identified in the matrix with a binary numbering scheme in which ‘1’ indicates a relationship and ‘0’ indicates none. The zeros are not shown in the snap shot to improve the readability of the matrix. A snapshot of the CIM used prior to any interview is presented in Figure 4.4.

	DESIGN								
	1	2	3	4	5	6	7	8	9
	Cost reduction	Thickness change (increase/ decrease)	Material change	Part consolidation	Material reduction through topology change	Part redesign	Design error	Incorrect installation layout	Incorrect BOM
1			1	1		1			
2						1			
3						1			
4									
5									
6		1	1						
7									
8									
9						1			

Figure 4.4 A Snap Shot of the CIM

4.5.3 Interview Questions

The questionnaire used in the interview process is presented in Table 4.4. The interviews were audio-recorded and conducted in a closed conference room with all questions following a triangulation scheme, as shown in Table 4.5, to establish validity of the results. For instance, the second question explores the reasons for the changes from the engineering design department, while the seventh question explores the same from a different perspective.

Table 4.4 Interview Questionnaire

Name: Title: Company: Years of experience: Industry: Date of interview: Time of interview: Location: Q1: What are the sources of change that you have experienced for a product in production? Q2: What are the types of change due to product redesign and cost reduction programs? Q3: What types of issues are raised by the assembly line and how that converts to a change? Q4: What types of change does your manufacturing department initiate? Q5: What different issues have you experienced from the supplier parts and therefore lead to change? Q6: How logistics has affected your assembly line and lead to change? Q7: Was there any change caused because of design office errors such as BOM, wrong installation, and design errors?

At the end of the interview, the interviewees were requested to verify the CIM and suggest any changes. All interviews were then transcribed and presented to the interviewee for their review regarding accuracy. Upon confirmation, this document was used to update the CIM with the newly identified reasons for changes and used in subsequent interviews. Readers can refer to Appendix A through Appendix F for the complete transcripts of the interviews.

Table 4.5 Triangulation Scheme for the Interview Questions

	Q1	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**
Q1							
Q2					x		x
Q3				x		x	
Q4			x			x	
Q5		x					
Q6			x	x			
Q7		X					

4.5.4 Protocol to Process the Interview.

The examples provided by each interviewee were processed using a predefined protocol. The objective was to determine the reason leading to an EC. Each example was studied in detail for its context (if provided by the interviewee), the event leading to an EC, and the cause and effect. A sample of the processed example is illustrated in Table 4.6.

Table 4.6 Protocol for Processing the Interview

Context	Event leading to change	Cause	Effect	Data source
In the chassis line, the front axle and the rear axle are placed in pairs for each vehicle based on a document called "traveler". The traveler contains all the part numbers to assemble for a vehicle. The operator pulls the appropriate axle and positions on the production line. The brakes, tie rod, steering arm are assembled at the subsequent station.	The steering arm meant for the subsequent vehicle in the assembly line was assembled. The steering arm offset was the only difference between the two axles. This misallocation was then appropriately identified and reported to engineering requesting a change to use the vehicle with a different steering arm.	Operator error	Incorrect assembly	Interviewee #5

After elucidating the context of each example suggested by the interviewee, the event leading to an EC was recorded in the second column. The result (effect) of the situation was then identified such as a 'wrong assembly', a 'material shortage', or a ‘process change’. The cause of this result is determined by a why-why analysis until a point at which cause represents the situation determined under study. For instance, in the above example, the ‘operator error’ is identified as the cause, and it was not further decomposed into why the operator made the error as it digressed from the context boundary. Also, the changes caused by supplier’s error were not examined in detail as they fall outside of the scope of this research. Readers can refer to Appendix G for the examples provided by the engineers.

4.5.5 Identifying Genesis and Propagated Change from CIM

After interviewing all interviewees, a consolidated CIM (as shown in Figure 4.5) was developed that captures the causal relationship of ECs for the examples elicited from all the interviewees. A genesis change is identified if entries in the column lacked any relationship with the entries in the corresponding row of that column while propagated changes are those that did not follow this rule. Additionally, entries without any relationships were deleted from this inquiry. Such non-relationship entries are also illustrated with a representative CIM in Table 4.7 where A, B, C, D, and E represent different reasons for ECs.

Table 4.7 Representative CIM

	A	**B**	**C**	**D**	**E**	**Row Total**
A		1		1		2
B				1	1	2
C						0
D					1	1
E						0
Column total	0	1	0	2	2	

It is inferred from Table 4.7 that an EC caused by reason 'A' is a genesis change because it led to other ECs such as 'B' and 'D'. The reasons 'B' and 'D' are propagated changes caused by a previous change, which in turn caused a subsequent change. There is one more category of propagated change, which was caused by other reasons causing no subsequent changes such as 'E'. The final category has no relationship with any of the entries; such entries are deleted from the consolidated CIM. Upon identification of propagated changes, the reasons for propagation can be directly read from the rows related to the corresponding column. For instance, D is due to both A and B.

	Design											Manufacturing					Assembly				Materials & Purhcase			Supplier							Marketing			Service				Quality	Inventory			Satelite units
	Cost reduction	Product improvement	Material change	Part consolidation	Part redesign	Design error	Incorrect Installation layout	Modify design specification	Introduction date error	Use of obsolete parts	Incorrect BOM	Operator error	Tool failure	Improper tool maintenance	Process change	Material shortage	Material shortage	Interference	Operator error	Wrong assembly	Logistics issues	Vendor Consolidaiton	Failure to order parts by purchase department	Logistics issues	Supplier initiated design	Alternate supplier	Change of supplier	Material shortage in the	Drawing not to specifications	Design error	High customer order	Customer order d delivery date change	New Customer requirement	Poor accessibility	Warranty	Field failure	Customer dissatisfaction	Non conformance - internal	Poor inventory tracking	Obsolete parts	Excess inventory	Available tooling
	1	2	3	4	5	6	7	8	9	#	11	12	13	14	#	16	#	18	19	20	21	22	23	24	25	#	#	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1			1	1	1																																					
2															1																											
3																																				1						
4																																										
5				1																														1								
6												1						1	1																1	1						
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Figure 4.5 Consolidated Change Interaction Model

4.6 Reasons for Propagated Changes

This section isolates the genesis and propagated changes for changes identified in section 4.4. Cost reduction, both internal and external, and customer requirement change are identified as genesis change from the consolidated CIM. Also, the document error rectification change acts as genesis change. For instance, a 'bill of material error' is due to (i) incorrect mention of part quantity, (ii) incorrect mention of part numbers, or (iii) incorrect mention of part life. These errors result in material shortage, which is illustrated by an example elicited by Interviewee #3.

"*The biggest cause of part shortages is the incorrect BOM. For example, we have small rubber caps that we placed inside of the bulkheads to cover up the screw heads. The BOM called up to 17 numbers whereas in reality each vehicle took up 60.*"

All other interviewees expressed similar views on this reason, constituting 9.7% of the total changes. As explained in section 4.4, the BOM error will compel the engineering design department to substitute with alternate parts, if it is feasible, to sustain the production line.

Inventory issues such as shortage of materials and holdings of obsolete parts are identified as propagated changes. As a propagated change, the reason for shortage of materials is due to incorrect BOM. Specifically, EC's on the BOM with incorrect part quantity cause production planner to plan only for the quantity described in the BOM, resulting in a line stop when material inventories are exhausted. To avoid this scenario, there must be manufacturing request to design to replace the existing part with a similarly equivalent part, thus, leading to subsequent change. Another inventory issue involves the obsolete material that ended up in inventory because of higher part quantities in BOM than required. Such excess inventory is also due to the release of ECs without considering the existing inventory in the plant. Interviewee #2 described this scenario.

"Marketing proposed a cost reduction suggestion with a decal. The engineering change propagated for all models while there were 200 numbers of old badge in the inventory. This led to a change."

Design error rectification is identified as propagated change emanating from the consolidated CIM. The term 'design error' encompasses design limitations such as poor design assumptions, incorrect installation layout, out-of-date CAD drawings and 3D models, a lack of understanding of the system by the designers, and failing to meet customer requirements. Interviewee #4 described such a scenario in which EC was released to address design limitations. He stated that:

"Several fuel tanks failed in the field and there was an immediate instruction to replace them. This led to a change."

Finally, manufacturing issues are also identified as propagated changes from the consolidated CIM because the methods for improving the product changed the existing production processes on the shop floor. Interviewee #4 again:

"We changed out to disc brakes. That was a process change for material handling because the components were heavier."

Here, hydraulic sliding shoe brakes were changed to hydraulic disc brakes to improve the final product. This product change, however, interfered with the material handing process, thereby mandating a change. Because the forklifts for carrying a set number of hydraulic brakes were not rated to carry an equivalent number of disc brakes, the process was redesigned to allow production to continue using altered loading criteria.

In another instance, an organizational initiative to consolidate vendors to reduce costs led to part consolidation also interfered with production processes, as described by Interviewee #2.

"Lights were purchased with multiple vendors and to consolidate the price purchasing department consolidates the vendors which lead to number of changes."

Similarly, raw materials were changed to reduce tool wear rate, design specifications were changed to accommodate the shortcomings of inadequate maintenance of the machine. Other causes for reworking existing processes involved design errors, and drawing errors such as incorrect installation layout.

Table 4.8 presents the identified propagated changes from the list of archival records, which account for 32.4% of the total in this OEM, of which manufacturing issues accounted for 14.3%. By considering recommended manufacturing changes from designers and communicating this change and its implications to production prior to implementation, such changes can be reduced.

Table 4.8 Propagated Change and Reasons for Propagation

Propagated changes	Reasons for propagation from the consolidated CIM
Inventory issues	• Incorrect BOM • Incorrect introduction date • Switching to alternate supplier
Manufacturing issues	• Process change • Design error
Design error rectification	• Incorrect installation layout • Out of date 3D model and drawings • Limited understanding of the system by the designers • Design limitation

Inventory issues accounted for 9.0%, which were due to the incorrect release of engineering documents such as BOM. Also, the designers included introduction dates in the ECN without communicating with the purchasing department, thus increasing the difficulty of making an efficient change in production. To avoid such communication errors, the decision-making responsibility for such production changes must be left to the purchasing department on the date of the change. Since the ECN is electronically controlled, it is possible to distribute the ownership of the document between the designer and the associate in the purchasing department, which will eliminate such errors. Logistics issues between the end-user in the OEM and its suppliers also contribute to inventory volatility. To ensure a steady supply of materials, redundancies must be developed to accommodate delays in shipment from natural disasters, supplier strikes, and incomplete shipment inventories.

Rectifying design errors account for 9.1% of all propagated changes, due to the release and reuse of out of date 3D models and drawings by the designer, incorrect installation layout, and limited understanding of the complex system. Though the designers use failure modes and effects analysis (FMEA) and structured design reviews to mitigate such changes, these tools are inherently limited in their ability to effectively support incremental product design. Such limitations must be identified to support product changes in complex systems during the production phase and thus reduce design errors.

4.6.1 Hypothesis Status for the Research Question 'RQ1.2'

The hypothesis, H1.2, that BOM and introduction date errors are the reasons for propagation due to non-part interconnectedness is ***rejected*** because there are additional reasons identified than what is hypothesized. Results clearly indicate how an engineering change in the engineering design department affects manufacturing and inventory, thereby leading to subsequent changes that are discernibly propagated through organization pathway. These results void the canonical assumption of the etiology for change propagation only due to the part interconnectedness.

4.6.2 Validity of this Research

Validation of qualitative research is classified into two aspects: (i) internal validity and (ii) external validity or generalization (Yin 2003). The internal validity of this research is achieved by using a data triangulation approach to present the findings; an approach in the case study research method that does not follow the replication logic as in the survey based research technique to establish a statistical sample (Stowe 2008; Teegavarapu et al. 2008; Teegavarapu 2009). This enables the case study research technique to generalize even with single case study; however, positivistic researchers express concern over this fact. Hence, it is addressed, to a degree, by explaining the problem associated with generalization and a means to address them by drawing examples from other qualitative research field such as social sciences and clinical research.

Generalization is the extent of applicability of the findings for a given study within a context to another problem elsewhere. It is a degree of judgment on the collected data which can be either confirming or disconfirming but not conclusive (Kennedy 1979). For instance, in clinical research, the study of a new medicine to the subjects either confirm or disconfirm the hypothesis that it alleviates the medical condition but need not present conclusive evidence. Therefore, developing a generalization from the data of the nature described above is not a binary decision; it is always judgmental which relies on the strength of the evidence (Kennedy 1979). Since, the data triangulation approach is used in this research, the findings are derived from multiple sources of evidence indicating increased strength of evidence, hence better reliability.

The other facet that influences the generalization is the number of data points observed (Merriam 2002; Yin 2003). The sample that is investigated can have wide range of attributes that is a representative of the population characteristics. Selecting a homogenous sample will only yield results that are applicable to a narrow range of population. For instance, selecting 100 school students from a low income group and selecting 10 students from different income group will have a different range of generalization. Therefore, generalization is not a function of number of data points observed; it is the kind of data point observed. The higher the range of attributes encompassed in a sample broader will be the range of generalization for the sample population that is under investigation. In this case study, the set of attributes to describe the investigated sample are: (i) commercial product with life cycle around ten to fifteen years; (ii) high degree of system complexity; (iii) high degree of product customization; (iv) manufactured using non-automated techniques; (v) production volume is around 11,000 vehicles per year;(vi) industry belongs to the class 'automotive';(vii) manufacturing plants located across the United States of America and South America with a mix of male and female population where male population being higher.

Further, the generalization of findings of a given study from a sample to a population is of two kinds. In the first one, a sample is connected to a population, which is similar using statistical techniques. For instance, to evaluate the quality of products in a manufacturing firm at the receiving inspection section, a sample quantity of the product is evaluated for its quality, and the whole population is either accepted or rejected based on the evaluation results from this sample. This technique is applicable when the size of the population and its characteristics are both known. In the second kind, a study sample is linked to a population that is assumed to have the similar characteristics as the sample, and hence, the findings from it are applicable to the population as well. This type of mapping is used when the size of the population and its characteristics are both unknown. This situation is, often times, found in interpretive research methodology such as case study (Stake 1978).

In single case studies, or a single case, the data obtained do not present an opportunity to generalize using statistical techniques because of the unknown population variability. However, not knowing the population variability does not imply that the findings are invalid. It is just that the population to which this finding relates is unknown. Proponents of single case study methodologies have proposed various arguments to mitigate this sampling limitation. One of the arguments in favor of single case study is to present the findings as 'user generalizable' with the detailed explanation of the context under which the study is conducted, thereby the user can make their own decision on the finding's applicability to their situation. Thus, the findings of the research question RQ1.2 is presented as 'user generalizable' results.

4.7 Conclusion

Two research questions have been investigated in this chapter. The aim of these research questions is to develop a deeper understanding about the etiology for change propagation through organizational pathway during the production phase of the product life cycle. Given the complex nature of the phenomenon, the case study research method is used in an automotive OEM for their investigation. In order to explore this phenomenon, a sub research question 'RQ1.2.1' is investigated for change reasons using the OEM's archival reports. It is inferred from the analysis of 1241 archival reports that 77.0% of changes are due to internal reasons while 23.0% are external. This trend directly aligns with a study conducted in the year 2007 of an aircraft engine manufacturer, and a study of a large compressor-and-pumps manufacturer. Although the products exhibit varying degrees of complexity and varying applications, the reasons for changes and their proportion were in remarkably good agreement. Such consistency implies that strategies used to contain propagation changes can be horizontally deployed from highly developed to less complex systems.

The reasons for changes and their proportion from three different case studies, including this one, indicate no significant improvement in the containment of ECs over the past quarter century, despite the increased EC research. Industries are still experiencing high volume of changes which directly affect product cost and lead-time. Thus, both the manufacturing and research community must increase their efforts to effectively develop tools and management strategies to contain these unplanned (propagated) changes.

Subsequently, these change reasons are classified into genesis and propagated changes to facilitate investigation of the primary research question RQ1.2 investigated in this chapter. A matrix based modeling approach is used to identify the reasons for propagation occurrence. A review of existing manufacturing design processes indicate that 32.4% of the total changes are propagated changes, which were primarily due to document and design error occurring during the engineering release. Industries can, perhaps, reduce EC time by one-third, and hence any associated costs, by creating sophisticated appropriate controls to provide redundancy in document release to avoid propagated changes in both supply inventories and manufacturing processes. In order to reduce propagation due to design limitations, such as field failure, suitable controls must be developed through the improvement of existing tools and in the development of new designs. In addition, these tools can also include features that can specifically guide designers to arrest the propagation that may stem from document changes during engineering release.

This study confirms that changes can propagate across the functional domain in a manufacturing firm causing unplanned changes, which is in contrary to the canonical concept of change propagation currently restricting the study of propagation within the product. Thus, it is essential to consider this aspect in future change propagation research which will enable the creation of new management tools to support changes in incremental product design.

4.8 Dissertation Roadmap

With an overarching goal of developing a new design tool, the existing design evaluation tools should be reviewed for their limitations. Understanding organizational pathway of propagation was essential prior to reviewing them. Since, this chapter has advanced the understanding in this aspect, the next chapter (Chapter Five) explores the limitations in the existing design evaluation tools while Chapter Six introduces the proposed design tool. The progress of this dissertation is shown in Figure 4.6 in which the completed chapter is highlighted in green.

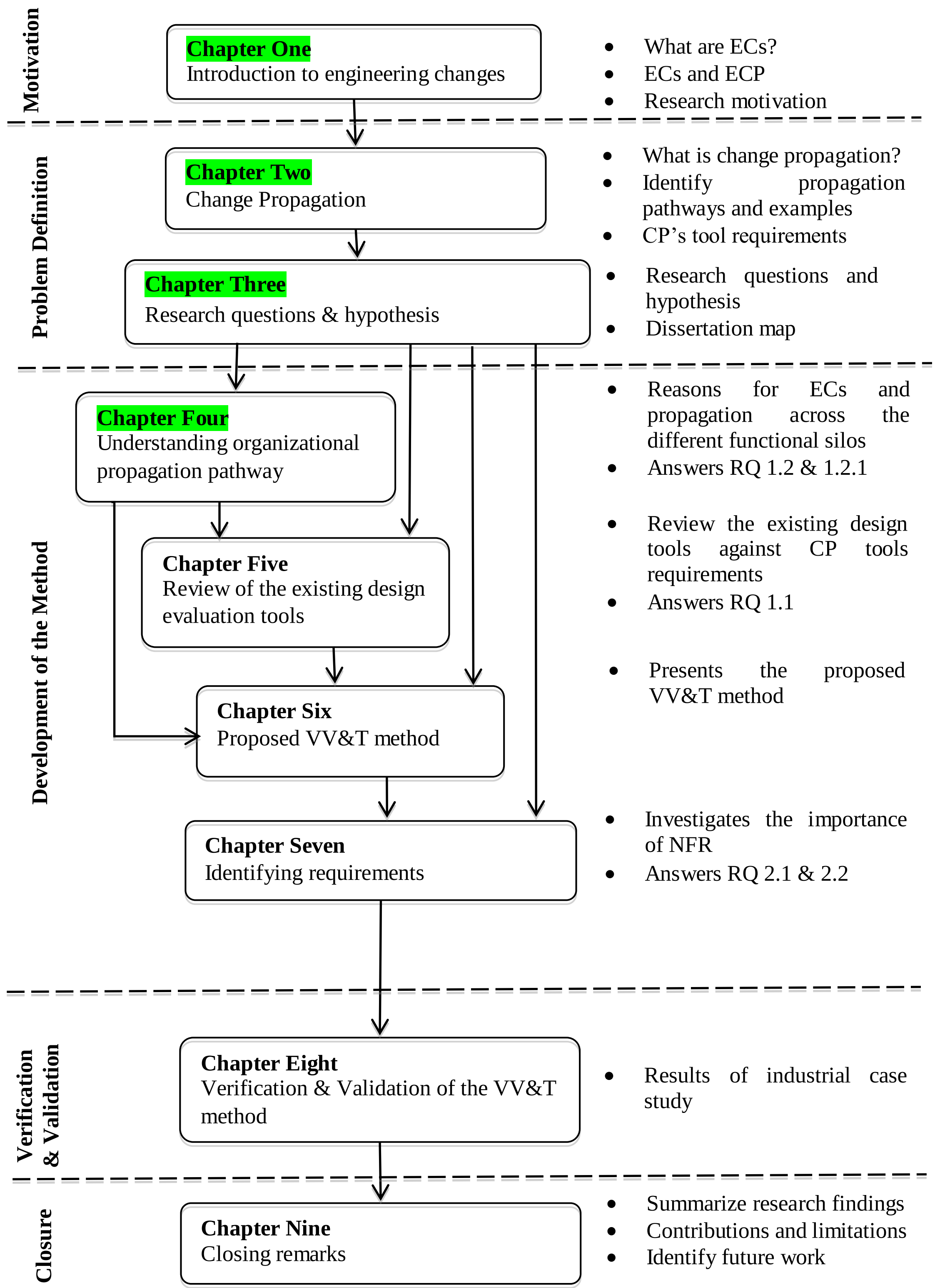


Figure 4.6 Dissertation Roadmap

CHAPTER FIVE : DESIGN EVALUATION TOOLS: A REVIEW

This chapter presents a review of the existing design evaluation tools to determine their suitability and limitations as a change propagation tool. The results from this chapter will be used to address the key research question RQ1, which is about developing a control to reduce design changes due to propagation. In order to be able to address RQ1, a sub research question RQ1.1 is investigated in this chapter, which is presented below along with its hypothesis.

RQ1.1 : *What are the limitations of the existing design evaluation tools that are used to evaluate engineering changes?*

Hypothesis1.1: *Organizational and variant pathways are not evaluated by the existing design evaluation tools*

The research method used to test this hypothesis is selected as archival analysis based on the answers to the following questions in Table 5.1.

Table 5.1 Justification for the Choice of Research Strategy for RQ1.1

Research Question	Question	Answer	Justification
RQ1.1	Form of the research question – is it exploratory or explanatory?	Exploratory	The research question ***explores*** different design evaluation tools that are used to reduce change propagation
	Does the researcher require control over the events?	No	The goal is to test the abilities of existing design tool. Hence, no control over the events is required
	Is the phenomenon under study a contemporary or a historical event?	Not applicable	Not applicable

As the research question is exploratory, and the researcher does not require control over the events, archival analysis is used as a research strategy to investigate this research question. The existing design evaluation tools identified from the literature are analyzed using a protocol scheme, which is described in the next section. Review of the design tools against this protocol is presented in section 5.2, and verified against the change propagation tools requirements in section 5.3.

5.1 Design Evaluation Tools' Review Protocol

Design evaluation tools capable of predicting change propagation effects are the primary focus of this review. However, failure analysis tools are also included because a failure mode can result from a change and can lead to subsequent ECs. The essential information considered in the design evaluation tools is: (i) whether or not propagation chain is predicted/identified; (ii) If it is a failure analysis tool, whether or not interaction-based failure modes are predicted/identified. The rationale is such failure type can implicitly address propagation effects where a failure can be degradation of the performance or loss of the performance.

Table 5.2: Identification of the Input Information

Tools	Input				
	Change mode	Failure events	Functions	Hazards	Change probability
FMEA[1]			✓		
CPM[2]					✓

1.FMEA – Failure mode and effect analysis
2 CPM – Change prediction method

The protocol is divided into three steps. First, the initial information to the design tools, as shown in Table 5.2, are reviewed to verify the first requirement of the change propagation tool (see section2.2.1 in Chapter Two), that is, whether or not change modes are analyzed. Second, what type of data and reasoning scheme is used in conjunction with the initial information to obtain the output information? As shown in Table 5.3, column (a) shows what is identified with the initial information; Column (c) shows two different means are used to identify items in column (a), that is, historical and model data. The sources for the historical data includes documents, human memory, and codified database while model-based include both graphical representation and computer-based simulation. Interactions being considered as a main contributor to induce propagation effects in the system, hence, modeling them is essential to identify propagation paths or to identify failure modes (Jarratt. et al. 2006; Giffin et al. 2009). Thus, for those tools where interactions are modeled, column (d) identifies what is modeled: interaction-interrelationship or interaction effect? Modeling interaction-interrelationship means modeling the geometrical connections between two components, or connection between two functions through energy, material, or signal transfer, and modeling interaction effect means modeling the physical behavior of the parts using first principles of physics or using the design parameters. Column (b) identifies what reasoning scheme is used: abductive or deductive? It is included for identifying whether or not the tool can be automated. Such reasoning scheme is predominantly used in most computer-aided design tools (Summers 2005). Therefore, if any of the tools use such reasoning scheme then it provides a window of opportunity for automation. Third, the output information is listed (see in Table 5.4) which could be the same as items in column (a) of Table 5.3 in certain instances.

Table 5.3: Input-Output Information of the Design Tools

Tools	How is the input information identified in Table 5.2 used?										
	What is predicted /identified?		Reasoning		How item in column - (a) is predicted/ identified through reasoning (b)?					How are system element interactions modeled?	
	(a)		(b)		(c)					(d)	
					Historical			Model			
	Failure modes	Propagation pathway	Abductive	Deductive	Document	Human	Codified	Representation	Simulation	Interaction inter-relationship	Interaction effect
FMEA	✓			✓		✓		✓		✓	
CPM		✓		✓		✓			✓	✓	

Table 5.4: Identification of Output Information from the Design Tools

Tools	Output information		
	Design controls	Failure risk	Change risk
FMEA	✓	✓	
CPM			✓

The entries in Table 5.2, Table 5.3, and Table 5.4 are for illustration purpose only. The complete list is provided at the end of section 5.2. Each tool is subjected to this protocol and the relevant information is filled in these tables. *Only those tools that use interaction based model data and identify propagation pathways are further analyzed to determine their limitations in terms of their model and the predicted pathways*. However, no separate section is provided for discussing the limitations, but it is included as a part of the discussion in section 5.2. Subsequently, in section 5.3, these filtered tools are verified against the change propagation tool's requirements in order to test the hypothesis.

5.2 Review of the Design Evaluation Tools

This section reviews different design evaluation tools identified from the literature. In this section, significant portion of time is spent on discussing the FMEA tool and its limitations because it is a widely used and accepted tool for design assessment during the process of changing designs. In addition, its fundamental concepts are used in different other tools.

5.2.1 Family of FMEA

Failure mode and effect analysis (FMEA) is a design tool used extensively in industries to model/understand the failure modes, to develop preventive measures in the design, and to prioritize the failures based on its risk (Bednarz and Marriott 1988; Teng and Ho 1996). As per SAE J 1739 standard (SAE 2009), FMEA is initially conducted at the system level and continued for other lower levels in the system hierarchy. At each level, the functions are identified by a cross functional team of engineers using a component block diagram (CBD) of the system with appropriate resolution of the system (depending on the level of FMEA) to facilitate function identification. The manner in which these components fail, termed as failure modes, are identified based on the team's prior experience. The possible cause and effect of these failures are analyzed among the team. Finally, the failures are rated by a metric called "Risk Priority Number (RPN)" that accounts for the likelihood of each failure mode, their impact, and the ability to detect it. Limitations in this tool in its different aspects are discussed in the next section.

5.2.1.1 How Good are the Inputs?

As per SAE's recommended practice for the FMEA, a component block diagram is used, which is analogous to function structure, for analyzing the components within the system boundary to identify their functions. Blocks represent the components while the interconnections between them are system parameters such as energy, material, and information. Both the components and their associated functions are listed by the designer in the recommended documentation template. Subsequently, the failure modes are predicted for these functions. The question posed here is: How effective will be the system description?

Technical systems are represented at the highest level of abstraction, that is functions, for distancing designers from the physical embodiment to escape fixation (Pahl et al. 2007). This approach is beneficial for synthesizing design concepts, but it may not be suitable for analyzing existing technical systems (Alink et al. 2011) for the following reasons:

(i) Design Cognitive Standpoint

Designer finds it difficult to consciously disassociate themselves from the physical embodiment and think what the design should do in abstract terms, such as function, because the functional properties of the system are stored in the designer's memory with close association to the physical embodiments (Albers et al. 2004). After switching to abstract terms, the inter relationship between the abstracted details of the components are dispersed in the designer's mind, which reduces the memory's retrieval capacity as the abstract-concrete relationship strength is weakened (Kosslyn 1980). As a result, a complete list of functions may not be retrieved even from an experienced designer's mind (Alink et al. 2011), thereby leading to an incomplete system description.

(ii) Perspective Change

Designers may end up listing fewer functions than what actually exists because of switching from concrete to abstract representation. In abstract terms, an input shaft's functionality in a motor is 'to transmit power' whereas the other features in it that supports manufacturing, such as centering feature, may not necessarily be identified in the analysis.

(iii) Notion Of Function

Designers with similar background have different notions for functions at different levels of abstraction in their mind, which can lead to different degrees of interpretation of the existing system (Alink et al. 2011). These differences can also lead to fewer functions identified in the system than what actually exists. These reasons can lead to incomplete description of the system's functionalities, which is highlighted by other researchers (Wirth 1996; Stone et al. 2005).

5.2.1.2 Notion of Functional Dependency on Single Components

Each component in a product are associated with one or more functions (Shankar et al. 2010). However, functions in technical systems are achieved by interaction between components (Albers et al. 2005), which is not considered in the existing FMEA method. It is assumed that each component will realize its associated function independently in FMEA. This notion, not limited to, may prevent designers from identifying failures that may arise from interactions. Such inability to identify interaction-based failures has been pointed out by several researchers (Stone et al. 2005; Kurtoglu and Tumer 2008).

5.2.1.3 Functional Propagation Idea

A top-down approach is followed during FMEA, that is, starting from system, sub-system to component level. The failure mechanism predicted at the system level, for each identified function, is carried forward as a potential failure mode at the sub-system level, and the process is continued until the last level. This hierarchical transformation can help identify functional-failure propagation (See Figure 5.1 for an example in the brake system). Therefore, interaction based failures can be prevented with the use of FMEA, as suggested by (Teng et al. 2006), *only if the failure mechanism is identified at the system level based on the interactions.* Two limitations reduce the value of this hierarchical transformation idea built in the method:

1. The association between functions at different levels of hierarchy is not traceable, as the existing documentation scheme does not have explicit provisions referring to affected upstream and downstream functions. As a result, designers may loose track of the association between them when performing FMEA for large technical system.
2. The identification process of failure mechanisms is based on the cross functional team's experience rather than a systematic process. Hence, the prediction is dependent on the team's best engineering judgment based on prior experience, which may not necessarily include interaction-based failures. The issue in relying on designer's memory is discussed in the following section.

System level FMEA											
Item/ function	**Potential failure mode**	**Potential effects of failure**	**Severity**	**Class**	**Potential causes/ mechanisms of failure**	**Occurrence**	**Current design controls**	**Detection**	**RPN**	**Recommended actions**	**Responsibility and target completion date**
Vehicle/ to be able to transport passengers from point A to B	No smooth forward movement of the vehicle	Customer dissatisfaction	8		Brake lining in constant contact with brake drum						
Sub – System level											
Brake assembly / To retract after braking	Brake lining in constant contact with brake drum	Brake overheating, vehicle at reduced performance	7		Reduced/no clearance between brake drum and lining		Incorporated at the component level FMEA				
Component level											
Shoe return spring/ to store energy	Permanent deformation	Reduced/no clearance between brake drum and lining	8		Insufficient material strength		Used stainless steel material with higher yield strength				

Figure 5.1 Functional Propagation Idea in FMEA

5.2.1.4 Reliance on the Expertise for Failure Mode Identification

The prediction of failure mode is not based on any systematic process that considers element interactions, as it relies on the team's experience (Tumer et al. 2003; Stone et al. 2004; Laurenti and Rozenfeld 2009). Such reliance on the expertise will also limit the range of prediction within their domain knowledge (Stone et al. 2005). There can be failure modes for similar functions in other domains that may be eliminated from the analysis. In addition, the use of expert domain knowledge leads to the following questions:

1. Can the degree of engineers' expertise hinder the recollection ability of the failure modes?
2. How relevant will be their recollection to the problem under investigation?
3. How many years of memory can be traced back to recollect the failure instances and their associated failure modes?
4. How reliable will be their recollection of thoughts?

The first two questions can be answered to a certain degree from cognitive studies. Experts do posses a greater stock of relevant designs in their mind, but they will have difficulty in escaping the similar current situations because of the stronger situation-action associations (Purcell and Gero 1996). This is a positive sign because designers may get cues about the failure modes from the past that they may have experienced. How suitable will be their recollection to the situation depends upon what type of expert are they. Two types of domain experts exist: Inflexible and flexible; Inflexible experts exhibit mental set and fixation while flexible experts do not exhibit such psychological effects in thinking (Bilalic et al. 2008). Even though both experts possess rich association between their factual and proceduralized domain knowledge, the inflexible experts will have trouble escaping the embodied tacit constraints experienced previously (Logan 1988; Wiley 1998). This means that inflexible experts may predict failure modes that may no longer be valid for the present situation. Although inferences from the past design-cognitive studies can be used to answer the above questions to a certain extent, further research is required on these aspects. For the third and fourth questions, it presents a window of opportunity for future research. However, relying on expert's memory is not viewed as a robust method in design which is why these failure modes are stored in a database (Stone et al. 2005).

Change modes are not documented in the existing format of FMEA. Therefore, designers while predicting the failure mode may overlook the possible failures due to the change mode during their past failure instance recollection process from memory. Currently, they may implicitly think about the failure modes based on change mode, for which no documented evidence is yet available.

5.2.1.5 Why Cannot FMEA Identify Interaction-Based Failures?

As component block diagram (CBD) models interaction inter-relationship, it has been used in industry to conduct cause and effect analysis for identifying failure modes. The limitation in the representation of the CBD is it prevents causal reasoning of the interaction effects, which is illustrated using a portion of the CBD, as shown in Figure 5.2, developed for a hydraulic brake system in passenger cars. Brake system circuit and its components functionality are identified from (Limpert 1999).

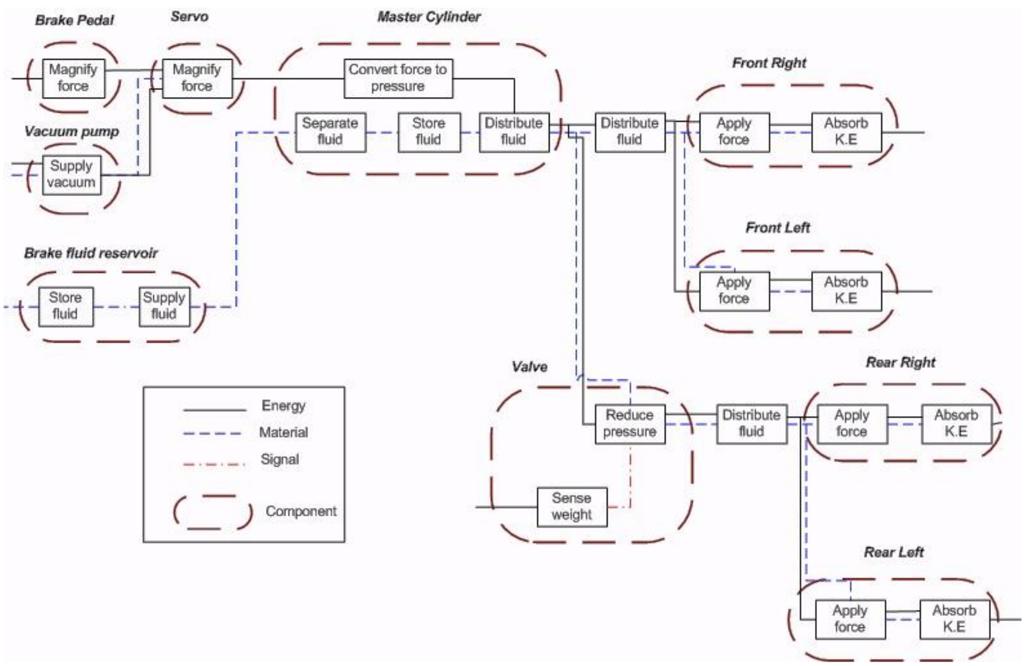


Figure 5.2 CBD for a Hydraulic Brake System

During a braking application by the vehicle driver, the brake pedal actuates the servo (otherwise called as brake booster) that magnifies the input pedal force to the required level. This component performs the "force magnification" action with vacuum assistance from a vacuum pump. For the purpose of illustration, it is assumed that FMEA is conducted on the component 'servo'. As per the FMEA standards, the component and its item function (in this case 'magnify force') is written in its standard template. This component receives an energy input from the pedal (ME1) and energy (ME4) and a material input (V1) from the vacuum pump (see Figure 5.3), magnifies the input, and outputs a magnified energy (ME5). The next step is to identify the failure modes. The designer examines the input lines and starts the analysis by removing the input energy line from the vacuum pump, as shown in Figure 5.3 with red crossed symbol.

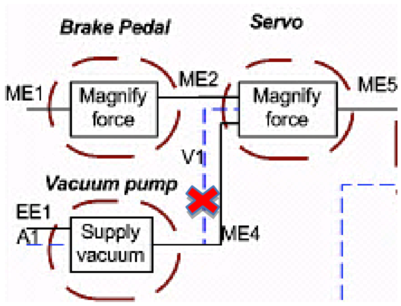


Figure 5.3 Servo and Vacuum Pump Portion of CBD

From this representation, what can be inferred is servo produces a magnified energy (ME5) with one material V1 and one energy input ME2. In reality, this doesn't make any sense because if there is a loss of energy (ME4) from the vacuum pump then there is an associated loss of material transfer, that is, vacuum (V1). Having recognized this limitation both the material and energy output from the vacuum pump to the servo is removed. Does it make sense now? No, because the diagram shows that ME5 is produced with ME2 without any vacuum assistance, which is not possible. ME5 from the servo is possible if and only if both ME4 and V1 are present in conjunction with ME2. The loss of function 'magnify force' due to the loss of vacuum is not reflected due to the lack of representation of dependencies and the logical relationships between the function flow lines. Therefore, ***this representation does not support causal reasoning of the interaction effects even at a qualitative level***.

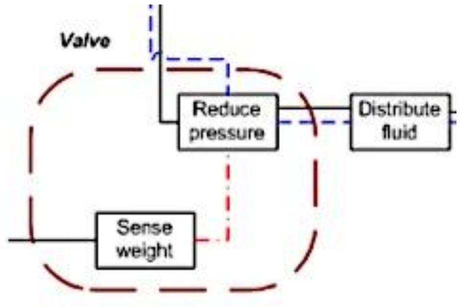


Figure 5.4 Valve Portion of the CBD

Change in state of the system can cause a change in the routing of the flow lines, which is not captured in CBD. The portion of the CBD with the component ‘valve’ is specifically examined to illustrate this limitation. As shown in Figure 5.5, the pressurized brake fluid is distributed to the rear brakes via a pressure-reducing valve. This is essentially included in the circuit to avoid rear wheel locking and vehicle instability only in the vehicle-unladen state (driver only condition). When the vehicle changes its state from unladen to laden, the input flow to the function ‘reduce pressure’ may be bypassed and directly distributed to the rear wheels through the distributor. In certain cases, the function ‘reduce pressure’ is required on both laden and unladen system states, but the point of initiation of this function is directly dependent on the braking dynamics, specifically, the deceleration point. Therefore, representing a function that is dependent on the dynamic state of the system as a quasi-static state independent function limits the correctness of the interaction analysis.

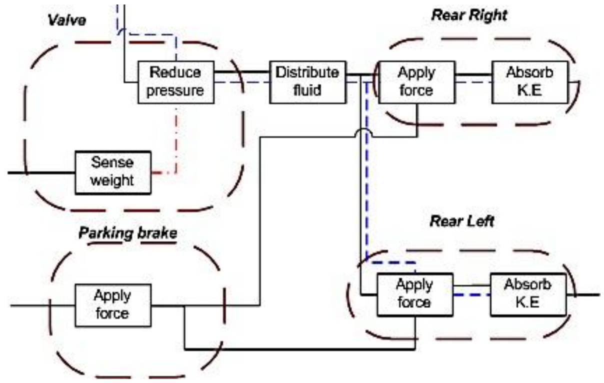


Figure 5.5 CBD with Parking Brake

To further illustrate the limitation in CBD representation, a parking brake circuit is also added, as shown in Figure 5.5. The components, rear brake right and left, will now receive an additional energy flow. The question here is: Does the rear brakes receive energy from the parking lever at all times during the vehicle operation? No, it receives energy from the parking brake only while the vehicle is parked and, occasionally, from both the parking brake circuit and the main circuit during an emergency while the vehicle is under operation. Hence, the dependency of the function's input on its mode of operation is not represented.

As identified above, CBD is independent of the operation modes of the system. In Figure 5.2, the flows relevant to the mode of operation 'apply brake' is represented. What will be the interactions during the mode of operation 'release brake'? Will it be the same? No, it is not the same because in rear brakes, the functions 'apply force' and 'absorb kinetic energy' obviously vanishes. Additionally, it requires a function 'release force' in this mode of operation, which is not even modeled. The inclusion/deletion of functions under different operational modes can have different interaction flows, which cannot be identified with this representation. Even if it is modeled, the other two issues discussed in the above paragraph may not aid designers for causal reasoning using this representation, thereby increasing the chances of not capturing some of the failure modes.

5.2.1.6 Lack of Clarity in the Definition of Terms

The terms used in FMEA are not well defined (Kara-Zaitri et al. 1991; Lee 2001). The term failure is not defined in the SAE J 1739 standard. A function can either loose its functionality or degrade. Which one should be considered for analysis – loss of functionality or degradation? However, the example provided on the passenger car's door in the SAE standard suggests that both types of failure should be considered, but a clear definition will enhance the understanding in the designer's mind of what type of failure should be considered for analysis.

The second vague definition is 'detection'. As per (SAE 2009) standard, the definition is:

'*Detection is an assessment of the ability to prevent the cause/mechanism or failure mode/effect from occurring, or reduce their rate of occurrence, detect the cause/ mechanism and lead to corrective actions, and detect the failure mode.*'

There are three possible interpretations: (i) From the quality department standpoint; (ii) from the design verification standpoint; (iii) from the user's standpoint. From the quality department standpoint, is it the ability to detect the failure mode by manufacturing firm's quality system? From the design verification standpoint, is it the ability of the verification tests to detect the failure mode? Finally, from the user's standpoint, is it the ability to detect the failure mode during the operation of the product?

For instance, a possible failure mode in the braking system is brake fluid depletion from the brake fluid reservoir. Which of the above three perspectives should be adopted while rating the detection? The person who is conducting FMEA can adhere to any one or more of these perspectives, which is supported by earlier researchers where they have highlighted that it has lead to confusion in the designer's mind (Teng et al. 2006). So, which of these interpretations have to be used while conducting FMEA?

Apart from the ones mentioned above users feel it is tedious and time consuming (Bednarz and Marriott 1988; Kara-Zaitri et al. 1991; Wirth 1996; Stone et al. 2004), it is often times used to satisfy quality audit purpose; it has vague representation of functions, failure modes, failure effects, failure causes, and detection controls; it has inconsistent formats across the supply chain; and lack of integrity of documents across the supply chain (Teng and Ho 1996; Teng et al. 2006). Because of all these limitations, this tool is discarded from further analysis.

5.2.2 Failure Mode and Effect Criticality Analysis (FMECA)

FMECA is an improved FMEA method that specifically addresses the difficulties in ranking failure modes. In FMEA, failure modes are prioritized using RPN, which can be misleading (Bowles 1998). For example, let two failure modes have same RPN of 120. Does it mean that both these failure modes carry the same rank? How to pick which one is more important? To address this ambiguity, criticality of the effect is determined as a mathematical function of both occurrence probability and the severity, which can be subsequently used to prioritize the failure modes. Apart from this difference, FMECA follows the FMEA procedure and its limitations. Hence, this tool is eliminated from further analysis.

5.2.3 FMEA for Modification

Neglecting change mode in FMEA prevents designer's from focusing on the possible failure modes due to a design change (Laurenti and Rozenfeld 2009), which is one of the limitation of the traditional FMEA. Therefore, the documentation template has been modified to account for the change mode, which enables explicit thinking of the failure modes specific to changes but not due to interactions.

5.2.4 Advanced Failure Mode and Effect Analysis

Advanced failure mode and effect analysis (AFMEA) is a semi-automated FMEA used to enhance product reliability at the conceptual design stage(Eubanks et al. 1996; Eubanks et al. 1997). The process begins with identifying key characteristic requirements from quality function deployment (QFD) that the system should meet. A function-behavior-structure (F-B-S) model is built to develop the knowledge about the product – an adopted approach from (Keuneke 1991). In this modeling philosophy, functions are what the product is intended to do while behaviors are how these functions are achieved, which indirectly refers to the individual components and their interactions. Behaviors are represented as a sequence of transitions of partial states. Readers may consult (Keuneke 1991; Chandrasekaran et al. 1993; Eubanks et al. 1996) for further details on behavior modeling.

The key function's behavior is decomposed into a sequence of partial transitional behavioral states at various levels of hierarchy. This behavior tree is mapped to the parts of the component in an assembly, thereby achieving a function-behavior-structure mapping. At each level of the behavior hierarchical tree, every behavior is qualitatively assigned the required initial and final states. The developed behavior model is then used for simulation to identify failure modes, which is defined as the inability to transit from initial or intermediate state to the final state or to an undesired state. Three different types of failures are identified: (i) non-behavior (loss of behavior); (ii) misbehavior (unintended behavior); and (iii) undesired behavior (degraded behavior).

The failure modes are predicted by selecting a behavior candidate, and assuming it to fail in the computer simulation. The resulting behaviors are compared against its desired state to identify any possible failures. Subsequently, these failure modes are entered manually in the standard FMEA template for further evaluation.

Since the failure modes are predicted based on behavior simulation, interaction-based failures can be predicted using this method. However, simulation is not based on the specific change mode rather it is a random choice by the user and it does not intent to identify ambient, variant, and organizational pathways. Apart from this limitation, this tool is a potential candidate for predicting change propagation. Nonetheless, it is focused on identifying failure mode during conceptual design stage rather than production stages of the design. Hence, this tool will not be further analyzed and verified against the change propagation tool's requirements.

5.2.5 Scenario Based Failure Mode and Effect Analysis (SFMEA)

Scenario based FMEA is focused on: (i) risk evaluation of each possible scenario of an identified failure; and (ii) prioritizing the failure scenarios based on their likelihood of occurrence and their cost impact (Kmenta and Ishii 2000).

As per SAE J 1739 standard, no explicit reference is made to consider multiple scenarios for each functional failure. In SFMEA, this limitation is addressed by explicitly analyzing multiple scenarios of failure. A scenario is a path, like a-b-c, in the function-failure mode-cause- effect tree, as shown in Figure 5.6.

In the context of this paper, this method carries forward the limitation of the traditional FMEA. Therefore, this FMEA technique cannot analyze change modes and their associated interaction-based failures; hence, eliminated from further analysis.

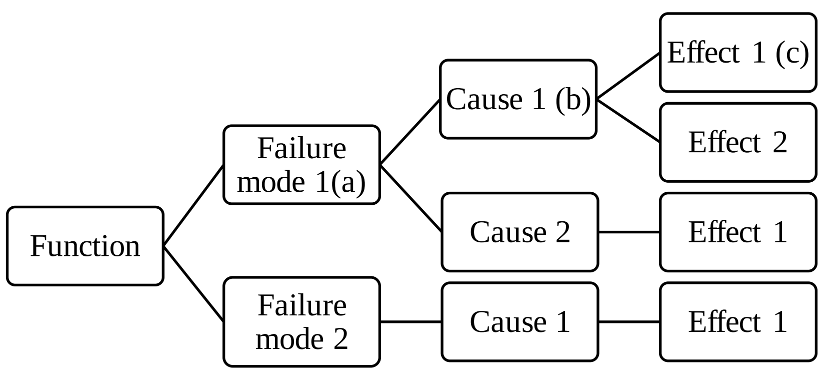


Figure 5.6 Scenario Tree

5.2.6 Conceptual Failure Mode Analysis (CFMA)

Conceptual failure mode analysis (CFMA) is another failure analysis tool with focus on concept design evaluation (Weiss and Hari 1999). The process begins with the functional analysis using a function analysis system technique (FAST) diagram (Wixson and CVS 1999). The product development team based on prior experience identifies the failure modes for these functions. Later, the team identifies the causes and effects of these failure modes. The occurrence (O), severity (Se), and the detection (D) of these failures are measured in a non-linear scale of 1, 2, 4, and 10 unlike the linear scale used in traditional FMEA. The product of O, S, and D is used as a metric to prioritize the failures, which is similar to RPN in traditional FMEA. Apart from the difference in functional analysis procedure and the rating scale of the failures, this tool is fundamentally not different from the FMEA. Therefore, their limitations are equally applicable in this tool too and hence, eliminated from further analysis.

5.2.7 WIFA

WIFA is a German acronym for knowledge-based FMEA (Wirth 1996). Three items are stored in the database: (i) historic FMEAs for easy access to the designers when they conduct new FMEAs; (ii) product descriptions such as system and function taxonomy, function failures, and failure modes; (iii) it stores the sequence of steps required for conducting FMEA. With this information, this technique aims to improve the FMEA quality. However, this carries forward FMEA's limitations and hence this tool is rejected from further analysis.

5.2.8 Function failure design method (FFDM)

Function failure design method (FFDM) is an approach that couples failure analysis at the conceptual stage of the design with a goal of reducing failures at later stages of the design (Stone et al. 2004; Stone et al. 2005). This method uses a matrix-based approach to populate the function-failure knowledge base in which designers identify the relationship between function-components (EC) and components-failure (CF). Using simple matrix multiplication, the relationship between function-failure (EF) is identified. The rows in this matrix represent functions and the entries in the columns corresponding to that row represent the number of components satisfying the function failed by the failure mode. Using this database, designers can analyze the possible failure modes for associated functions early in the design, and thereby, reduce the design changes at a later stage.

The primary advantage of using this method is moving away from the reliance on designer's memory on the past failure modes, which is a major drawback in FMEA. Nevertheless, this tool does not identify propagation pathway; therefore, it is eliminated from further analysis.

5.2.9 Function Failure Identification And Propagation (FFIP)

Function failure identification and propagation (FFIP) is a framework to identify the functions that may fail due to propagation effect (Kurtoglu and Tumer 2008). This framework, as shown in Figure 5.8, uses a low fidelity high level functional model to analyze the possible functional failures of the system using behavior models and an associated reasoning model. This framework is used as a pro-active tool to evaluate the propagation effects at the conceptual design stage when the system components and their design parameters are not yet known.

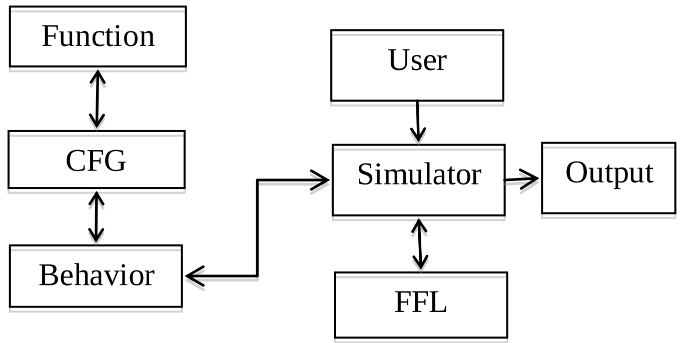


Figure 5.8 FFIP Framework

FFIP is built on a function-configuration-behavior architecture of a system at a high level of abstraction with a function failure logic (FFL) reasoner to support fault analysis and their consequences without relying on the expert opinion. The process of developing this framework begins with development of a function model using standardized taxonomy of functions. An abstract description of components for these functions are identified based on (Kurtoglu et al. 2005) and represented as a graph termed configuration flow graph (CFG). The functions in the function model are mapped to the components in the CFG. The third layer is the behavior model used in conjunction with CFG to conduct behavioral simulation. Each component's behavior is defined by their input and output relations, and their underlying physical principles. The behavior of each component can be viewed as an event-mode-behavior architecture where a user specified event triggers an operational mode that results in a behavior. The transition from one mode to the other is triggered by an event that can be due to the environment interaction, due to the human interaction, or due to the component malfunction. During the modeling stage, the user prescribes the different conditions in which the intended functionality cannot be achieved. This logic of condition prescription is termed as function failure logic reasoner in the framework.

The computer-based simulation is initiated by initializing the state variables to their nominal modes and executed in a continuous time frame. The physical state of the system is fed to the reasoner where it evaluates the function failure logic for the received state at the end of each intermittent state of the system. After evaluation, it returns the information to the simulator for further simulation. User can initiate different failure events to determine what functions can fail due to propagation effects. The simulation will continue until a prescribed end state or for specific number of time steps.

This tool models interaction effects and identifies propagation pathway except that it is not specific to any given change mode. Since it is focused only for the conceptual design stage, this is deemed unsuitable for the purpose of this dissertation and hence, eliminated from further analysis.

5.2.10 Change Prediction Method (CPM)

Change prediction method is a tool to predict the elements that are affected due to change propagation using probability-based risk analysis (Clarkson et al. 2004). In this method, two matrices are developed based on the designer's experience. In the first matrix, the likelihood of change in one component affecting the other is captured in a structural connectivity design structure matrix (DSM). In the second matrix, the degree of impact a change can have on the other component is captured. Since the values in the likelihood and impact matrix are valid only for the direct connections, a predictive model is developed to take into account the effects of a change on a component due to indirect relations. An average likelihood of change resulting from all different connections is computed. Subsequently, using probabilistic risk theory, the risk and the impact of a change is predicted from the predicted average likelihood matrix. This risk matrix is further used to identify components affected in the chain of propagation through structural pathway.

There are three assumptions in this method. First, it is assumed that changes to an element can cause propagation irrespective of the type of change mode, that is, whether or not it is active or inactive. The effect of not considering it in this tool encompasses a nature to predict elements that are not affected.

Second, this tool assumes the applicability of probability theory on the likelihood information elicited from the design engineers, which is captured in the likelihood matrix. Probability theory can be applied when the measured quantity's uncertainty is non-deterministic and objective (Dubois 2006). Thus, the fundamental question here: is the information captured in this tool deterministic or non-deterministic? In an electro-mechanical system, which is governed by a set of physical principles, the effect of a change in an element on the other, in a specific change mode, is deterministic, but it may not be known to the designer due to the lack of knowledge for various reasons such as limited experience or limited modeling capabilities. A second question that follows the first is: On what basis does the engineers' provide the likelihood numbers? Were they subjective or objective? It is understood from the literature that the numbers provided in the likelihood matrix are not based on the variability obtained from a repeated set of experiments under controlled conditions rather based on their best guess, which is subjective. Thus, the two requirements for the applicability of probability theory are not met; therefore, the risk prediction needs a different approach to model the uncertainty than what exists.

Third, the likelihood numbers provided by the designers assume that every change in a given component followed the same propagation pathway in the past, which is not necessarily true. Indeed, some change mode can initiate propagation through an entirely different pathway even when the component where the change initiation is the same. Therefore, the construction of the likelihood matrix lacks rigor, and hence, the risk predicted using this approach might not produce reliable results. CPM identifies propagation pathway by modeling the component interactions. Thus, this tool will be reviewed further.

5.2.11 Integrated CPM with Channel and Contact Model (C&CM)

The motivation to integrate CPM with channel and contact model (C&CM) is to provide designer's with two different perspectives of the product: (i) abstract level using functional representation; and (ii) concrete level (Keller et al. 2007). This switching between perspectives from abstract to concrete representation of the product and vice-versa enables designers to solve problems more efficiently (Pahl et al. 2007). With two different representations, designers' ability to understand the system is enhanced, and, with added product information, a better decision-making process to assess the change risk is possible.

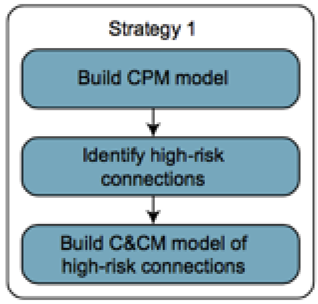


Figure 5.9 Integrating CPM with C&CM- A Strategy (Keller et al. 2007)

A strategy to integrate CPM and C&CM, as shown in Figure 5.9, have been proposed in this modeling approach in order to estimate the change risk. In this strategy, a CPM model is developed using a high-level component design structure matrix (DSM). After identifying the high-risk connection path from this model, C&CM is applied to focus on the components in this path to have a more deterministic view of the change effects. The use of CPM implies that the limitations discussed in section 5.2.10 are applicable in this tool also. However, the change effects can be identified in the deterministic sense using C&CM method, which will be beneficial to the designer, provided the limitations in the CPM tool are addressed. However, this tool identifies propagation pathways, and hence it will be reviewed further.

5.2.12 Requirement based Change Propagation

The effects of a change in a component on the system level requirements are studied using a matrix-based requirement-modeling scheme (RMS). Three different modeling schemes exist in the literature. First, a model mapping three information domains in the design: requirement to function, function to component, and component to engineering characteristics (Mocko 2007). Second, this modeling scheme is extended to capture more design information by mapping seven different domains: requirements, functions, working principle, components, design parameters, tests, and test parameters (Maier 2007). Third, an eight-domain modeling scheme that includes non-functional requirements is proposed to address the limitation in the earlier modeling scheme (Shankar et al. 2010). Using any of these models, the components that may get affected due to a requirement change or vice-versa can be determined using a series of matrix multiplication.

The fundamental limitation in this model is it cannot identify propagation pathways, as the geometric interdependency between the components is not modeled. It can only provide the set of components that participate in a function, not the propagation pathway. Hence, this tool is eliminated from further review.

5.2.13 Fault Tree Analysis (FTA)

Fault tree analysis (FTA) is one of the most widely used techniques for studying system reliability and safety. In this technique, a foreseeable undesired scenario of high risk is considered for analysis, such as unexpected loss of braking functionality in the passenger car during highway operation (see Figure 5.10), and then analysis is conducted on the system to identify the basic events, the causes, that may result in the occurrence of such an event (Vesely et al. 1981; Xing and Amari 2008).

In Figure 5.10, the failure causes are indicated in two different shapes; failure in the rectangular box indicates that they can be further decomposed, also termed as basic events, while the ones in the circular shape cannot be decomposed any further. The basic events could be component hardware failure, human errors, environmental conditions, or any other reason. The sequence of these events leading to the described high-risk failure is represented in a graphical representation using logic gates (see (Dugan and Doyle 1997) for more information on gates). Such logical interconnections are built through system analyses using functional block diagram (FBD), which is similar to CBDs described earlier but only functions are represented in FBD with no references to the components (Frankel 1988). For each of these failure events, the probability of failure is assigned based on the historical data, and the failure probability of the top-level event is determined using probability theory. In addition, sensitivity analysis is also performed to identify the sub-events that act as the significant contributors to the high-level failure scenario.

Each branch in the tree represents a failure path; therefore, propagation pathways can be identified using FTAs. However, since FBDs are used to identify the different causes for failures, as indicated in section 5.2.1.5, they do not support causal reasoning, which implies that failure paths identified may be incorrect, failure paths identified may be incomplete, or failure paths identified may be suitable only for a given system state or mode of operation. In addition to this limitation, FBDs are not consistent for a given technical system if standardized taxonomy of functions are not used, as indicated by (Stone and Wood 2000). The implication of this limitation is the propagation pathways that are identified by the designers based on FBD are going to vary between designers. Thus, the pathways identified become subjective rather than objective, which in turn implies that the failure probability is also subjective.

The propagation effects are also not evaluated, specifically performance degradation, while conducting FTA (Fussell 1975). Implementation wise, it is time consuming and expensive to construct (Allen 1984). Automating this tool, in order to reduce time, is also not possible because it uses abductive reasoning to identify different events that may lead to a failure state. In addition, it is often times used in the conceptual stage of the design in order to justify the investment in both resources and associated cost. Thus, these reasons lead to eliminate this tool from further analysis.

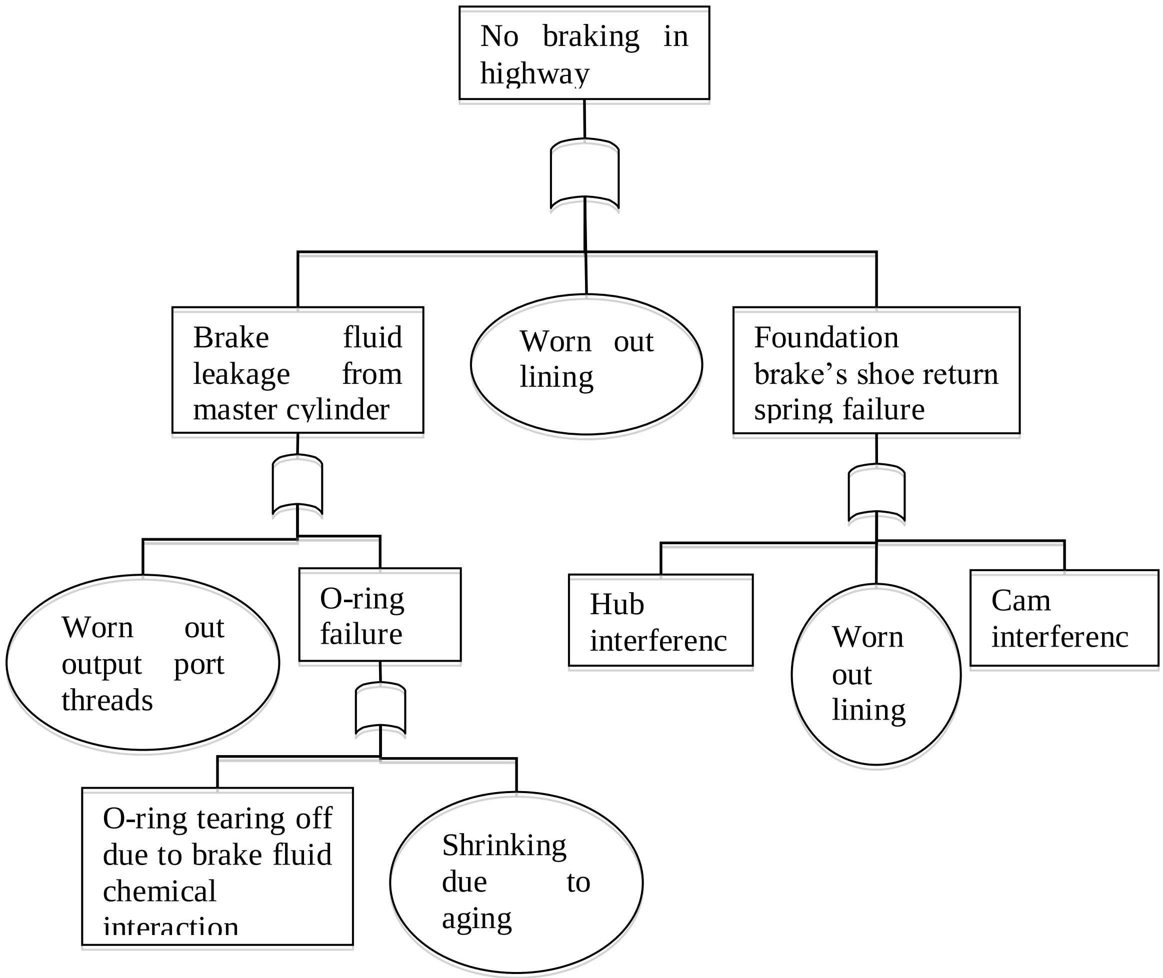


Figure 5.10 FTA Example for a High-Risk Failure in Brake System

5.2.14 Event Tree Analysis (ETA)

Event tree analysis (ETA) is used to identify the consequences of the occurrence of a potentially hazardous event (Andrews and Dunnett 2000), which is in contrast with FTA where causes for a hazardous event are identified (Andrews and Moss 1993). ETA begins with identification of an initiating event, such as fluid leakage in the brake's master cylinder, and then identifying the consequences of this event in different system elements using component block diagrams. In Figure 5.11, reading from right to left, the different outcomes are identified by postulating a success or a failure of all the connected system elements. An event tree analysis of the event ‘ poor braking’ is shown in Figure 5.11. For instance, failure of the vacuum supply from the vacuum pump will eventually lead to a failure by the servo to magnify the input brake pedal force, thereby leading to poor braking (hazardous event). At each branch point, the failure probability of success (Su) and failure (F) is determined using FTA. Each outcome in this diagram is a functional failure propagation path; however, there is always one path that is a success path (e.g., outcome 1), which can be omitted for propagation analysis.

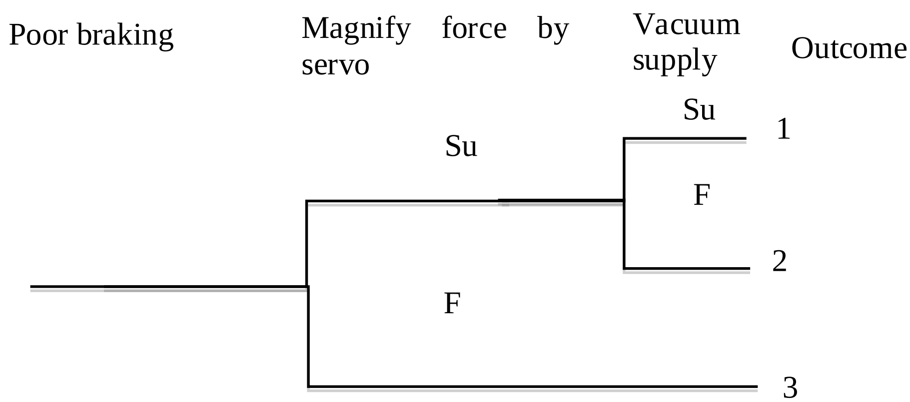


Figure 5.11 ETA Example on a Brake System

This tool does identify propagation pathways, but it is identified by the designers using their experience and with the help of component block diagrams. As the limitations of using these two techniques in identifying interaction-based failures have already been discussed in the earlier tools, it is not discussed here. In addition, computing event probabilities for each of these pathways can consume long time and can consume significant human resource, as FTA is needed to determine the failure probability of the interacting systems. The analysis is limited only to hazardous failures whereas design changes can result in performance degradation, minor failures, or major failures due to propagation effects, which can further result in expensive design changes. Thus, these limitations lead to eliminate this tool from further analysis.

5.2.15 Probabilistic Risk Assessment (PRA)

Probabilistic risk assessment (PRA) is used to predict the risk of a system failure based on the impact of the resulting hazardous event. It extends the ETA and FTA model, as shown in Figure 5.12, to predict the risk of failure scenarios by multiplying the failure probability, hazardous event's occurrence rate, and its consequence. The major outcome of this tool is prioritizing the system elements based on their degree of contribution to the failure risk. An exhaustive and systematic procedure is followed for conducting PRA (Modarres 2008). The important output from this tool is identifying elements that contribute most to the failure risk using sensitivity analysis and ranking them using importance measures (See (Fussell 1975; Modarres et al. 2000) for more details on importance measures). Limitations in this tool are same as what is identified in ETA and FTA, hence, not discussed in detail, which also implies that this tool is eliminated from further analysis.

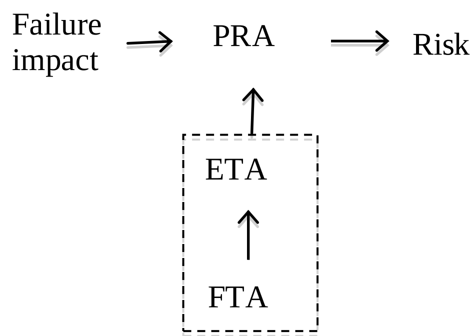


Figure 5.12 PRA Framework

5.3 Summary of the review of design evaluation tools

The consolidated tables used for analyzing the design tools are presented in Table 5.5, Table 5.6, and Table 5.7.

Table 5.5 Identification of the Input Information

Tools		Initial information								
		Change mode	Failure events	Functions	Hazards	Failure modes	Change probability	Failure probability	Requirements	Change component
Failure & Criticality	FMEA			✓						
	AFMEA			✓						
	CFMA			✓						
	FMEAM	✓		✓						
	FMECA			✓						
	FFDM			✓						
	SFMEA			✓						
	WIFA			✓						
Change paths	CPM						✓			
	CPM, C&CM			✓			✓			
	RMS								✓	✓
Risk	ETA		✓					✓		
	FTA		✓					✓		
	PRA		✓					✓		
Scenarios	FFIP					✓				

Table 5.6: Input-Output Information of the Design Tools

Tools		How is the initial information identified in Table 5.5 used?												
		What is predicted/identified?				Reasoning		How item in column - (a) is predicted/ identified through reasoning in column - (b)?					How are system element interaction modeled?	
		(a)				(b)		(c)					(d)	
								Historical			Model			
		Failure modes	Failure probability	Failure risk	Propagation pathway	Abductive	Deductive	Document	Human	Codified	Ab / G	Simulation	Interaction-relationship	Interaction effects
Failure & Criticality	FMEA	✓	✓	✓			✓	✓	✓		Ab		✓	
	AFMEA	✓	✓	✓	✓		✓	✓	✓		Ab	✓	✓	✓
	CFMA	✓	✓	✓			✓	✓	✓		Ab		✓	
	FMEAM	✓	✓	✓			✓	✓	✓		Ab		✓	
	FMECA	✓	✓	✓			✓	✓	✓		Ab			
	FFDM	✓					✓			✓				
	SFMEA	✓	✓	✓			✓	✓	✓		Ab	✓	✓	
	WIFA	✓	✓	✓			✓	✓	✓	✓	Ab		✓	
Change path	CPM				✓		✓		✓		G	✓	✓	
	CPM, C&CM				✓		✓		✓		G	✓	✓	
	RMS											✓	✓	
Risk	ETA		✓		✓	✓		✓			Ab	✓	✓	
	FTA		✓			✓					Ab	✓	✓	
	PRA		✓	✓	✓	✓		✓			Ab	✓	✓	
Scenarios	FFIP				✓		✓				Ab	✓	✓	✓
Ab: Abstract; G: Geometric														

Table 5.7: Identification of Output Information from the Design Tools

Tools		Final information							
		Design controls	Failure modes	Failure probability	Failure risk	Change risk	Affected element set	Affected elements in the propagation chain	Affected functions in the propagation chain
Failure and criticality	FMEA	✓			✓				
	AFMEA	✓			✓			✓	
	CFMA	✓			✓				
	FMEAM	✓			✓				
	FMECA	✓			✓				
	FFDM		✓						
	SFMEA	✓			✓				
	WIFA	✓							
Change paths	CPM					✓		✓	
	CPM, C&CM					✓		✓	
	RMS						✓		
Risk	ETA			✓					
	FTA			✓					
	PRA				✓				
Scenarios	FFIP								✓

From Table 5.6, it is inferred that out of the fifteen design evaluation tools that are reviewed in this chapter, only seven of them predict or identify the propagation pathway using interaction-based models. They are: AFMEA, CPM, CPM and C&CM, ETA, FTA, PRA, and FFIP. Out of these seven, AFMEA and FFIP are specifically designed for conceptual design stage, hence it is out of scope of this research, and it will not be analyzed further. ETA, FTA, and PRA are specifically used to evaluate the designs, often times at the conceptual stage, for high-risk failures such as fire hazards, rocket launch failure. Thus, these tools are eliminated from further analysis, however, those that cleared this first stage of review is verified against the change propagation tool's requirements.

In order to ensure that the tools reviewed comprises the wide spectrum of the tools that are available in the literature, these seven tools are grouped based on the nature of the output information, which is qualitative, quantitative, subjective, or objective, as shown in Table 5.8. For instance, FFIP outputs qualitative information that is objective whereas qualitative-objective (e.g., failure modes) and quantitative-subjective information (e.g., risk) is obtained from AFMEA. After eliminating five out of these seven tools, based on the review conducted in section 5.2, it is identified that there are two domains – qualitative-subjective and quantitative-objective – yet to be explored. Hence, in an exhaustive literature review conducted, none of the design evaluation tools that lie in qualitative-subjective domain is identified. However, verification tools, such as CAD (computer aided design) and CAE (computer aided engineering), used to verify the design requirements are determined to be in the quantitative-objective domain (Maropoulos and Ceglarek 2010). Although these tools are not designed to specifically address change propagation, they have the inherent ability to identify the propagation effects and hence, the pathways. As quantitative-objective nature of design evaluation tools uses concrete product information and output concrete details, which is different from the ones reviewed in the earlier section (quantitative-subjective and qualitative-objective), they are verified directly against the change propagation tool's requirements with some additional details, which are described in the next paragraph.

Table 5.8 Grouping of the Design Evaluation Tools

	Qualitative	Quantitative
Objective	AFMEA[1] FFIP[1]	CAD CAE
Subjective	-NIL-	AFMEA[1] ETA[1] FTA[1] PRA[1] CPM CPM and C&CM

1 – Tools eliminated based on the review

5.4 Verification of the Tools against Change Propagation Tool's Requirements

In this section, the design evaluation tools, both filtered tools and CAD and CAE tools, will now be verified against the change propagation tool's requirements:

1. Whether or not it can be used in the production phase;
2. Whether or not it is specific to change modes;
3. Whether or not it identifies/predicts the propagation pathways. If so, what different types of pathways are predicted;
4. Whether or not it evaluates the effects in the propagation chain.

If the tool predicts the propagation chain, two identifiers are used to indicate how the tool displays the propagation chain information:

1. Internal (I) – propagation chain information not displayed to the user but used for further processing internally in the tool;
2. External (Ex) – explicit display of the information to the user.

In addition, if the tool evaluates the propagation chain then seven different identifiers are used to indicate what is evaluated in the propagation chain, as shown in Table 5.9.

Table 5.9 Propagation Chain Evaluation Identifiers

Identifiers	Symbol	What is evaluated?	Example
Geometric relationship	G	Associations within and between components on geometric parameters such as size and shape	Design of gear based on parametric relationship between its different features
Spatial relationship	SP	Associations on distance and position between components	Axle's orientation with respect to the chassis in a commercial vehicle
Tolerance relationship	To	Associations between components on their manufacturing tolerance.	Stack up tolerance effects in mechanical assemblies
System dynamics	SD	Associations between design parameters within and between components of a system	Performance evaluation of suspension system
Elasto- statics	ES	Kinematics of material deformation	Deformation behaviour of a vehicle Tire
Elasto-Dynamics	ED	Kinetics of material deformation	Stresses in the ball bearings during the motor shaft operation
Elasto fluid dynamics	EFD	Kinetics of material deformation due to fluid flow	Heat transfer analysis in engine components

Each of these design evaluation tools are also tied back to a specific stage in the ECP in order to identify where in this process can these tools be used. Implications of engineering change proposals are assessed in the third step of the ECP, that is, during the second stage where ECO is reviewed for its approval, as shown in Figure 5.13. This identification is based on the ECP studied while conducting a case study in an automotive OEM (see section 4.2.2 in Chapter Four) and based on published journals (Jarratt. et al. 2006).

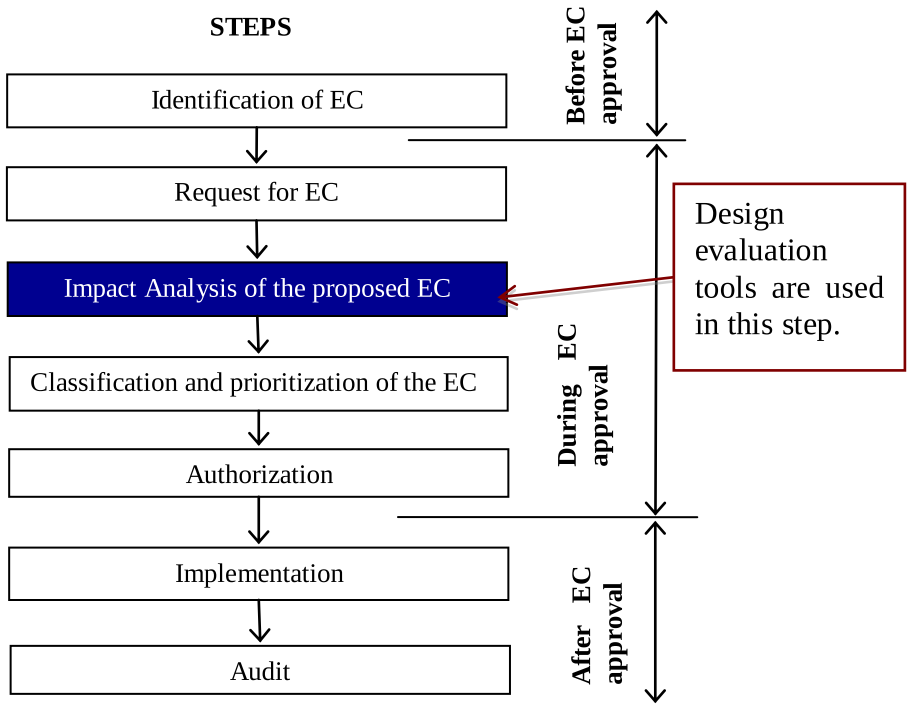


Figure 5.13 Steps in the Engineering Change Process (Jarratt et al. 2006)

The results of the requirement verification are tabulated in Table 5.10. In the quantitative-subjective category of tools, which is CPM and CPM integrated with C&CM, only geometric propagation pathways are predicted, and the pathway is displayed externally to the user.

Table 5.10 Existing Design Tools Ability to Predict Pathways

Tools		Production stage	Propagation pathway type						Propagation chain	Evaluate the effects of propagation chain
			Behavior pathway	Functional dependency pathway	Geometric dependency pathway	Ambient pathway	Variant pathway	Organizational pathway		
Used in the third step in the ECP, During ECO approval	CPM (Clarkson et al. 2004)	✓			✓				Ex	
	CPM, C&CM (Keller et al. 2007)	✓			✓				Ex	
	Pro-E, UG, Solidworks, CATIA	✓			✓				I	G, To, SP
	Dymola, Simulia	✓	✓						I	SD
	Adams, Simpack		✓						I	ED
	Abaqus, Ansys	✓	✓						I	ES, ED
	Fluent, STAR-CCM		✓			✓			I	EFD

I- Internal; Ex-External; ED- Elasto dynamics; ES-Elasto statics; EFD- Elasto fluid dynamics; G-Geometric relationship; To- Tolerance relationship; SP-Spatial relationship; SD- System dynamics;

In the quantitative-objective category of tools, CAD tools, such as Pro-E, Unigraphics, CATIA, and Solidworks models the component's interdependencies at a concrete level of the design; that is, it captures the geometric interdependency of the components, such as size, shape, spatial, and tolerance relationships. The propagation chains are computed internally, and the results are visible to the user for interpretation. Thus, it can identify the propagation pathways only due to geometric interdependencies.

Similarly, computer aided engineering (CAE) tools such as Dymola and Simulia, a modeling and simulation software, can predict the propagation effects in the system due to their behavior, thereby identifying behavior pathways. Adams and Simpack are other tools that fundamentally extend the capability of Dymola and Simulia to an extent where system dynamics and the kinetics of material deformation can also be studied. Abaqus and Ansys evaluate both kinetics and kinematics of material deformation and their resulting behavior. Fluent and STAR-CCM evaluate the system behavior due to the fluid flow and the resulting deformation thereby evaluating the propagation effects through ambient and behavior pathways. In these tools, behavior pathways are evaluated internally.

5.5 Conclusion

This chapter presents a detailed review of the design evaluation tools and identified those that are currently used to reduce change propagation along with their limitations. A bi-level review of the design tools is conducted where, in the first level, those tools that cannot predict propagation pathways are eliminated while the rest are analyzed in detail at the second level. However, the essential points from this extensive review of the design evaluation tools are presented next.

FMEA, if conducted systematically, has the ability to reduce the function failure propagation effects. The limitations in the interaction model representation, use of functional representations, notion of functional dependency on individual components, reliance on designer's memory, lack of clarity in the definition of terms presents a myriad of problems to this tool. Despite these limitations, industry, especially automotive, widely uses this tool and believes failures can be prevented, which is not necessarily true. A similar argument holds true for the tools in the FMEA family, as identified in this dissertation.

The framework of FFIP and AFMEA design tool, though tailored for conceptual design, can be extended to support propagation prediction during later stages of the design. As it is focused only for conceptual design, it is out of scope of this research. RMS has in-built features to identify, but not limited to, the affected system level requirements from a component. Since geometric dependency of the product is not captured, it lacks the ability to identify propagation pathways, though it can output a set of components that are involved in achieving a function. Hence, it is also eliminated from the list of potential candidates.

CPM is another tool that has the potential to identify propagation paths due to change. However, the use of probabilistic modeling approach to model subjective information is strongly opposed by subjectivist researchers in the uncertainty field. Although it has glaring limitations, it is verified against the change propagation tool's requirements and identified that it is suitable for use in the production phase with an ability to determine potential propagation pathways due to geometric relationships only.

Review of the verification tools, such as CAD and CAE, also indicated that they are limited to identify only certain types of pathways: behavior, geometric, and ambient pathways. None of these tools, either individually or in combination, can identify organizational and variant pathways (see Table 5.10), which ***confirms*** the hypothesis H1.1.

RQ1.1	**:**	*What are the limitations of the existing design evaluation tools that are used to evaluate engineering changes?*
Hypothesis1.1	**:**	*Organizational and variant pathways are not evaluated by the existing design evaluation tools*
Status	**:**	***Confirmed***

The answer to this research question RQ1.1 forms the basis to investigate the research question RQ1, which is to develop a control to reduce ECs, as discussed in the next chapter.

5.6 Dissertation Roadmap

With an overarching goal of developing a new design tool, the existing design evaluation tools is reviewed in this chapter for their limitations. It has been understood in this chapter that organization and variant types of propagation pathways are not identified using the existing design evaluation tools. With this identified limitation, the next chapter (Chapter Six) introduces the proposed design evaluation tool. The overall progress of this dissertation is shown in Figure 5.14 in which a green tick mark is included to indicate the completed chapter.

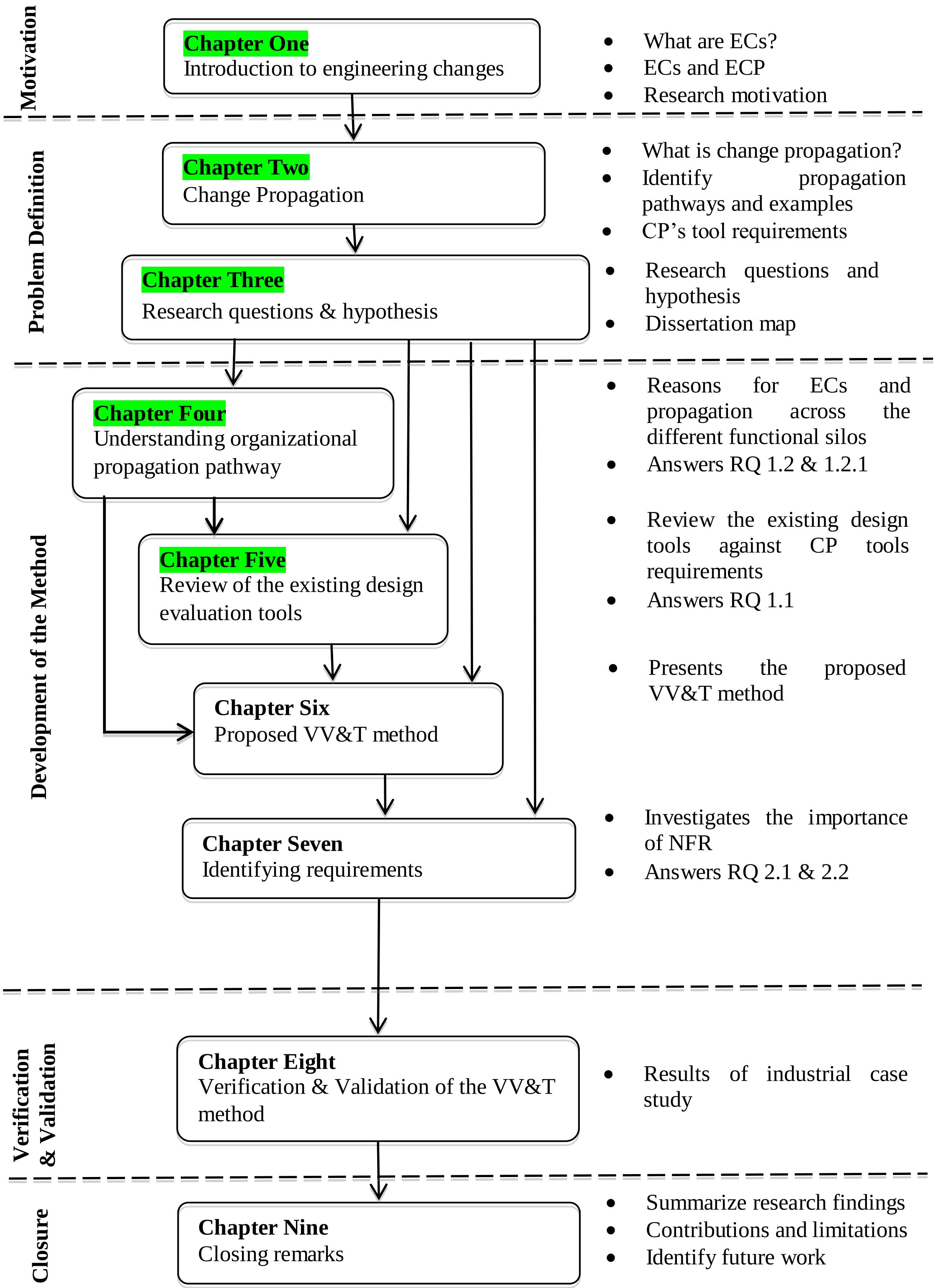


Figure 5.14 Dissertation Roadmap

CHAPTER SIX : PROPOSED DESIGN CONTROL TO REDUCE EC

This chapter presents the proposed design control to reduce engineering changes caused due to change propagation phenomena. The research question and the hypothesis that is specifically addressed in this chapter are:

RQ1:	*How to reduce the engineering changes caused due to change propagation?*
Hypothesis 1:	*A systematic planning of verification, validation, and test method can reduce engineering changes due to change propagation*

The key research question, RQ1, is addressed in this chapter. The proposed design control specifically addresses the limitations of the design evaluation tools identified in the Chapter Five, namely the lack of addressing organizational and variant propagation pathways. The rationale for selecting this hypothesis is detailed in Section 6.1, the limitation in the current verification, validation, and test (VV&T) planning method is presented in Section 6.2, and the proposed VV&T planning method is found in Section 6.3.

6.1 Why Verification, Validation, and Test (VV&T) Approach?

In complex systems, such as automobiles, aerospace, and space shuttle systems engineering methods are employed for system development. In such systems, the design evaluation is conducted through a systematic verification, validation, and testing (VV&T)

method, which is an important phase in the system development process (Kossiakoff and Sweet 2003). The term "verification and validation" has different definitions (Maropoulos and Ceglarek 2010). However, in this dissertation the definition that is widely accepted in the systems engineering domain is adopted in which, colloquially, verification is the process of checking if the system is built right while validation is the process of checking if the right system is built (Sage and Lynch 1998; Bahill 2005; Nagano 2008). Therefore, VV&T is a set of processes, tools and analysis techniques used for detection and correction of system flaws, thereby reducing the risk of system failures and ensuring customer satisfaction (Pineda and Kilcay-Ergin 2011). Design changes can introduce a chance of failure in the system due to propagation effects that has to be managed effectively to ensure safety and customer satisfaction on one hand while holding down the rework costs on the other (Kidd and Thompson 2000; Clarkson et al. 2004). One way of managing it is to evaluate these change propagation effects using numerical methods, as shown in Table 5.10, and physical tests, which are fundamentally different types of verification methods identified under VV&T plan. Hence, this approach of developing VV&T plan is adopted in this dissertation. Such an approach is recommended as one of the strategies to manage the ECs (Fricke et al. 2000).

A generic systematic approach for conducting VV&T exists in the software systems or embedded systems that are currently tailored to other industries depending on the user's needs. Standards describing this approach and the methods to tailor include ISO/IEC 15288, ANSI/EIA 632, CMMI (capability maturity model-integration), Government Electronics and Information Technology Association (GEIA) EIA 731-1, and IEEE/EIA 12207 (Hoppe et al. 2007). These processes are tailored typically for number of development phases and activities, the roles and responsibilities of individual actors, document formats, frequency of reports, and reviews (Tokmakoff et al. 1999). Ultimately, the success of validation depends on using a systematic method to plan VV&T techniques. Lack of planning has been identified as the major reason for the design changes during the design and development of a complex system (Pineda and Kilcay-Ergin 2011). This is the reason hypothesis H1 has been formulated to investigate the research question RQ1.

6.2 Existing VV&T Planning Method and its Limitations

A generalized systematic approach, based on the different standards listed above, is proposed by (Grady 1998; Grady 2007) on how to develop a verification plan, as presented in Figure 6.1. The preliminary step in this systematic approach is to collect the requirements and identify verification requirements. In the initial systems requirements review (SRR) phase during the system development stage, requirements verification is conducted in which a preliminary strategy is agreed upon how a requirement will be verified. This activity forms the basis to establish verification requirements that are formed after critical design review (CDR) phase in the system development process. Subsequently, a series of matrices are used to document the system requirements and its associated verification requirements, verification methods, and verification task management information. It is recommended that these matrices be created for every level in the system hierarchy, as shown in Figure 6.2. These steps can be used also to develop validation plans. Henceforth, this approach will be referred as 'existing method' for simplicity in this dissertation.

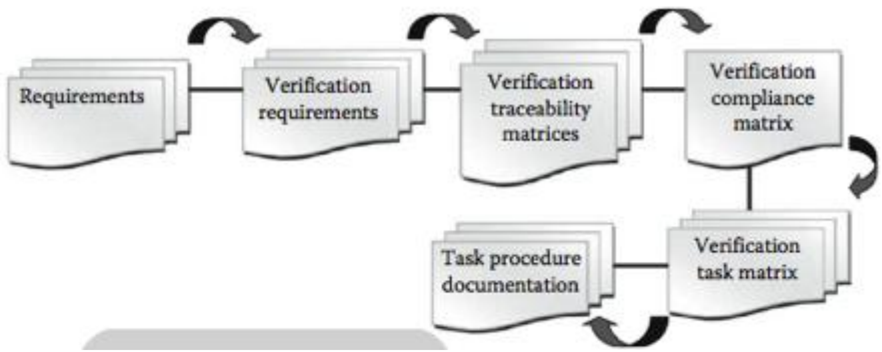


Figure 6.1 Systematic Approach for V&V Planning in Software Systems (Pineda and Kilcay-Ergin 2011)

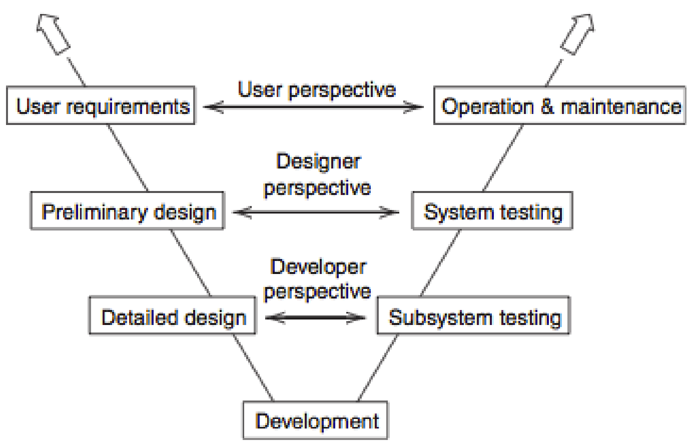


Figure 6.2 Generic 'V'-Model of System Development (Blanchard 2008)

The challenge in adopting this approach for addressing variant and organizational pathway of propagation in mechanical design is to incorporate a means to guide designers in identifying and documenting the different assembly configuration variants that are necessary to consider during the planning process. The current process lacks any such recommendation, which may be due to the following reason. VV&T is interpreted as a process limited to system development phase by many researchers as indicated by (Hoppe et al. 2007), thereby neglecting the production phase. Product variants are introduced only after the product has entered the production phase (Duhovnik and Tavcar 2002), as shown in Figure 6.3.

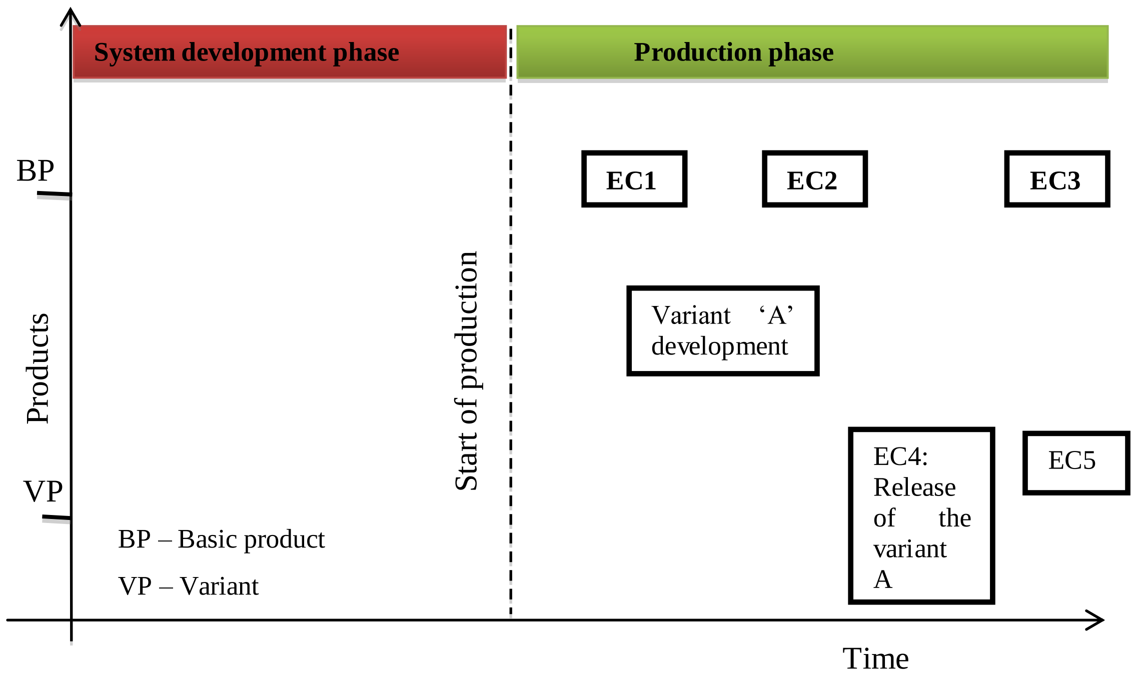


Figure 6.3 Variant Development and Introduction Timeline in the Product Life Cycle (Duhovnik and Tavcar 2002)

Another challenge in this approach is to enable designers to identify the organizational pathways due to multiple suppliers, which is also lacking in the existing verification planning method. Therefore, the proposed method includes these aspects into the existing verification planning method. However, it does not limit itself to these aspects but extends to incorporate suitable representation and qualitative computation schemes to conduct trade-off analysis to manage the testing schedule and associated resources for testing. The proposed method is presented next.

6.3 Proposed verification and validation (V&V) strategy to address configuration and organization pathway

A seven-step method is proposed to develop a design verification and validation plan that can potentially address configuration and organization pathways. This method is extended from the existing verification method of the software systems, as shown in Figure 6.1, by combining and introducing additional steps.

6.3.1 Seven-Step Method: An Overview

An overview of the seven-step method to develop design verification and validation test (VV&T) plan is presented in this section while the details of each step are explained in subsequent sub-sections using the brake drum heating problem described in the Chapter Two. The proposed seven-step method and its difference with respect to the existing method are shown in Figure 6.4 The first step in the process is to identify the requirements to be verified and validated, which is the same as the existing method. In the second step, system analysis is conducted using design structure matrices (DSMs) to enable designers understand the component interactions. In the third and the fourth step, the different assembly configuration variants that may stem from the product variants and different suppliers are analyzed. In the fifth step, the information obtained from the previous steps is documented, and the different tests for various requirements are identified, which is the same as the second step in the existing method. In the sixth step, acceptance criteria for the tests are identified, and this information is fed back to the previous step for completing the VV&T plan.

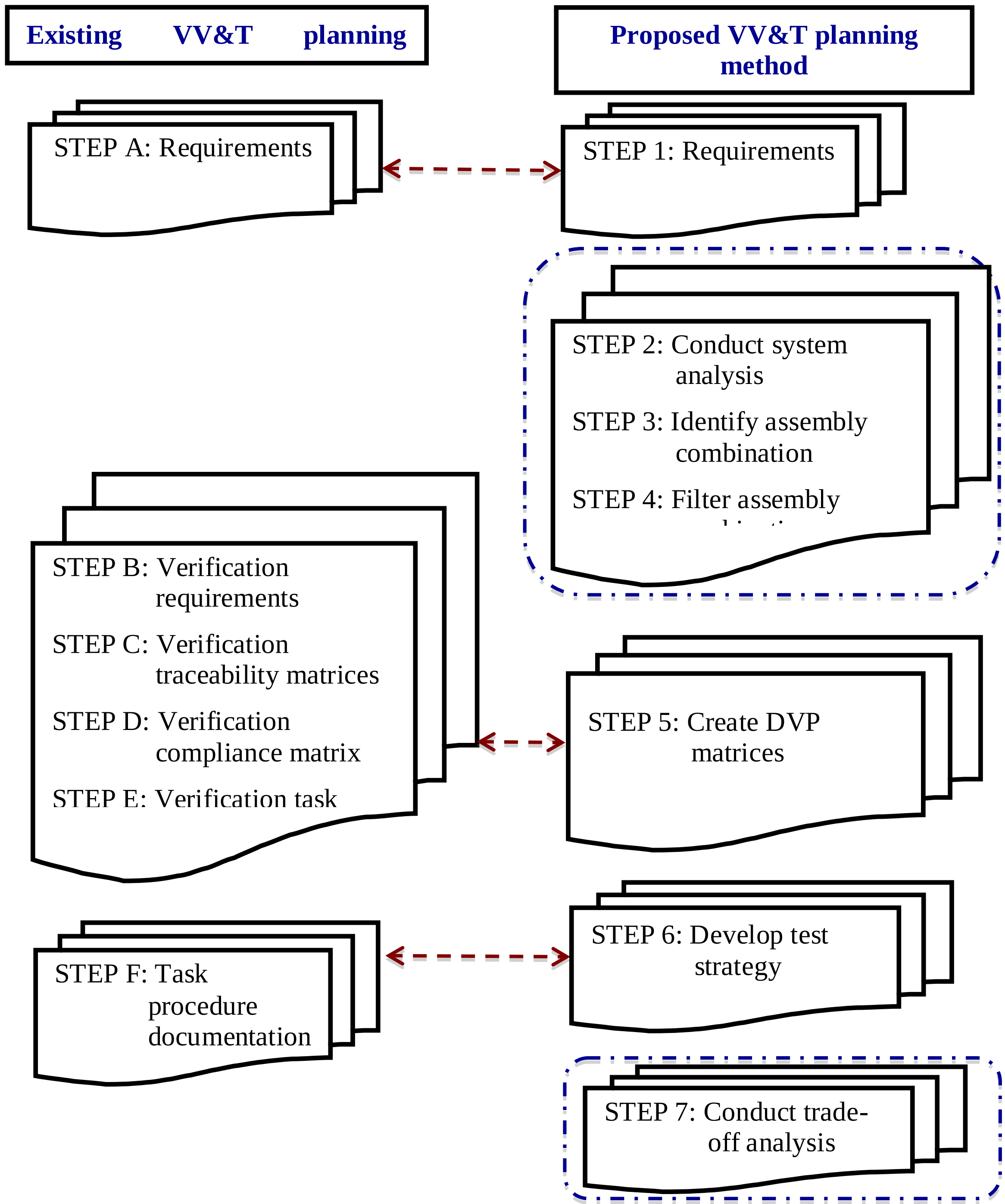


Figure 6.4 Existing and Proposed Method for Planning VV&T Activities

Finally, a trade-off analysis is conducted in order to prioritize the tests that can help in test scheduling and test resource management. The steps 2, 3, 4, and 7 (enclosed in a rectangle with a blue dotted line in Figure 6.4 are the new steps introduced in comparison to the existing method from software systems. In addition, step 5 in the proposed method is an integration of all the matrices as described in the Step C, Step D, and Step E of the existing VV&T method. Step 5 in the proposed method also includes the process of identifying verification requirements, which is step B in the existing method. The brown colored arrows indicate the comparable steps in both the proposed and the existing method.

6.3.2 Step-1: Requirements Identification

The first step in the process is to identify the design requirements of the system at the immediate higher level in the system hierarchy for creating validation plan, and in order to develop verification plan, identify the design requirements at the same hierarchical level of the component/sub system being changed. It is recommended to conduct both verification and validation tests based on the reasons of famous design failures that happened in the past century in different fields ranging from refrigerators to space ships (Bahill 2005). For instance, Hubble's telescope experienced a disastrous failure because of not validating the system level requirements, which eventually required a billion dollar to address the problem. Other validation failures include, but not limited to, the Chernobyl nuclear power plant (U.S.NRC 1986), space shuttle Challenger (Tufte 1997), and the Lewis spacecraft (NASA 1998). In another instance, General Electric (GE) implemented a design change in their refrigerators by replacing reciprocating compressors with rotary compressors in order to reduce the part count. Additionally, manufacturing processes were also changed to reap benefits in terms of manufacturing costs (Chapman et al. 1992). Although they did validation tests for their compressors, lack of verification tests lead to one million defective compressors. Interested readers may refer to (Bahill 2005) for other famous failures and their reasons. Thus, it is inferred ***conducting verification test is necessary but not sufficient.*** This makes further sense under the context of change propagation because for validating the requirements at any given level in the hierarchy, the system has to be tested as a whole rather than individual system elements, thereby providing an opportunity to identify and evaluate the propagation effects. This is true for changes initiated at any level in the system hierarchy. A similar approach to identify requirements at higher level in the system hierarchy is also recommended by practitioners of design for six sigma (DFSS) practitioners (Yang and El-Haik 2003) and reliability engineers in automotive industry (Hijawi and Levine 2009). In a 'V'-model of the vehicle, as shown in Figure 6.5**,** for instance, a material change in the brake lining should be tested for its both part integrity (verification) and the system in which it is assembled (validation); in this case, brake assembly. Subsequently, the brake assembly will be validated against the requirements in its immediate higher level, that is, the chassis level requirements and so on and so forth.

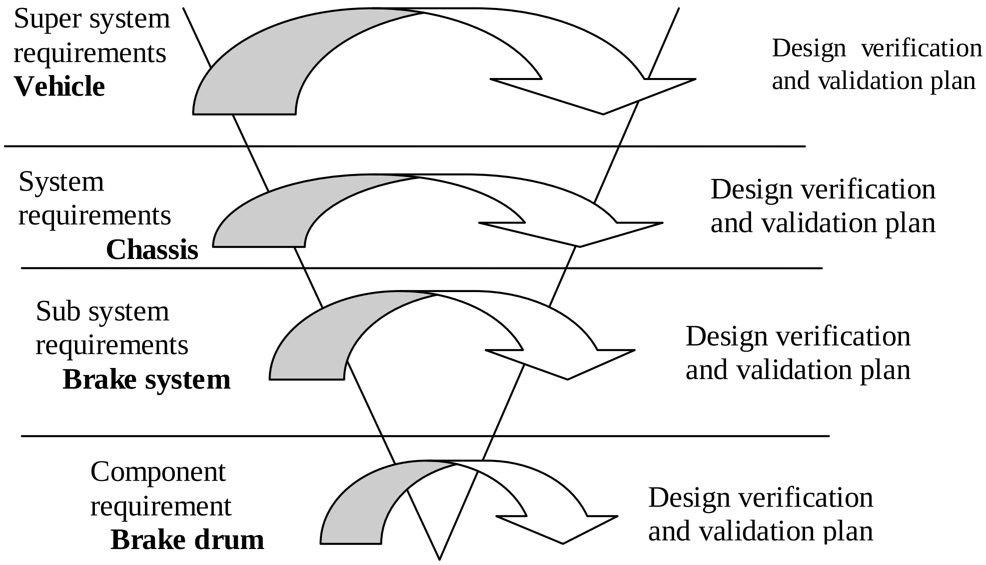


Figure 6.5 ‘V’ Model for a Brake System

A hierarchical ‘V’-model is used in this method because it is a widely used product model in automotive, aerospace, and software systems (Maropoulos and Ceglarek 2010). From a cognitive standpoint, such hierarchical structure of the product model facilitates humans to manage the large chunks of information into manageable ones (Ariyo et al. 2007). For instance, an aerospace vehicle may have 10,000 components. It is impossible to remember all these components and their relationship during design, as human memory capacity is limited (Miller 1956; Cowan 2011). Acknowledging the fact that representing the product in a hierarchical structure can also present challenges, this dissertation assumes that a product can be represented hierarchically using the best practices followed in automotive, aerospace, and software industries. As the focus of this dissertation is not to delve into the aspects of product decomposition and representation, it is not discussed any further in this dissertation.

The requirements that are to be considered for verification and validation test on each level of the system hierarchy depend upon the relationship between the requirements and the change component. In order to facilitate such identification of affected requirements at the higher level of the system hierarchy, a tool is presented in the next chapter, which aids in completing step-1 of the proposed VV&T method. In this tool, a matrix-based requirement-modelling scheme is proposed in which information between different design domains is captured. The different domains are:

(1) Requirements

(2) Functions

(3) Working principle

(4) Non-functional requirements

(5) Components

(6) Design parameters

(7) Test measures

(8) Tests

Using matrix operations, requirements that are affected due to a change in the components can be identified. The details of this modeling scheme are presented in Chapter Seven as the focus of the current chapter is to discuss the VV&T method. Industries not using such modeling scheme can still use this VV&T method by identifying specific type of requirements at the system level based on their team's experience.

Requirements that affect product design has been extensively studied in order to develop a taxonomy (Gershenson and Stauffer 1999). Based on this research, it is recommended to identify the legal, manufacturing, shipping, and service type of requirements. Legal requirements can include safety, reliability, and functional performance requirements; manufacturing requirements can include machine tool capability, ease of assembly, and raw material availability — not addressing these requirements during an EC change has caused propagated changes, as presented in Chapter Four; shipping requirements include packaging, warehouse, and transportation requirements; service requirements include diagnostics, maintenance, repair, customer-support, and spare parts requirements. Additional requirements for the aforementioned requirement categories can be identified from things gone right (TGR), or things gone wrong (TGW) reports. These reports are a requirement for companies who adhere to ISO/TS 16949 standards (Smith et al. 2004).

This step of identifying the requirements at different levels in the system hierarchy is the most important step to establish a robust validation plan, as pointed by several other researchers (Grady 1998; Kossiakoff and Sweet 2003; Blanchard 2008). After completing this step, system analysis is conducted to understand the direct interactions between the change elements, which is discussed next.

6.3.3 Step-2: System Analysis

The second step in this method is to analyze the system under consideration. In order to do so, a system boundary is defined to essentially breakdown the design problem into a manageable one, and subsequently, the elements within and external to this system boundary are identified. The elements identified within this boundary can be different depending upon where in the system hierarchy the change is initiated. For example, an engineer in an OEM will consider the vehicle as a system while the braking circuit is considered as a sub system. On the other side, a brake manufacturing company may consider the elements of the braking circuit as a system while their components as sub system. Hence, depending upon where the change is initiated in the system hierarchy, engineers may define their own system boundary.

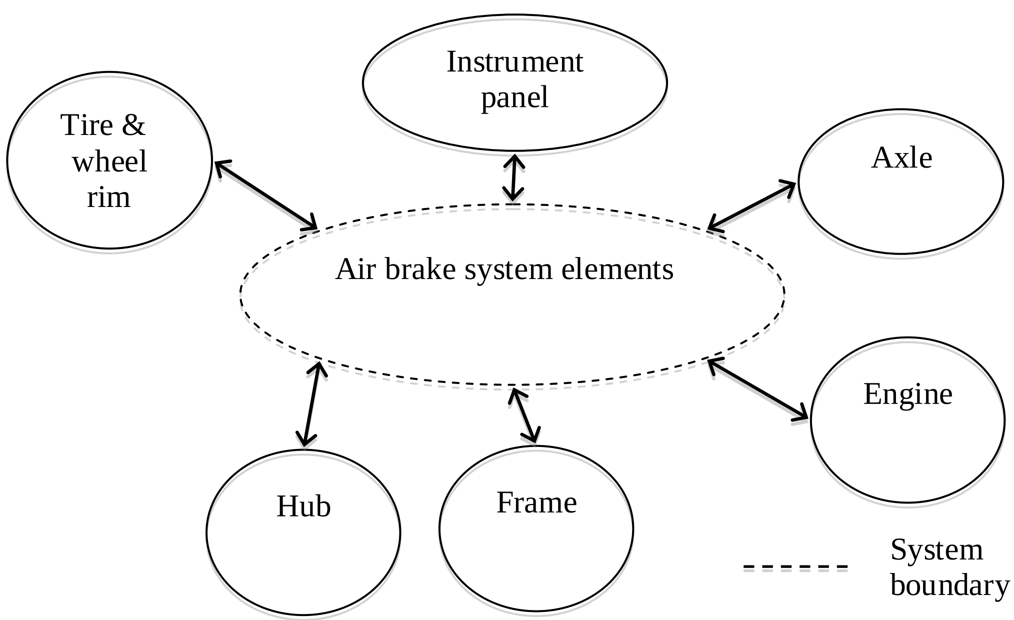


Figure 6.6 System Boundary Diagram with External Interfaces

As propagation effects are due to the interactions of the system elements internally and externally to other systems, it is essential to identify the interacting elements. These interactions has been one of the major causes of product failures, as indicated by several researchers (Eubanks et al. 1997; Cohen et al. 2000; Albers et al. 2004; Clarkson et al. 2004; Hijawi and Levine 2009). Therefore, the interacting system elements, within and external to the system boundary, are identified for an air brake system, as shown in Figure 6.6. The elements internal to the system boundary are not shown in it due to space constraints, but they are shown in Figure 6.7.

After identification of the system boundary and the interacting elements, a DSM is used to model the interactions between these elements. Such modeling approach has been extensively used to analyze the system, to decompose the system, and to integrate the system (Browning 2001). DSM, a matrix based representation, is chosen over several other representations, such as node-link diagrams (Keller 2006) and connectivity graph (Snider et al. 2006) because it enables easy visualization of the relationships between the elements of the complex system of moderate size and density. However, for systems with sparse number of elements, depending upon the user's preference, either of these representations can be advantageous in terms of ease of interpretation and visualization of the information. If the number of elements in the underlying graph network is large, the difficulty in visualization with models other than DSMs will be high. For a highly complex system, even DSMs can get difficult to visualize and interpret, but this representation is easily modeled in computers with which designers can be assisted to identify the interactions (Jarratt et al. 2005) . Therefore, matrix based representation is selected for modeling and analyzing the system interactions.

A DSM is a square matrix with identical column and row headers, as shown in Figure 6.7. To specifically analyze the interaction of the elements within and external to the system boundary, a grouping of internal and external elements is suggested, which is unlike the conventional approach of developing DSMs. A relationship between any two elements is indicated using binary digits '1' or '0' where '1' indicates interaction while '0' indicates otherwise. In order to improve the readability of the matrix, '0' may or may not be included.

After constructing the DSM, designers need to identify the change component in the row header of the matrix and read along the corresponding column in order to identify the interacting components, both internal and external to the system. These elements will be used in the next step to determine the different possible assembly combinations. However, before describing step-3 in this method, it is essential to analyze the interfaces of these interacting elements.

Interfaces are medium – solid, liquid, or gas- through which the interaction takes place, and they can come into existence in different states of the system, such as static and dynamic state. Identifying and analyzing such interfaces is considered as an essential step in systems engineering (Sage and Lynch 1998). Interface analysis can be conducted by identifying the working surface pairs (WSPs) and channel and support structures (CSS) (please refer (Albers et al. 2005) for further details on WSPs and CSSs) of the interacting elements and question: What would be the effect on the structural properties of WSPs and CSSs due to the change mode? Will there be any effect in the geometrical interfaces of these WSPs in the change mode? Past research has indicated that using channel and contact model approach has helped designers for a deeper understanding of the system (Albers et al. 2008; Alink et al. 2011). Thus, drawing parallels from that research, the above two questions are suggested in this step to analyze the interfaces. Subsequently, designers may address the interacting elements (other than the change element) because of this analysis. Thus, this Step-2 provides an opportunity for the designer, early in the design change process, to address propagation effects of the elements before conducting any verification or validation tests.

	Component name		Internal to the system boundary											External to the system boundary					
			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Internal to the system boundary	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
	E2 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 to the system boundary	Axle	L	1																
	Hub	M		1															
	Tire and wheel rim	N		1															
	Engine	O											1						1
	Instrument panel	P							1										
	Frame	Q						1	1	1	1	1					1		

Figure 6.7 Interaction Matrix

The above DSM is constructed based on the information provided in (Limpert 1999), internet resources (Bendix 2011), and author's prior work experience. Since the brake drum is changed, the interacting elements: tire and wheel rim, brake lining, and hub are analyzed for the change mode and used in the next step.

6.3.4 Step-3: Identification of Assembly Combinations

The purpose of this step is to direct the attention of the designers to identify the different assembly combinations, thereby providing an opportunity to consider the interactions of the change element with the variants of the affected element. As a step further, this step-3 also develops an identifier that can be used in the VV&T plans to facilitate test engineers for planning on which assembly combinations to be tested.

As shown in Figure 6.8, each element can have multiple suppliers and each supplier can have multiple variants (Balakrishnan and Chakravarty 2008). If there are ‘n’ affected elements, ‘m’ suppliers for each affected element and ‘q’ variants for each supplier, and then how to document all these different combinations? These different element-supplier-variant (E-S-V) combination leads to different assembly combinations, which is termed as *combination vector*. The question is: How to determine the number of combination vectors?

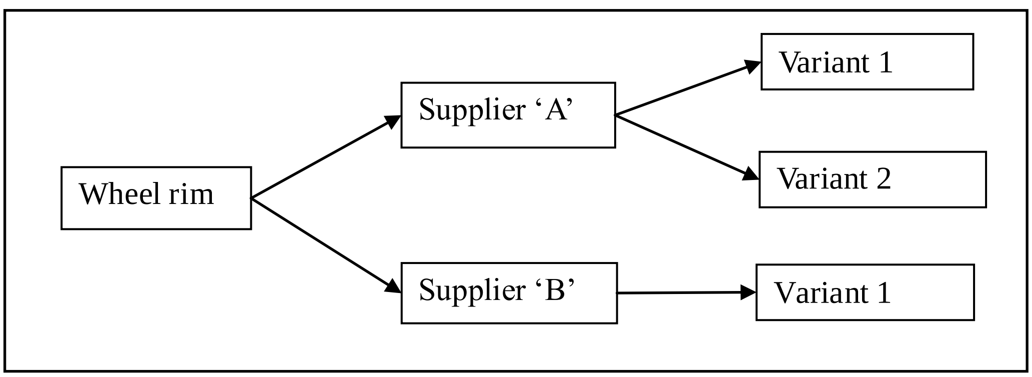


Figure 6.8 Element-Supplier-Variant Tree Diagram

In order to answer these questions, a template, as shown in Table 6.1, is proposed. In this template, the elements and their associated supplier and variants are identified. Symbolic representation of ‘S’ and ‘V’ is used to indicate suppliers and variants respectively for the purpose of illustration. Detailed descriptions can be used according to user’s choice for clarity purpose.

Table 6.1 Analysis and Selection of Variants

Affected Elements	Supplier	Variants	E-S-V identifier	Element-supplier-variant combination selection	Reason for selection/ rejection	No of E-S-V's identified per element
Brake lining	S1	V1	B.S1.V1	✓	Two suppliers supplying the same variant	2
	S2	V1	B.S2.V1	✓		
Wheel rim	S3	V3	W.S3.V3	✓	Two variants from different suppliers	2
	S4	V4	W.S4.V4	✓		
Hub	S5	V5	H.S5.V5	✓	Variant V6 is not used for this platform	1
	S5	V6	H.S5.V6	x		

An element-supplier-variant (E-S-V) combination is identified using the following identifier scheme: (element.supplier.variant). For instance, B.S1.V1 represents the element brake lining's (B) variant 'V1' supplied by the supplier 'S1'. The column next to the identifier column is recorded with the information whether or not the E-S-V combination is considered for further tests. It is essential to document this because some of these combinations can be consciously eliminated by logical reasoning. In the on-going example, the E-S-V combination H.S5.V6 is eliminated because this variant of the hub is used for a different platform with a different brake drum. Thus, it is not necessary to consider in the test planning activities. Similarly, a worst-case analysis can also be used to eliminate some of the E-S-V combinations. The E-S-V combination B.S1.V1 and B.S2.V1 are selected for further test planning activities because two suppliers are supplying the same variant. Therefore, it is not possible to eliminate one of the combinations from testing. The reasons for selecting a combination or rejecting a combination should also be documented in the appropriate column. In the last column, the number of selected E-S-V combinations is documented. Since two different E-S-V combinations are selected for further tests, the number '2' is indicated in the last column. These numbers are used in computing the total combination vectors that would stem from these selected E-S-V combinations using the following formula:

Equation 1

The number of combination vectors is the product of selected E-S-V combination for each element. In Equation 1, 'NE' indicates the total number of affected elements and 'i' indicates the counter for the elements, 'Ei' indicates the i^{th} element. Therefore, in the on-going example:

Equation 2

Equation 3

Thus, there are four combination vectors to be considered for test planning activities. These combination vectors are represented, as shown in Table 6.2, in the form of binary identifiers. Reading column wise for each combination vector, '1' indicates the presence of the corresponding E-S-V combination while '0' indicates absence. For instance, combination vector 'C1' indicates one of the assembly configuration that has to be tested contains the following combination of elements: B.S1.V1, W.S3.V3, and

H.S5.V5. Subsequently, analyze the interfaces for each combination vectors similar to the Step-2.

Table 6.2 Combination Vector Table

Affected Element	E-S-V combination	Combination Vectors (Read column wise)			
		C1	C2	C3	C4
Brake lining	B.S1.V1	1	0	1	0
	B.S2.V1	0	1	0	1
Wheel rim	W.S3.V3	1	1	0	0
	W.S4.V4	0	0	1	1
Hub	H.S5.V5	1	1	1	1

A question that may prevail in the readers mind is: How can writing down the knowledge already possessed by the designer is beneficial? Based on the research in cognitive psychology, the process of writing in itself is a thinking process (Kosslyn 1980; Irish 1999; Menary 2007). Human memory is divided into three systems: long term memory (LTM); short-term memory (STM); and working memory (WM) (Kosslyn 1980; Someren et al. 1994). LTM is a system where the information is stored for more than few seconds while STMs store information for a very shot interval. Recently, the theory of working memory is used over the theory of STM, which is defined as an integrated system for holding and manipulating information during complex cognitive tasks (Baddeley 2000). WM replaces the unitary storage system of the STM with a multi-functional integrated system. This system is activated during the complex cognitive task. During problem solving, which is a complex cognitive task, information stored in long-term memory is retrieved into the working memory whose contents are processed by external manipulation, that is, writing (Menary 2007). Thus, writing aids in thinking, and hence, it will facilitate designers to retrieve information either from their biological memory or from other external knowledge source, which may be asking questions to managers about the variants and suppliers.

The use of forms - tables, questionnaire form, questions, and pre-defined answer forms - has been used extensively to study the human cognitive processes in psychology and knowledge acquisition. The advantage of using such structured forms is it enables to generate direct requests for new information (Someren et al. 1994). Therefore, using such forms and asking the designers to fill the different sections in the form will enable them to understand the interaction of the change element with the affected element.

6.3.5 Step-4: Filter Assembly Combinations

Testing the identified combination vectors, as identified in the earlier step, for all requirements may not be feasible due to cost and time constraints. Therefore, a filtering method is required to reduce the number of combination vectors tested for each requirement, which is the purpose of this step.

Variants are created with a difference in one or more design parameters with respect to the parent element (Simpson 2005). It is also known in the engineering design that each design parameter contributes to some of the requirements. Therefore, if the requirements and the design parameters of the variant element are mapped with each other and the design parameters causing the variation are identified, then it is possible to determine those requirements that are affected by the variant's design parameters. ***Subsequently, those affected requirements shall only be tested with the combination vectors stemming from this variant.*** Thus, the number of tests to be conducted can be reduced, thereby saving cost and time. This whole scenario is illustrated using the example discussed thus far.

The design parameters for the wheel rim, as shown in Table 6.3, are obtained from (Page 1913; Knowles 2003; SAE 2007). In this example, two different suppliers are supplying two different variants of the wheel rim. The difference in the design parameters between these two wheel rim variants is assumed to be ‘wheel rim offset’ and ‘air ventilation area’, which are highlighted in yellow color. When these parameters are mapped to the brake system’s requirements, it is identified that one of the two parameters, that is, ‘air ventilation area’ has an impact on the two out of the three requirements while the other, ‘wheel rim offset’, has no relation. Therefore, requirements R2 and R3 should be tested with combination vectors consisting of both variants of wheel rim. However, as described in the problem definition section, the wheel rim with the low air ventilation area will retain more heat in the system and may cause performance degradation. Therefore, based on this worst-case analysis, the combination vector associated to the wheel rim possessing low air ventilation area is *only* selected for further testing. Assuming W.S4.V4 possess low air ventilation area, combination vectors, C1 and C2, associated with W.S3.V3 (highlighted with red color) are eliminated, as shown in Table 6.4. Therefore, only C3 and C4 combination vectors have to be tested. Further elimination is not possible, in this case, because these two combination vectors are due to two different suppliers.

Table 6.3 Requirements to Design Parameter Mapping

Brake system level requirements	Requirements index	Design parameters of the variant element, the wheel rim										
		Wheel rim offset	Radial stiffness coefficient	Radial elasticity	Air ventilation area	Hub hole diameter	Mounting hole diameter	Vertical stiffness	Material stiffness	Drop centre height	Rim diameter	Wheel height
Stopping distance should be less than 60ft	R1											
Stopping distance should not exceed 75 ft. after down hill test	R2				1							
Brake lining life should not be less than 40000miles	R3				1							

Table 6.4 Filtered Combination Vector Table

Element	E-S-V combination	Combination Vectors (Read column wise)			
		C1	C2	C3	C4
Brake lining	B.S1.V1	1	0	1	0
	B.S2.V1	0	1	0	1
Wheel rim	~~W.S3.V3~~	1	1	0	0
	W.S4.V4	0	0	1	1
Hub	H.S5.V5	1	1	1	1

6.3.6 Step-5: Design Validation Plan (DVP) Matrix

After identification of the requirements and the combination vectors, the next step is to create a design validation/verification plan (DVP) matrix. This matrix is a combination of verification traceability matrix, verification compliance matrix, and verification task matrix in the existing VV&T method. The fundamental difference between these matrices in the existing method and the proposed method is the documentation of combination vectors for each requirement. The template of the DVP matrix, as shown in Table 6.5, is divided into three sections, which are explained below.

6.3.6.1 Section I

The top left hand side portion of the matrix is referred to Section-I. In this section of the template, details relevant to the program/ design change are recorded. The ‘DVP#’ indicates the numerical identity of the document. The ‘DVP ver#’ indicates the version number of the document. The first revision may start with ‘00’ and subsequent revision might be indicated with ‘01’,’02’, etc. The revision of this document might be required for any addition/deletion of the tests due to requirement changes. The ‘program#’ indicates the numerical identification number of the program. The ‘program description’ describes the program such as ‘Brake drum improvement’**.**

6.3.6.2 Section II

The top right hand section of the matrix is referred to Section-II where the system for which this validation plan is created will be documented. In addition, the team members who involve in this process are also documented, and the space next to each team member’s name is used for sign-off. A group of participants from different departments are necessary for a robust validation plan (Kossiakoff and Sweet 2003). It is essential because the design engineer have to plan different tests based on the availability of the test equipment and facility. For instance, a requirement may require brake dynamometer for brake lining validation. Engineer may plan the test in the next month whereas the equipment may be reserved for several other tests for a long period. Hence, it is essential to involve the test engineers in planning for the validation activities in order to make a realistic plan. Similarly, virtual simulation and validation has been on the rise recently (Maropoulos and Ceglarek 2010); thus, including virtual test engineers in creating this validation plan will help develop a practical validation plan. In addition, it is found from the findings of Chapter Four how communication gap between the design department and other departments can lead to ‘propagated’ changes. Hence, a team-based approach is essential which is why it is proposed in this method.

In an extended enterprise setup, which is often times the case in automotive industries (Clark and Fujimoto 1991; Dyer 2000), suppliers and OEM share the test responsibility (Nagano 2008). In such setup, the final product is achieved through a set of firms in the value chain. Therefore, validation plans without considering the suppliers may lead to unrealistic plans and lead to expensive design changes, as indicated by (Nagano 2008).

The manufacturing department is also included in the document as they may have to plan for the pre-production trials, new tooling, manufacturing feasibility of the modified design, ease of assembly of the modified design, change of documents, logistics re-arrangement and planning, and gearing up for production introduction. Lack of communication between design and manufacturing has been highlighted as a major issue in the engineering change management by several researchers (Balcerak K J 1992; Huang and Mak 1997; Pikosz and Malmqvist 1998; Fricke et al. 2000; Jarratt et al. 2011); thus, involving them in this method can reduce the problems due to communication errors.

Table 6.5 DVP Matrix

DESIGN VALIDATION PLAN MATRIX

DVP #	210	Date	06.27.2011
DVP Ver #	3	System	Brake system
Program #	1155	Team	
Requirements doc #	2245	Physical test engineer	
		Virtual test engineer	
		Development engineer	
		Supplier	
		Manufacturing	
		Service	
		Marketing	

Requirement Index	Requirement	Test	Combination vector	V&V method	Test measurable	Acceptance criteria	Need for legal certification	Responsibility	Start date	End date	Remarks
R1	Stopping distance should be less than 60ft	As per FMVSS 121	C3, C4	Vehicle test	Distance in ft.	As per FMVSS 121	Y	A	07/10	08/10	Pass
R2	Stopping distance should not exceed 75 ft. after down hill test	As per FMVSS 121	C3, C4	Vehicle test	Distance in ft.	As per FMVSS 121	Y	A	07/10	08/10	Passed with C3, failed with C4
R3	Brake lining life should not be less than 40000 miles	Fit the lining in field vehicle and observe	C3, C4	Field demonst-ration	Lining wear in in	Average lining life > 40000 miles	N	B	07/10	10/10	Achieved 39000miles, team accepted

Service engineers are also included in the creation of DVP because they are required to conduct certain confirmation tests, such as accessibility studies, service time studies and training to dealers/mechanics about the use of modified design, and preparation for after-sales maintenance and repairs (Goffin and New 2001). Earlier research has indicated that service team has been involved only late in the design process thereby leading to products that are difficult to maintain and repair, which can lead to excessive warranty and service costs (Keith 1990; Anthoney and McKay 1992; Page 1993). Therefore, it is important to introduce experienced service engineers to address customer support requirements during the VV&T development stage itself, as implied by (Hull and Cox 1994), not only to support the planning activities, but also to maximize the value they add to the design (Knecht et al. 1993).

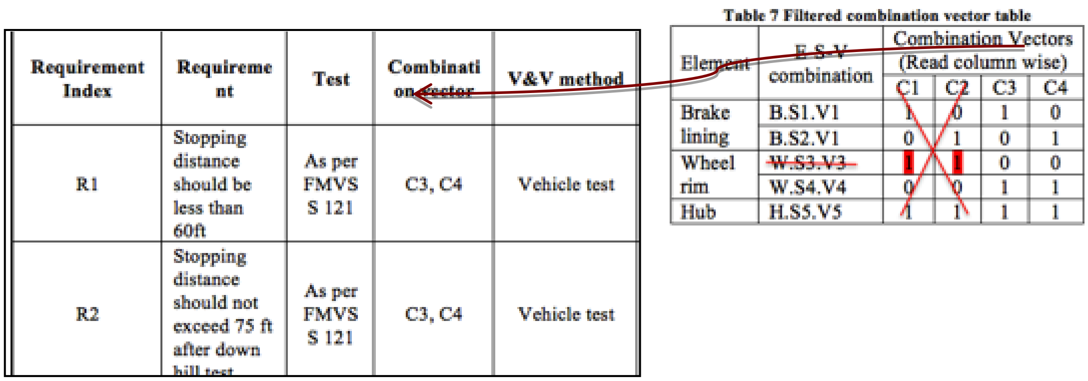
Finally, a team member from marketing is also included because marketing handles shipping, warehousing, and packaging (Gershenson and Stauffer 1999). Requirements for these sub-divisions of marketing can be further qualified by the marketing team, as they are aware of the feasible mode of shipping, associated packaging requirements, and warehousing methods based on how much customer is willing to pay and when they require the product. If the designer does not identify these requirements in Step-1, then it is possible to include at this stage and prevent a possible future design change. Shipping requirements are essential because past failures have indicated how shipping of electric high power transformers using railroad has caused weld stress failure (Stone et al. 2005). Evidently, designers did not consider the vibrations caused due to railroad transportation and hence, did not test it.

6.3.6.3 Section III

The bottom section in the DVP matrix is referred to section III. It starts from the series of column headers starting from requirements index to remarks column. In the first column, the requirements index identified from the requirements document, or the requirements from the requirements-traceability software (will be presented in the next chapter) is documented. In the second column, description of the requirements is documented while in the third column the test description is documented. This 'test' description column is equivalent to the 'verification requirements' step in the existing method.

In the fourth column, the combination vectors for each associated requirements are identified from Step-4, as shown in Figure 6.9. The combination vectors resulting due to product variants are applicable only to those requirements that are highlighted in Table 6.4. However, in the on-going discussion of the brake drum example, the combination vectors, C1 and C2, are eliminated based on worst-case analysis. The other two combination vectors, C3 and C4, are primarily due to two different suppliers, therefore, both of these combination vectors are tested for all requirements.

In the fifth column, appropriate validation/verification method is identified and documented. Analysis, inspection, test, and demonstration are the four different types of verification/validation methods (Pineda and Kilcay-Ergin 2011). In analysis V&V method, mathematical and numerical quantitative techniques are used to obtain evidence of whether or not the design meets the requirements. Test method is a well-recognized controlled test procedure to obtain performance data of the test sample where they can be in-door test, out-door test, or both. Inspection method includes verification/validation of the specification of the physical features of the product, such as receiving inspection in the quality department. Finally, in demonstration V&V method, the products are tested in real environment, such as field trials of the mobile devices. These different methods are identified based on the team's experience and the nature of the requirements. Readers can also refer to (Maropoulos and Ceglarek 2010) for the different V&V methods in mechanical design, which may be useful in completion of this column.



Requirement Index	Requirement	Test	Combination vector	V&V method
R1	Stopping distance should be less than 60ft	As per FMVSS 121	C3, C4	Vehicle test
R2	Stopping distance should not exceed 75 ft after down hill test	As per FMVSS 121	C3, C4	Vehicle test

Table 7 Filtered combination vector table

Element	E-S-V combination	Combination Vectors (Read column wise)			
		C1	C2	C3	C4
Brake lining	B.S1.V1	1	0	1	0
	B.S2.V1	0	1	0	1
Wheel rim	W.S3.V3	1	1	0	0
	W.S4.V4	0	0	1	1
Hub	H.S5.V5	1	1	1	1

Figure 6.9 Information Flow from Step-4 to DVP Matrix's Combination Vector Column

The sixth column header 'Test Measurable' indicates what quantity is being measured from the identified test. This column drives the team to think upfront in the project such as what is being measured. It also drives the test engineer to think about the requirement, availability, and capability of test instruments. In certain qualitative requirements such as 'easy to service,' this column drives the service engineer to explicitly spell out the test measurable in the best possible way, such as 'time to replace the brake lining'.

The seventh column ‘acceptance Criteria’ indicates what level of output quantity is accepted for the identified test. It forces the team to think and arrive at a consensus on what is expected out of that test. For example, for a requirement like ‘easy to service’, the acceptance criteria could be ‘time to replace the brake lining should be less than one hour’. The column ‘need for a legal certification’ is identified with symbol ‘Y’ or ‘N’ where the symbol ‘Y’ indicates the necessity for such certification while N’ indicates otherwise.

The ‘Test Responsibility’ column indicates the person who is responsible for conducting the test. In an extended enterprise business model, it might be possible to have a shared responsibility between the supplier and the OEM. In those scenarios, it is recommended to have both parties name written in the document. The ‘Start date’, ‘End date’ column represents the planned start and end date for each test. As the test engineers (both physical and virtual), suppliers, and other participants from different department are all included in the development of this plan, the dates committed by the engineers are expected to be more realistic based on the resource availability. Finally, the ‘remarks’ column records the test status, that is, whether a test meets or fails to meet the acceptance criteria. In addition, any rationale for accepting the result of a test that did not meet the acceptance criteria can also be recorded, as shown in the DVP matrix (refer Table 6.5) for R3. These managerial constructs in the DVP matrix are considered essential for an effective validation plan by reliability experts in automotive industry (Hijawi and Levine 2009).

Practical experience gained in a vehicle manufacturer company, located in USA, during a graduate internship lead to develop an understanding that acceptance criteria are not well defined for many of the requirements. This is because some of the products are nearly twenty-five years old, prior test results documentation is not linked to the product information, or there was no need for generating such information in the past. However, formalizing the VV&T activities necessitates engineers to document the acceptance criteria. In order to obtain such information, a supplementary step to support Step-5 is included in this process, which is discussed next.

6.3.7 Step-6: Development of Test Strategy

In this step, information about acceptance criteria is generated by conducting tests on the existing design for those requirements where such information is unavailable. These tests are termed as 'baseline' tests whose results can be directly used as an acceptance criteria for the modified design and documented in the DVP matrix, or these results can be marked up to improve the performance of the modified design from the baseline design. A table, as shown in Table 6.6, is recommended to document the baseline test strategies that are developed to define acceptance criteria for the modified design. In this table, the test for which the baseline evaluation is needed is identified in the 'Test' column, its associated combination vector in the successive column, baseline test description, and the acceptance criteria for the modified design in the last two columns respectively. Any one of the combination vectors is sufficient to conduct the baseline tests, as the goal is to identify acceptance criteria for the modified design.

However, when the modified designs are tested, they should be tested with as many number of combination vectors as identified in the DVP matrix.

Table 6.6 Baseline Test Strategy

Test	Combination for baseline	Baseline test description	Acceptance criteria for the modified design
As per FMVSS 121	C3	With the existing vehicle, identify the stopping distance	The new system should be at par with the existing vehicle

With this information, the DVP matrix can be completed with which the designer can follow up with various executives who are responsible for the test and ensure whether or not the modified design meets the requirements. Nonetheless, prior to conducting tests on these requirements, a trade-off analysis is recommended to prioritize and group tests in order to meet the cost and time targets of the project, which is conducted using Step-7.

6.3.8 Step-7: Trade-Off Analysis Matrix

The final step in the proposed VV&T method is to conduct a trade-off analysis on the developed test plan. Every requirement in the DVP matrix is tested at least once whereas some might be tested more than once because of varying scenarios, because of varying system states, or because of different V&V methods (Rosenberg et al. 1998). As cost and time are always the constraints during the implementation of an EC, comprehensive testing of the tests identified in the DVP matrix is not always feasible, thereby necessitating a trade-off analysis.

The intent of the trade-off analysis is to identify opportunities where some of the tests maybe eliminated, using previous test data, or some of them might be grouped in order to meet the budget and time constraints of the EC project. This can be achieved if only the criticality of each requirement is known in terms of the cost, the time, and the ranking of the requirements; in other words, how complex is it to verify each requirement. Thus, a metric termed 'verification complexity index (VCI)' is proposed to help direct the attention of both the test and design engineers.

The computation of VCI is achieved through a matrix-based approach where the requirements and the tests identified in the DVP matrix are mapped to each other. The matrix consists of a requirements column and the associated severity column, as shown in Table 6.7. Severity of a requirement refers to how important is that requirement relative to others, and the degree of severity is indicated using 1-3-9 cardinal numbering scheme to indicate low, medium, and high degree of severity respectively, as used in the quality function deployment's house of quality (HOQ) (Hauser 1988). Legal requirements, for example, will take the value '9' as the degree of severity because it is the most important requirement to be met while all other requirements are rated relative to this requirement. Such relative ranking schemes has been used and accepted in the engineering design community (Dym et al. 2002).

Table 6.7 Trade-Off Analysis Matrix

Requirement	Severity	Tests							Verification complexity index	Ranking
		A	D	D	D	D	D	D		
		T1	T2	T3	T4	T5	T6	T7		
R1	9	1	3		3		3		=9*[1*9+3*81 +3*9+3*81] = 2727	2
R2	9		3	3		3			=3159	1
R3	3							5	=135	3
	Cost/test	3	9	3	9	3	9	3		
	Lead time/test	3	9	9	1	3	9	9		
	Performance indicator	9	81	27	9	9	81	27		

In the third column ‘Tests’, there are two adjacent rows where the top row indicates the verification methods - such as A, D, F - while the bottom row documents the different test identified in the DVP matrix. The cells below these rows are where the requirements and the tests are mapped to each other. ***A relationship between them are indicated not simply by ‘1s’ or ‘0s’ but by the number of times a test has to be performed corresponding to that requirement.*** A test, for example, to establish 90 % reliability with 90% confidence level may require 22 samples which means 22 times of testing whereas a performance test evaluation could be a single run in a computer based simulation software (Kleyner and Sandborn 2008).

After populating all the necessary cells in the matrix, the cost associated with each test is indicated using cardinal numbering scheme of 1-3-9 where ‘9’ indicates high cost while ‘1’ indicates low in the ‘cost/test’ row. This numbering scheme is chosen to normalize the perception of cost of a test between a TIER I supplier and an OEM. For instance, a TIER I supplier who manufactures fuel injector will rate $100,000 to conduct a test as high, whereas for an OEM it could be rated as ‘Medium’. However, companies can form their own cost classification scheme depending upon what they consider to be high and low cost of testing, thereby minimizing the subjectivity of the evaluation within the company.

In a similar manner, the next row titled ‘lead time/ test’ is also identified using cardinal numbering scheme. Even in this case, TIER-I suppliers and OEM can have different views on what they consider long. For example, a month of field test for brakes is short for OEM whereas it might be long for a brake hose manufacturer. Again, these perceptions can be normalized by using the 1-3-9 numbering scheme. However, for internal verification tests, OEM and TIER-I suppliers can have their own system of evaluation depending on what they consider long and short time for testing. Performance indicator ‘PI’ is computed by multiplying the values in the cells ‘cost/test’ and the ‘lead time/test’ for each column.

With the information gathered above, it is now possible to compute the verification complexity index (VCI). The formula to compute VCI is:

Equation 4

The trade-off analysis matrix for the on-going discussion of the brake drum example is shown in Table 6.7. Since the requirements R1 and R2 are legal requirements, they are assigned ‘9’ in the severity column while requirement R3 is assigned ‘3’ because it is relatively less important than the other two. The numbers in the relationship cells indicate the number of times the corresponding test in the column has to be repeated. For example, T2 has to be repeated three times to partially verify requirement R1. VCI indicates that R2 is more complex to verify than R1 even though they are of equal severity. If the VCI numbers are equal, then it gives an opportunity to explore if the common tests between these two requirements can be grouped, thereby identifying the chance to save the cost and the time.

VCI's can be ranked to help focus the team's attention on a particular requirement to further explore the opportunities for trade-off consideration and prioritization of the tests. After focusing on high ranked VCI's, the tests required to satisfy the corresponding requirement can be prioritized based on the paired sequence of cost/test and lead-time/test, such as *(cost/test, lead-time/test)*. For instance, a low lead-time and high cost test can be considered as the top priority because if this test fails then it does not make sense to invest cost and time in setting up a long-lead time test. Subsequently the other tests that are necessary to verify a requirement are ranked using a zigzagging method, which is identifying the next pair in the Table 6.8 along an imaginary line that starts from (1,1), moving horizontally towards right till (9,1) pair, and moving diagonally towards (1,3) pair, so on and so forth till the line ends at (9,9) pair.

Table 6.8 Performance Indicator Pairs

Lead-time/test				
	High (9)	(1,9)	(3,9)	(9,9)
	Medium (3)	(1,3)	(3,3)	(9,3)
	Low (1)	(1,1)	(3,1)	(9,1)
		Low (1)	Medium (3)	High (9)
		Cost/test		

From Table 6.7, it is inferred that the requirement 'R2' has the highest VCI. So, the tests: T2, T3, and T5 get the primary focus whose performance indicator pairs are (9,9), (3,9), and (3,3) respectively. Using the zigzagging method, test 'T5' is prioritized as the first test to be conducted while tests 'T3' and 'T5' are prioritized as the second and third test respectively.

Reading column wise for the test 'T2', this test is repeated thrice for both requirements 'R1' and 'R2'. This may provide an opportunity for the team to consolidate this test and repeat it only three times instead of six, but it depends whether or not a different follow-up test is required after verifying each of this requirement. For instance, a 'stopping distance' test is mandatory immediately after conducting a 'down-hill' test in a braking system while an exclusive 'stopping distance' test is also required soon after bedding the brake linings. In such case, consolidation of 'stopping distance' test into one is not possible. Hence, the team has to ensure if there are any dependent tests before consolidating the test whenever there is an opportunity.

After completing these steps in the method, the designer has to follow up with various testing agency to ensure successful completion of the tests. This DVP matrix will have to be authorized by the team before a drawing is released for production.

6.4 Verification of the Proposed Method Against the Change Propagation Tool's Requirements

In Chapter Five, various design evaluation tools are reviewed, and it is identified that organization and configuration pathway are not evaluated. In order to address this limitation, a design control from the verification and validation standpoint is proposed in this chapter. The identification of combination vectors and testing them is the most important element in this VV&T method in view of addressing this limitation. This method's ability is now verified against the change propagation tool's requirements to show that this method addresses this limitation, as shown in Table 6.9.

Table 6.9 Proposed VV&T Method Vs. Change Propagation Tools' Requirements

Tools		Production stage	Propagation pathway type						Propagation chain	Evaluate the effects of propagation chain
			Behavior pathway	Functional dependency pathway	Geometric dependency pathway	Ambient pathway	Variant pathway	Organizational pathway		
Prior to ECO approval	CPM (Clarkson et al. 2004)	✓			✓				E	
	CPM, C&CM (Keller et al. 2007)	✓			✓				E	
	RMS (Shankar et al. 2010)	✓			✓				E	
After ECO approval	Pro-E, UG, Solidworks, CATIA	✓			✓				I	G, T, SP
	Dymola, Simulia	✓	✓						I	SD
	Adams, Simpack		✓							ED
	Abaqus, Ansys	✓	✓						I	ES, ED
	Fluent, STAR-CCM		✓			✓			I	EFD

	Proposed VV&T method	✓	✓		✓	✓	✓	✓		I	G, T, SP, SD, ED, ES, EFD

I- Internal; E-External; ED- Elasto dynamics; ES-Elasto statics; EFD- Elasto fluid dynamics; G-Geometric relationship; T- Tolerance relationship; SP-Spatial relationship; SD- System dynamics;

The proposed method evaluates change mode in Step-2 and Step-3, evaluates the propagation pathway through different verification methods, and evaluates different aspects, such as tolerance relationship, spatial relationship, and most importantly, it can be used in the production phase of the product life cycle. However, the method has to be validated to ensure if the theoretical estimation on the ability of the proposed VV&T method to address different propagation pathway types.

6.5 Dissertation Roadmap

This chapter presented the design control to reduce the design changes caused due to change propagation. The design control is a seven-step method to develop a VV&T plan. This method begins with identifying system level requirements, identifying and filtering assembly combinations, developing DVP matrix, developing test strategy in situations where acceptance criteria is not well defined, and finally, conducting trade-off analysis for prioritizing the tests. The validation of this VV&T method, which is conducted in multiple industries, and the results of the hypothesis, H1, is presented in Chapter Eight. However, the support tool that aids in Step-1 of this VV&T method for identifying system level requirements is presented in the next chapter. The overall progress of this dissertation is presented in Figure 6.10.

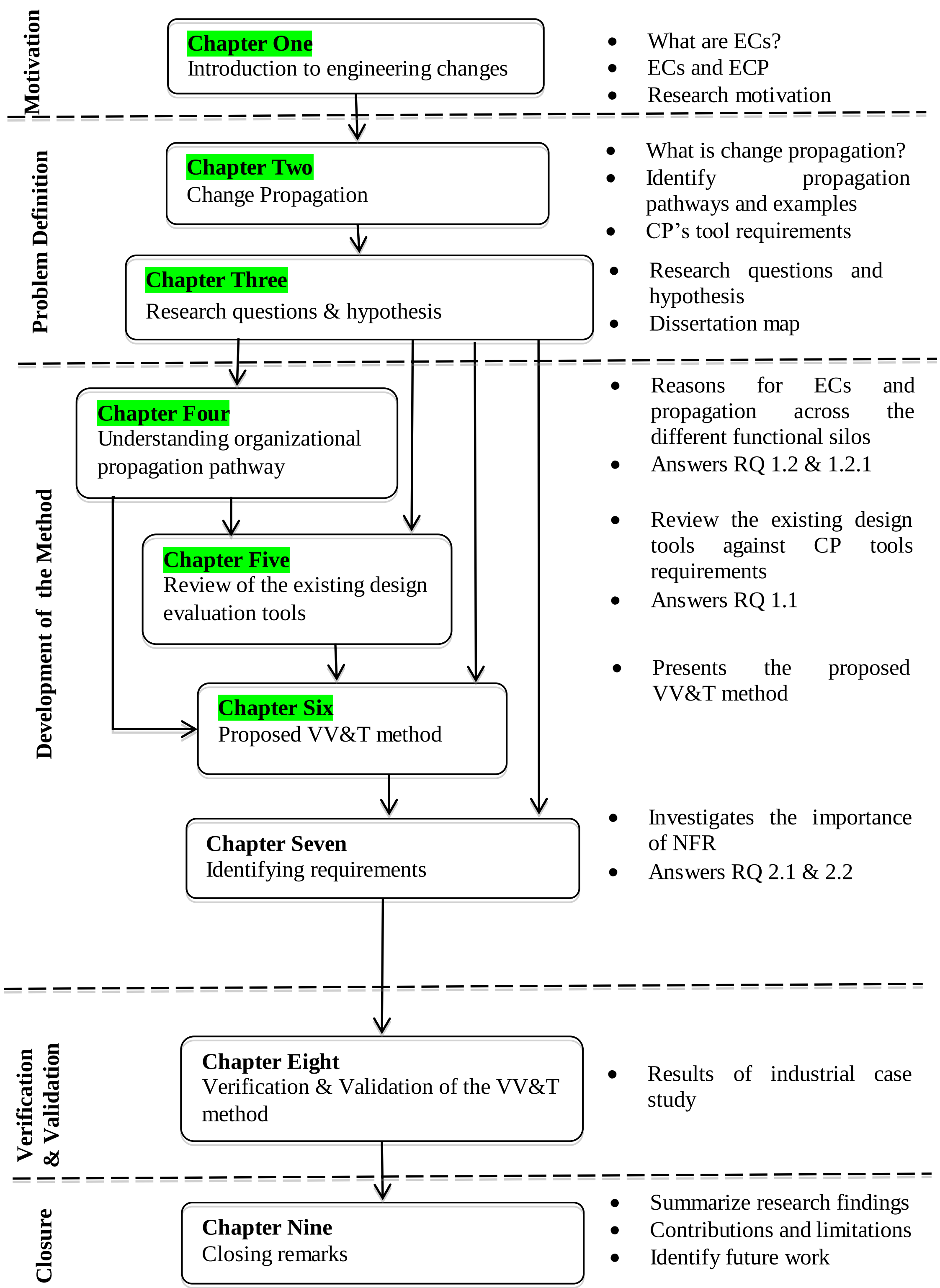


Figure 6.10 Dissertation Roadmap

CHAPTER SEVEN : A HIERARCHICAL REQUIREMENTS-MODELING SCHEME

This chapter presents a tool that aids in the completion of Step-1 in the proposed VV&T method in Chapter Six to identify the system level requirements. A hierarchical requirement-modeling scheme is proposed by (Ezhilan 2007; Maier 2007) as a tool to aid in identifying such requirements. This modeling scheme is advanced in its state-of-the art by including non-functional requirements (NFRs) in the scheme. To this end, two research questions, RQ 2.1 and RQ 2.2, as presented below, are investigated.

RQ 2.1	**:**	*How do non-functional requirements (NFRs) contribute to the design process in mechanical system?*
Hypothesis 2.1	**:**	*NFRs drive design change decisions*
RQ 2.2	**:**	*Where in the sequence of domains, as presented in the existing modeling scheme, should the NFRs domain be incorporated?*
Hypothesis 2.2	**:**	*NFRs can be sequenced after working principle domain*

These research questions are investigated using case study research method, which is selected based on the answers to the following questions presented in Table 7.1.

Table 7.1 Justification for the Choice of Case Study Research Method

Research Question	Question	Answer	Justification
RQ1.1	Form of the research question – is it exploratory or explanatory?	Exploratory	The research question ***explores*** how NFRs contribute to the design process
	Does the researcher require control over the events?	No	The goal is to understand the existing process. Hence, no control over the events is required
	Is the phenomenon under study a contemporary or a historical event?	Contemporary	The design process under study is a contemporary event

The two research questions are exploratory in nature as the goal is to explore if the NFRs contribute to the design process in the mechanical system. The researcher also does not require any control over the events, as the objective is to study the existing process and draw inference. Finally, the event under study is a contemporary one because the existing design process is studied to understand if NFRs drive the design change decisions. Thus, based on these reasons, case study research method is selected as a suitable research strategy to investigate these research questions. The hypothesis "H2.1" is selected because changes to the design are expensive and time consuming, as indicated in Chapter One Section 1.4.

The motivation to include NFRs in the modeling scheme is presented in Section 7.1, the research method is presented in Section 7.2, the results of the research question "RQ2.1 and RQ 2.2" are presented in Section 7.3 and Section 7.4 respectively, and finally, the proposed modeling scheme is presented in Section 7.5.

7.1 The Motivation to Study Non-Functional Requirements

A requirement modeling scheme is needed to help designers in identifying the effect of change of one component on the others through requirements and, in turn, on system level requirements. This scheme should also help designers in capturing conceptual design information in domains of interest thereby visualizing the relationships of the captured design information both between domains and within a domain (Maier 2007). The main working steps in the systematic design process encompassing a set of design activities (Pahl et al. 2007) is termed as a domain. The motivation for including NFRs is discussed next after a brief overview of different requirement modeling approach in the engineering design.

7.1.1 Overview of Requirement Modeling Approaches

In engineering design, requirements may be modeled using tools and management approaches such as Quality Function Deployment (QFD) (Hauser 1988; Olewnik and Lewis 2005). The House of Quality (HOQ) is a tool within the QFD approach that supports information processing and decision making in product design (Hauser 1988; Olewnik and Lewis 2005). Essentially, it is a conceptual map that relates the customer requirements and design and manufacturing information through the following sequence (Hauser 1988; Olewnik and Lewis 2005): customer requirements to engineering requirements, engineering requirements to part characteristics, part characteristics to key process operations, and key process operations to manufacturing requirements. These sequence of domains captured in the HOQ tool is presented in Figure 7.1.

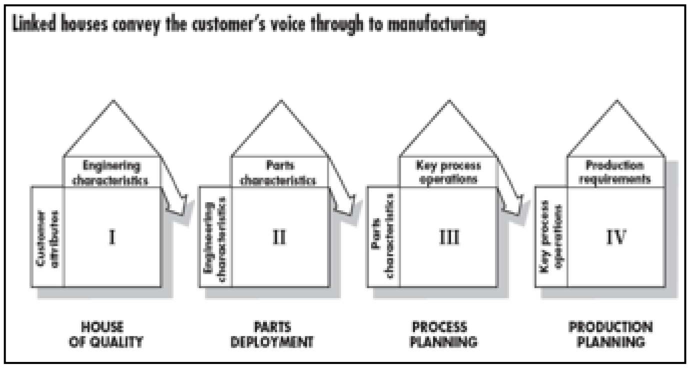


Figure 7.1 House of Quality (Hauser 1988)

The HOQ helps the designers in identifying customer requirements, both explicit and implicit (Huang et al. 2000). Though it has other managerial advantages, the process of mapping the relationship strength between customer requirements and engineering requirements in the initial stages of the design process, specifically for a *de-novo* design, has the potential to mislead the design effort towards unimportant customer requirements (Olewnik and Lewis 2005).

The systematic design process is broadly classified into three stages:

1. Conceptual stage,
2. Embodiment stage, and
3. Detailed design stage.

Several steps are listed in the conceptual and embodiment design stage before the designer is able to define the engineering characteristics from the initial set of customer requirements (Pahl et al. 2007). The steps in the conceptual design stage are:

STEP I : Identifying essential problems

STEP II : Establishing function structures

STEP III : Search for working principles and working structures

STEP IV : Combine and solidify into concept variants

STEP V : Evaluate against technical and economic criteria

STEP VI : Developing principal solution (concepts)

STEP VII : Preliminary form design, material selection, and calculation

The step VII is in the embodiment design stage and determines the engineering characteristics.

The HOQ maps the customer requirements and the engineering characteristics in the first step, but the systematic design process requires seven intermediate steps to determine engineering characteristics from customer requirements. Therefore, it is essential for a requirement-modeling scheme to capture this information found in the intermediate steps. This fundamental difference is partially overcome by a modeling scheme that maps three domains: requirements to function, function to components and components to engineering characteristics (Mocko 2007). However, it does not capture the necessary steps required to transform from the customer requirements to engineering characteristics as described in the systematic design process. This limitation has since been addressed by extending the number of domains to seven (Maier 2007):

1. Requirements (R)
2. Functions (Fn)
3. Working Principles (WP)
4. Components (C)
5. Design Parameters (DP)

6. Test Measures (TM)
7. Tests (T)

Various other requirements modeling approach have also been reviewed extensively for their ability to analyze different factors such as requirement elicitation, analysis, allocation, traceability/tracking, verification/validation, taxonomy and propagation (Maier 2007). The seven-domain requirement-modeling scheme, as shown in Figure 7.2, is developed to potentially overcome the limitations identified in this review, first of its kind in the mechanical engineering domain. Hence, this will be taken as the benchmark *existing modeling scheme* when comparing approaches in the following sections.

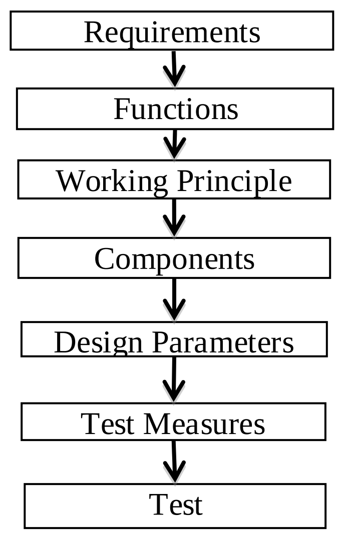


Figure 7.2 Seven-Domain Matrix Based Modeling Method (Maier 2007)

These seven adjacent domains are mapped explicitly by designers populating matrices such as Requirements to Functions (R-Fn), Functions to Working principle (F-WP) and so on. Nevertheless, this modeling scheme also has the following limitations:

1. The mapping of STEP IV to VI is not captured between the domains "WP' and "Components".
2. The use of "component" domain extends itself into the embodiment design stage. The primary step in the embodiment design stage is to identify the embodiment determining requirements such as spatial constraints, safety, ergonomics, production, and assembly requirements (Pahl et al. 2007). This model does not take into account of these types of non-behavioral requirements.
3. This model has an underlying assumption that the components are manifested only from functional requirements, which may not hold true because of the limitation stated above in (2).

The omission of the activity of defining the embodiment stage requirements, which are often non-behavioral and solution specific, in this modeling scheme, leads to the following motivating question: **Do non-behavioral requirements contribute to the realization of a product artifact?** It is discussed next after a brief introduction to what are functional and non-functional requirements.

7.1.2 What is a Functional and Non Functional Requirement?

In the literature that addresses classification of requirements, there appears to be a broad consensus with respect to the definition of Functional Requirements (FRs). This consensus does not appear when discussing Non-Functional Requirements (NFRs) (IEEE 1998; Kotonya 1998; Lamsweerde 2001; Glinz 2007). Essentially, the definition for FRs is either “what a product must do (Robertson 1999)”, “a function that a system must be able to perform (IEEE 1990)”, or “what the system should do”. Others have slightly refined this view by saying that the FRs are the resulting behaviors of the system (Glinz 2007). In all definitions, the FRs is describing either an action or function of the system, either desired or actual. Though there appears to be no strong consensus in the definition of NFRs, several definitions are offered (IEEE 1990; Mylopoulos 1992; Davis 1993; Anton 1997; IEEE 1998; Kotonya 1998; Jacobson 1999; Wiegers 2003; Glinz 2007; Chung 2009). NFRs refer to quality attributes as it describes the quality of the system (Gross 2001), goals (Roman 1985), and constraints (Glinz 2007; Chung 2009). For this research, NFRs are defined as the requirements that describe the non-behavioral (non-action, non-function) aspects of the product/system such as performance targets, usability measures, reliability and durability objectives, interface requirements, and other physical specifications.

7.1.3 Importance of Non Functional Requirements

NFRs plays a vital role in the system development and serves as the filters and selection criteria to choose a decision among the myriad of decisions (Mylopoulos 1992). However, NFRs are often considered late in the system development process (Chung 1995) where late consideration may lead to conflicts and ambiguities in these requirements (Feather 1993). Also, late consideration of NFRs leads to expensive design changes (Boehm 1987). Hence, it is recognized that NFRs should be considered and addressed from the beginning of the system development (Chung 1995). Literature also suggests that NFRs are the most expensive and difficult to deal with (Cysneiros 1999;

Cysneiros 2004). Thus, while NFRs are recognized as critical in design, they are not well understood or modeled.

7.1.4 Challenge with Non Functional Requirements

The difficulty in addressing NFRs arises from the fact that they are often subjective, relative, and interacting (Chung 1999). They are subjective as the same requirements can be viewed, interpreted, and evaluated differently by various stakeholders, such as manufacturing engineers, machinists, suppliers, and sales. For instance, ride and handling in a car is evaluated subjectively by professional test drivers, by focus groups and by the engineering staff as they attempt to translate the "ride and handling" into engineering metrics of vibration frequency, amplitude, and energy dampening. In subjective evaluation, one evaluator can be satisfied with the ride while another may not be satisfied. NFRs are relative because the importance and interpretation may vary depending on the particular system being considered. For example, in the suspension system, the target mass of the subsystem may be set as a critical target for the supplier, but the integrating assembler may be willing to accept a heavier suspension if it can result in mass savings in other systems. NFRs also interact with each other; one NFR may have a positive effect on the system while it might introduce a negative effect on a different NFR. For instance, in cargo vehicle design, low rear axle weight is preferred in unladen vehicle to maximize the payload. However, this will adversely affect the wheel locking deceleration of the vehicle in unladen condition.

7.1.5 Distillation into Research Questions

The vital role of NFRs in the success of a system is emphasized extensively in literatures (Roman 1985; Boehm 1987; Mylopoulos 1992; Feather 1993; Chung 1995; Landes 1995; Cysneiros 1999; Gross 2001; Cysneiros 2004; Glinz 2007; Chung 2009). Interestingly, much of the attention to requirements modeling has been in the software engineering arena and recently applied to different fields such as banking and hospital. The fact that NFRs are vital in different field provides the basis to assume that it will be equally important in the design of mechanical systems. However, there exists limited literature explaining the importance of NFRs in the design of mechanical system. The crucial role of NFRs in the success of a system combined with the limitation presented in the existent modeling scheme provided the motivation, which distilled into the research questions RQ 2.1 and RQ 2.2. These questions are investigated using a case study on the design and development of rear-bumper re-enforcement, which is discussed next.

7.2 Case Study

A case study research method is selected to investigate the research questions "RQ2.1 and RQ 2.2" based on the answers to the questions that help to choose appropriate research strategy presented in Table 7.1. It is an empirical research method used to investigate a contemporary phenomenon, focusing on the dynamics of the case, within its real life context (Roth 1999; Yin 2003). Specifically, the role that NFRs have in an industrial oriented development project is of interest, rather than hypothetical design situations. Case studies are widely deployed in design research (Roth 1999;

George and Bennett. 2005; Flyvbjerg 2006; Sheldon 2006; Stowe 2008). Several design methods have been developed based on the extensive observation in the industry and from the result of large informal case studies (Frost 1999; Pahl et al. 2007; Teegavarapu et al. 2008). Hence, a case study approach is used to investigate these research questions.

An industrial case study from an automotive OEM is considered here. The author worked as an intern in an automotive OEM, a leading school bus manufacturer in the USA, on an eight-month project. The project was initiated by the author as a cost reduction proposal, yet it involved a senior management team in the design department, managers in manufacturing, a validation team, production workers, and service and marketing representatives. The objective was to develop a rear-bumper re-enforcement at a cost below that of the current product. This project was not considered an incremental design of simply tweaking the design parameters of the current product; rather, an open-ended approach was taken.

7.2.1 Method

This section describes the objectives of the case study, case requirements, rationale for the data collected, how is it collected, what is inferred, and the possible conclusions that may come out of this case study.

The objectives of this case study are to determine:

1. If NFRs should be considered in the sequence of domains, and
2. Between which of the two consecutive domains in the existent modeling scheme, the NFRs can be included.

To address the first objective, the design activities involving a design change, and/or influenced the decision making process are analyzed to identify if they are influenced by NFRs. The result of this analysis will determine the importance, and hence, the need to consider the NFRs in the existing modeling scheme. If the outcome of the above analysis is true, the second objective in this case study will be addressed.

To conduct this study, a design project undertaken with an open-ended approach will be an ideal candidate. Such approach provides an opportunity for the designer to engineer a product by following the steps provided in the systematic design process from the conceptual design stage, for the existing modeling scheme is meant for capturing conceptual design information. If NFRs influence the early design changes, capturing such information in the conceptual design phase using such modeling scheme will help identification of the affected NFRs of a change component when ECs are conducted later in the production phase, which is the focus of this dissertation. Therefore, a design project with an open-ended approach starting from the conceptual design is preferred.

Data that is necessary for conducting this study is to understand what factors in a design activity lead to design changes, and if that factor is of non-behavioral in nature, or simply, a non-functional requirement. Thus, a design activity is defined as an activity in the design project if it is found either explicitly or implicitly in the systematic design process described by (Pahl et al. 2007). These design activities in the project are identified from multiple sources of data, such as documents and participant observation — the author acts as a participant observant in this study. Documents include digital computer-aided design (CAD) files, e-mails exchanged between the author and different executives involved in the design project, design review document, presentations, and meeting notes. CAD files are reviewed to understand what is changed between different file versions and the date of change. E-mails are traced back to this date of change for understanding the context in addition to the design review documents and meeting notes whenever necessary. These sources of data are used to triangulate the information obtained on the factors in a design activity causing the design change. The confidentiality agreement between the author and the OEM limits sharing this information in this dissertation. The design activities identified from the above listed data sources are listed and coded numerically in Table 7.3**.**

Each of these activities is analyzed if they led to a design change. If the answer is in affirmative, the factors that lead to this design change are analyzed using multiple sources of data to develop insights. In order to obtain what domain these factors belong to, the main working steps that help designers to develop engineering characteristics from customer requirements are identified with a domain name, as shown in Table 7.2, which is subsequently associated with the identified different design activities, as shown in Table 7.4. This protocol to study the first objective is pictorially presented in Figure 7.3.

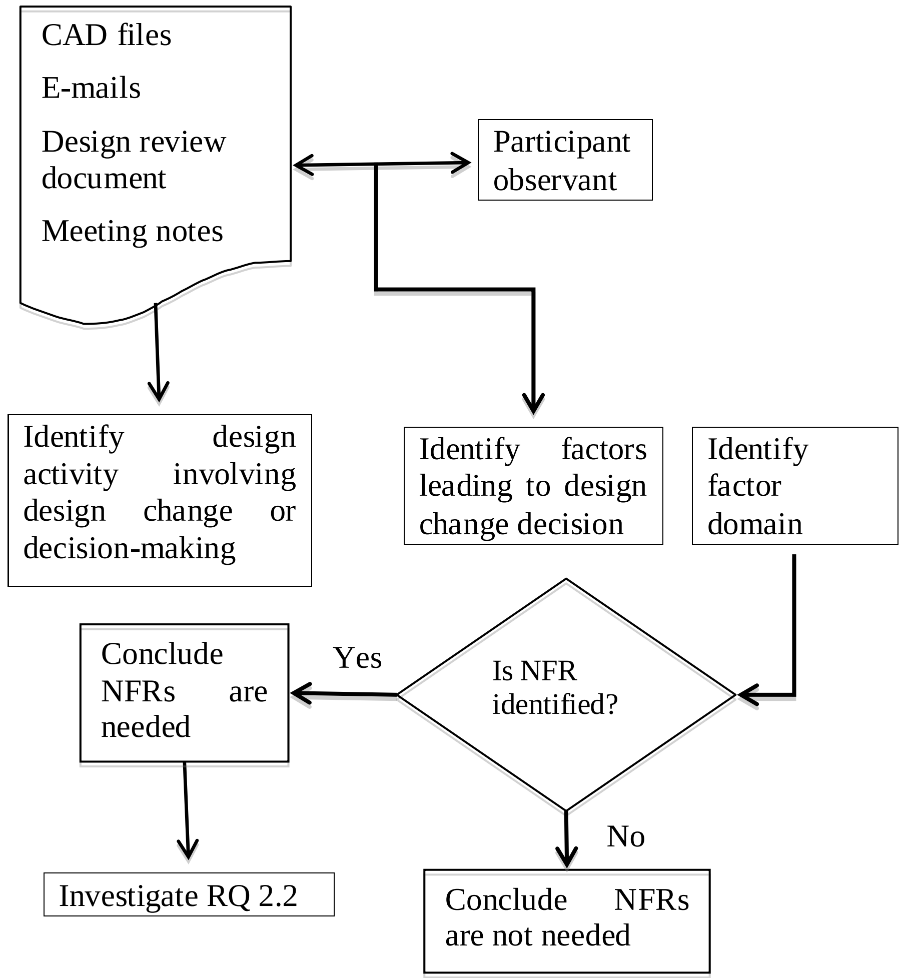


Figure 7.3 Case Study Protocol to Investigate Research Question 'RQ 2.1'

Table 7.2: Domain Definition

Main working steps identified in systematic design process	Domain Name
Requirements list (requirements gathering, clarification, documentation, updating requirements)	FR and NFRs
Establish Function structures	Function (Fn)
Search for working principle (WP) and working structure (WS)	WP, WS
Combine and firm up into concept variants	CV
Evaluate against technical and economic criteria	Design Review (DR)
Principal Solution (working concept)	WC
Identify embodiment determining requirements	NFRs
Preliminary form design, material selection and calculation	Design Parameters (DP)
Select best preliminary layouts, refine and improve layout	Component (C)
Evaluate against technical and economic criteria	Design Review (DR)
Prototypes	PR
Test	Test

Table 7.3: List of Design Activities

List of Activities	Activity #
Requirements gathering (Design requirement document, NSTSP[1] experienced executives, and other internal sources)	1
Requirements clarification	2
Benchmark reports	3
Literature review	4
Functional concepts	5
Concept review with the engineering manager	6

[1] NSTSP : National school transportation specifications and procedures (NCST (2010). National School Transportation Specifications and Procedures. Warrensburg, Missouri, University of Central Missouri.

Performance, serviceability, durability requirements gathering	7
Manufacturing requirements gathering	8
Previous test reports gathering to identify and clarify performance requirements	9
Performance requirements finalization with a design review	10
Concept development (3D packaging layout)	11
Material selection, sizing, stress, etc.,	12
Review with experienced engineers - Generates new manufacturing requirements based on their experience	13
Two out of four concepts were selected from the design review based on cost, service and manufacturing constraints	
Product costing conducted for the identified concepts- identification of potential cost savings – cost target fixed	14
Study of manufacturing process – identification of new manufacturing constraints	15
Concept refined with a new introduction of part to suit new manufacturing constraints in the earlier step	16
Design review conducted with two developed concepts	17
Additional requirements for galvanization and manufacturing accessibility was introduced	18
Design review conducted for program approval	19
Release of DFMEA[2] and DVP[3]	20
Release of conceptual prototype #1 drawings	21
Request for FEA[4]	22
Conceptual prototype #1 received	23
Fitment trials conducted in the vehicle using conceptual prototype #1	24
Concept refined to meet manufacturing requirements of safety and ease of assembly	25
Existing manufacturing process simulated and points of design improvement to suit manufacturing were noted	26
Detailed tolerance analysis conducted, concept refined	27
Manufacturing review reported to program manager	28
Performance test conducted to verify strength aspect (physical test)	29
FEA reports received	30

[2] DFMEA :Design failure mode and effect analysis
[3] DVP : Design validation plan
[4] Finite element analysis

Concept refined based on performance test and FEA test	31
Release of conceptual prototype #2 drawings	32
Conceptual prototype #2 received	33
Fitment trials conducted in the vehicle	34
One out of two concepts selected after fitment trials. One of the concepts was not accepted due to manufacturing constraints	35
Tests conducted as per the developed DVP	36
Tool dub samples requested for pilot test	37
Pilot test conducted	38
First formal drawing release issued with an engineering release note	39
Production break in	40

Table 7.4: Domain Name vs. Design Activity

Domain	Design Activity #
FR	1, 2
WP	3, 4, 5
WC	11, 16, 25, 31, 35
DP	12
DR	6, 13, 17, 19, 20
NFRs	7, 8, 9, 10, 14, 15, 18
PR	21, 23, 32, 33
T	22, 24, 26, 27, 29, 30, 34, 36, 37, 38

To investigate the research question "RQ 2.2", that is where to sequence the NFRs domain in the existing modeling scheme, the information flow between different domains is analyzed. To facilitate such analysis, the design activities are sequenced based on the document analysis. The information flow between them is analyzed using activity based Design Structure Matrix (DSM) (Browning 2001), as shown in Figure 7.5 in Section 7.4.2, using which the domains are sequenced. Since the activities are sequenced, the order in which the information is passed on to subsequent domains is the order in which the modeling scheme should exist. However, in case of bi-directional information flow between any two domains, logical reasoning is used to sequence them, so that the relationships between them are captured in a sequence the design progresses. By doing so, it is possible to capture as much direct relationship as possible rather than obtaining the information between any two domains using a series of matrix multiplications, which may result in loss of information. In addition, sequencing the adjacent domains that aligns with the sequence of the design process makes engineering sense. For example, capturing the relationship between FR and Test domain as a sequence to begin with does not make any engineering sense because there are several intermediate steps before a designer can have related information in the Test domain. Thus, DSM is used only as a guideline to aid in the sequencing process, not as an only source to base the decision. The outcome from this analysis, which will be a sequence of domains, will be compared with the existing modeling scheme to decide on where to include the NFRs domain.

7.3 Analysis To Determine The Importance of NFRs: Investigation of Research Question 'RQ 2.1'

In this section, the research question 'RQ 2.1' is investigated as per the protocol described in Section 7.2.1. An open-ended redesign project of a rear bumper reinforcement of a school bus is undertaken by the author[1] during an eight-month internship for investigation.

The driving factor behind a design change and/or decision-making are analyzed in this section in order to determine the nature of the factor that is driving the design decisions. The subject of interest from this analysis is if the factor causing design change is non-behavioral then it confirms the hypothesis 2.1, which in turn presents the need to include them in the requirement-modeling scheme. The design activity in which a design change is conducted and/or a decision about the design is made, the factors involved in such decision making, and the domain that the factor belong to is analyzed in Table 7.5.

In the initial stage of the design process, the working principle (activity #6) is selected based on the following factors: cost, project duration, and technical feasibility. These factors are non behavioral, but they influenced the selection of the working principle. The material selection (activity #12) is driven by the factors such as the material availability in the market, cost of the material, ease of manufacturing, and material availability with the approved suppliers by the OEM. These factors are non-behavioral and acted as selection criteria from a wide variety of commercially available materials.

Activity #16, which is a concept refinement activity, involved a design change, which is to split a component into two in order to meet a manufacturing constraint. Initially, an integral component was designed to reduce the assembly time, the number of parts, and the cost. However, a requirement from the manufacturing to provide adjustability to the integral component enforced a design change. Hence, a non-behavioral requirement led to a change in the artifact and modified the way the functionality is realized. Activity #18, a requirement from the manufacturing for easy accessibility of the assembly tools, and a protective coating requirement from the service department introduced a design change. In this case, the protective coating didn’t introduce a change in the profile of the artifact whereas the accessibility requirement did. Activity #25, a validation trial of the assembly process in the vehicle, introduced a design change because the assembly supervisor was not satisfied with the degree of tool accessibility to the mounting fastener, thereby introducing a change in the sizing of the component.

Table 7.5: Factors Driving Design Decisions

Design activity #	Design change	Factors driving design decision	Factor domain
#6 : Working principle selection through design review	N.A	Cost, engineering judgment, project duration	Non Functional
#12: Material selection	N.A	Commercially available material, cost of the material, ease of manufacturing, and locally available and approved supplier	Non Functional
#16: Concept refinement	A new part introduced	Manufacturing constraint	Non Functional
#18: Introduction of coating and manufacturing accessibility requirement	Protective coating type, change in the dimensions of the component for facilitating accessibility	Accessibility requirement and environmental constraint	Non Functional
#25: Concept refinement	Change in dimension to increase accessibility	Vehicle fitment trials revealed space constraint for the tool accessibility	Non Functional
#27: Concept refinement	Change in tolerances and installation drawings	Process validation in the assembly line revealed the preferences of the line supervisors and their constraints	Non-Functional
#31: Concept refinement	Change in dimensions such as thickness and radius	High stress concentration	Design Parameter
#35: One out of two concept selected	N.A.	The concept that required the following is selected: No process change Ease of assembly Meets all manufacturing constraints such as adjustability, handling No tool change	Non Functional

Activity #35, a validation trial in the assembly line for selecting the concepts, restrained the author from selecting a concept that had potential to save higher cost per component because it required a change in the assembly sequence. The space constraints in the shop floor restricted the assembly line supervisors from accepting the concept. In activity #27, a concept that aligns with the existing process is validated. The assembly line supervisors expressed their concern in the order of assembly of the redesigned components, the torque requirement on the fasteners for the tools they possessed, the ease of assembly by the operator, and the ergonomic factors. This introduced a design change and hence, a change in the artifact.

From this analysis, it is found that the design decisions are driven by the non-functional requirements, thereby confirming the hypothesis “H2.1”. It also appears that some NFRs act as constraints and some as goals. In addition, these NFRs evolve as the design progresses. The term evolve refers to addition or modification of the NFRs. ***The NFRs, being evolving in nature, and exhibiting a significant role in the product development process, should be included in the modeling scheme unlike the existing modeling scheme.*** Thus, the research question ‘RQ 2.2’ has to be investigated to identify where in the sequence of domains should NFRs be located, which is discussed next.

7.4 Sequencing NFR Domain

In this section, research question ‘RQ 2.2’ is investigated to determine where in the sequence of domains of the exiting modeling scheme should NFRs be located. As described in the case study protocol in Section 7.2.1, the design activities are grouped before conducting the information flow analysis. The details of how the activities are grouped under different domain are discussed next.

7.4.1 Activity Grouping

Activity #1 and #2 are grouped under FRs domain as the two activities involved gathering and clarifying requirements. The NSTSP document (NCST 2010) describing the requirement elicited only three FRs for the bumper while others are NFRs, as shown in Table 7.6. These FRs are used to develop the concepts for the bumper re-enforcement. However, thirty-three NFRs are generated totally during the project out of which some of them are presented in Table 7.6 and discussed here. For example, the durability requirement, R1.11, describes the need to resist various environmental changes and the performance timeframe. The manufacturing requirements: R1.13, R1.14, and R1.16, described the need for ease of accessibility during manufacturing, constraints on the use of existing tools, and constraint on the required adjustability on the bumper reinforcement to take into account of the manufacturing variations. NFRs also stemmed from production line supervisors with a recommendation to use the existing manufacturing process (R1.12) in the redesign. Similarly, marketing supervisors recommended maintaining commonality between different products in its family (R 1.19).

Table 7.6 Requirements Document

Requirement index	Requirement	Type	Justification
Requirements from NSTSP document			
R1.1	The bumper on Type A-1 buses shall be a minimum of 8 inches wide (high). Bumpers on Types A-2, B, C and D buses shall be a minimum of 91⁄2 inches wide (high).	NFR	Provides dimensional specifications, a non-action type of requirement
R1.2	The bumper shall wrap around the back corners of the bus.	NFR	Provides interface requirements, a non-action type of requirement
R1.4	The bumper shall extend forward at least 12 inches, measured from the rear-most point of the body at the floor line	NFR	Provides dimensional requirements, a non-action type of requirement
R1.3	The bumper shall be mounted flush with the sides of the body or protected with an end panel.	NFR	Provides interface requirements, a non-action type of requirement
R1.4	The bumper shall be attached to the chassis frame in such a manner that it may be removed.	NFR	Provides interface requirements, a non-action type of requirement
R1.5	The bumper shall be braced to resist deformation of the bumper resulting from impact from the rear or the side.	**FR**	Describes what the bumper should do, an action type of requirement
R1.6	The bumper shall be designed to discourage hitching	**FR**	Describes what the bumper should do, an action type of requirement

Requirement index	Requirement	Type	Justification
	of rides by an individual.		
R1.7	The bumper shall extend at least one inch beyond the rear-most part of the body surface, measured at the floor line	NFR	Provides interface requirements and dimensional specification, a non-action type of requirement
R1.8	The bottom of the rear bumper shall not be more than 30 inches above ground level.	NFR	Provides interface requirements and dimensional specification, a non-action type of requirement
R1.9	The bumper shall be of sufficient strength to permit being pushed by another vehicle of similar size and being lifted by the bumper without permanent distortion.	**FR**	Describes what the bumper should do, an action type of requirement
Internally generated requirements			
R1.10	Weight should not exceed the existing design. Reduction is beneficial	NFR	Describes the quality of the bumper reinforcement, a non-action type of requirement
R1.11	The bumper should be durable for ten years	NFR	Describes the quality of the bumper, a non-action type of requirement
R1.12	The modified design should not induce any change in the manufacturing process	NFR	Describes a manufacturing requirement, a non-action type
R1.13	The ease of accessibility during assembly should be maintained	NFR	Describes a manufacturing requirement, a non-action type
R1.14	Bumper should be	NFR	Describes a manufacturing

Requirement index	Requirement	Type	Justification
	adjustable in the assembly line to suit the body alignment		requirement, a non-action type
R1.15	The bumper reinforcement design should not exceed assembly time of X seconds	NFR	Describes a manufacturing requirement, a non-action type
R1.16	The modified design should use only the existing assembly tool for assembly	NFR	Describes a manufacturing requirement, a non-action type
R1.17	The modified design of the bumper reinforcement should not cause any externally visible changes	NFR	Describes an aesthetic requirement, a non-action type
R1.18	The bumper reinforcement modification should not cause any interference with other components that are in close proximity	NFR	Describes a spatial constraint, a non-action type
R1.19	The modified bumper reinforcement should be common across the product family	NFR	Describes a commonality constraint, a non-action type

Conventional methods for searching working principles such as studying benchmark reports (activity #3) and reviewing literature (activity #4) — which includes published journal; peer reviewed conference papers; and books — and intuitive methods are used to develop concepts (activity #5). Thus, these three activities are grouped under WP domain. The activities —#11, #16, #25, #31, #35— involve developing preliminary layout and its refinement, design refinement, and concept selection pertaining to the development of working principle into principal solution; therefore, they are grouped under WC domain. Activities such as design review with the managers and other members in the design team (activities #6, #13, #17, #19) and preparation of DFMEA and DVP (activity #20) are grouped under design review domain.

The material selection process and preliminary product sizing based on the limiting stress and based on the preliminary layout involves identification of design parameters; thus, these activities (activity #12) are grouped under DP domain. The prototype domain includes design activities, such as drawing release for prototype and receiving prototype parts; activities #21, #23, #32, #33 fall under this domain. Finally, the 'test' domain includes testing related design activities such as virtual testing (finite element analysis), physical testing, vehicle fitment test, and process simulation test. Nearly 25% of the activities fall in this domain and they are: #22, #24, #26, #27, #29, #30, #34, #36, #37, and #38.

7.4.2 Information Flow Analysis to Sequence NFRs Domain in the Existing Modeling Scheme

This section presents the information flow analyses between the activities to identify where to locate the NFRs domain in the existing requirement-modeling scheme. In this analysis, the activities are divided into two sets for the ease of analysis. In the first set, design activities #1 through #12 are included. To begin with the analysis, the WP domain uses FRs gathered (activity #1) and clarified (activity #2) from the FR domain.

This information is used further to develop working principles along with the benchmark reports (activity #3) and literature review (activity #4). The information flow between these two domains is sequential.

The selection of the working principle is through the process of design review (activity #6), which included a team of senior managers and chief engineer from different departments. Each of the proposed working principle is reviewed and selected by the factors such as cost, engineering judgment, and project duration. This process of reviewing also helped to gather performance and legal requirements (activity #7, #8) that were not identified earlier. The outcome from the design review is the selection of a working principle and elicitation of performance requirements, manufacturing constraints, and durability requirements, which are non-behavioral type of requirements. Past records of testing also provided additional information on functional performance requirements (activity #9) that was reviewed for clarity through a design review meeting (activity #10).

The concept development, grouped under the WC domain, involved sizing of the product artifact using mathematical models, stress analysis using first principles, and layout analysis using 3D (three-dimensional) computer aided design (CAD) model (activity #11). In the DP domain, the activity #12 of material selection is driven by the factors such as commercially available material, cost of the material, ease of manufacturing, and locally available and approved supplier, which is also non-behavioral type of requirements. Thus, the DP domain uses information from both the NFRs and FRs domain, and subsequently, the WC domain uses it. Therefore, the WC domain uses information from both the NFRs and DP domain. At the end of the 12th activity, four working concepts are developed based on the selected working principle, the selected materials, and the elicited NFRs. The information flow pattern encompassing this group of design activities is presented in Figure 7.4.

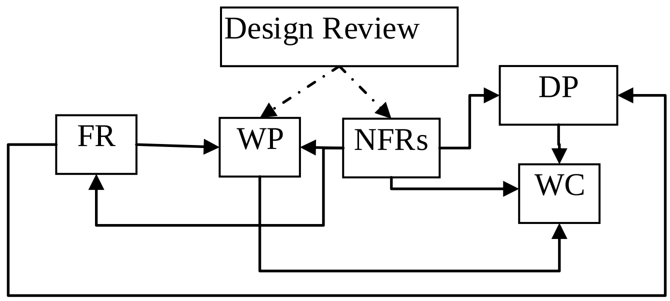


Figure 7.4 Information Flow for the First Set of Design Activity

It is inferred, so far, that new NFRs identified during the design process leads to identification of new FRs, thereby leading to additional activities pertaining to the domains WP and WC. Thus, FRs and NFRs are closely related domains.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
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Figure 7.5 Design Activity DSM – Capturing Dependency / Information Flow between Activities

The second set includes design activities #13 through #40. As mentioned earlier, out of four working concepts, two are reviewed in the design review meeting within a team of design managers and a chief engineer (activity #13). In this meeting, the working concept selection is based on the factors such as the working concept's potential to meet the performance requirements, cost of the system, ease of manufacturability, potential to suit the existing assembly process, ease of assembly, and serviceability. The outcome of the design review included elicitation of manufacturing constraints, serviceability constraints, and suggestions to study the existing manufacturing process, which are all non-behavioral. Later, the cost of the selected working concept is estimated (activity #14) and the potential cost savings are determined.

As an outcome of the design review meeting, the manufacturing constraints of the existing assembly process (activity #15) are studied, identified, and updated in the requirements document. Therefore the design activity - costing, and study of manufacturing process- are grouped in the NFRs domain and the information is captured as feedback in the DSM. The results of the study necessitated a change in the design (activity #16) where an integral form of design is split into two. This modified design is again reviewed in a design review meeting and two additional requirements are elicited (#17, and #18). Of the two requirements, one described the requirement on the protective coating, and the other described the ease of tool accessibility during the assembly process. These two elicited requirements are again classified into the NFRs domain. After modifying the design, a design review is once again conducted with the senior management for program approval (activity #19) followed by conducting a DFMEA (activity #20) document and developing a

DVP, which again fed information to NFRs. Thus, there is a closed loop of information flow between WC, DR, and NFRs domain.

Prototypes are developed (activity #21, #23) and fitment trials are conducted on them (activity #24). A qualitative opinion about the ease of assembly and the safety concerns during the assembly operation are obtained from the line operator. These set of prototypes are also used to simulate the assembly process of the redesigned bumper reinforcement (activity #26). The findings from these trials presented the limitations in the design to suit manufacturing and assembly, which are non-behavioral, using which further design modifications were conducted (activity #25, #27). Thus, there exists a cyclic information flow between PR, NFR, and WC domain.

The second concept prototypes are built (activity #32, #33) and fitment trials are conducted in the vehicle (activity #34). One out of two concepts are selected based on the manufacturing review (activity #35), which is again non-behavioral. Subsequently, the selected prototype is tested according to the develop DVP (activity #36).

In the mean time, virtual validation, that is FEA, is conducted (activity #22) and the design is modified based on the report (activity #30). Thus, information from ‘Test’ domain is feedback to the WC domain. Unlike the results of physical prototype tests where NFRs evolved, FRs remains unaffected. However, in some cases, new FRs is identified if new NFRs are identified.

A Pre-production trial is conducted (activity #39, also called as pilot test) using tool dub samples (activity #38) that are created based on the engineering drawing meant for production (activity #37). Finally, the start of production date is finalized (activity #40). The information flow pattern encompassing the second group of design activities is presented in Figure 7.6 with red dotted arrow headed lines.

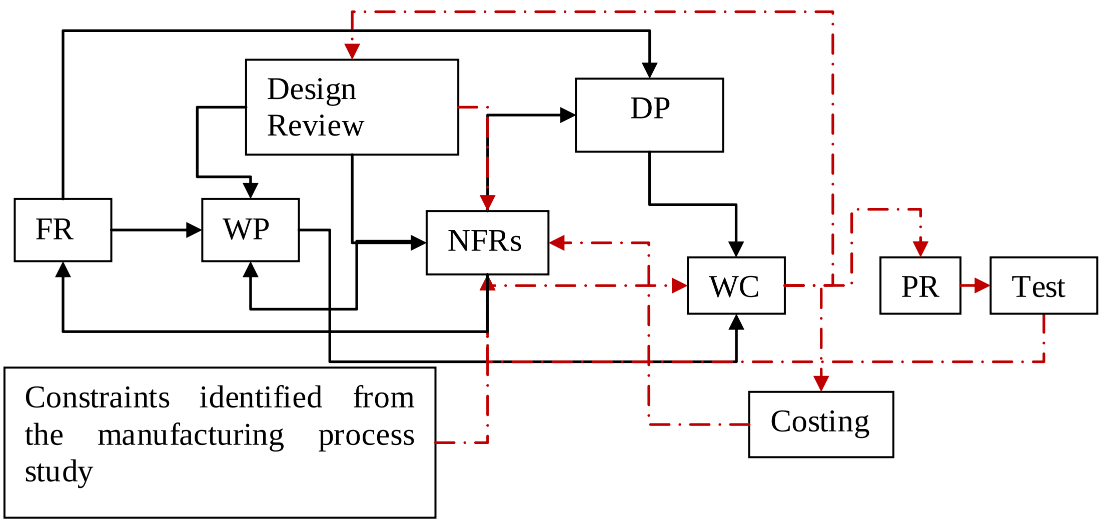


Figure 7.6 Information Flow Diagram (group #2)

7.4.3 Comparison of the Identified Sequence of Domains with the Existing Modeling Scheme

The identified sequence of domain differs from the domains identified in the existing modeling scheme in the following ways:

1. Requirements domain is split into functional requirement (FR) domain and non functional requirement (NFRs) domain;
2. Both functional requirement and function domain is captured in the FR domain.

3. A Prototype (PR) domain is identified in this analysis. It appears that the inclusion of this domain will help capture information regarding the type of prototypes built to test different components. However, the need to consider the PR domain in the modeling scheme is out of scope in this dissertation.

The complete information flow diagram is presented in Figure 7.7 from this analysis. WP domain receives information only from FR and DR domain (Ref Figure 7.6), and it is directly dependent on the FRs because working principle is developed based on them. Hence, NFRs domain is not sequenced between these two domains. However, WC domain receives information from NFRs, WP, and DP domain. Therefore, it provides an opportunity to sequence the NFRs domain between WP and WC domain.

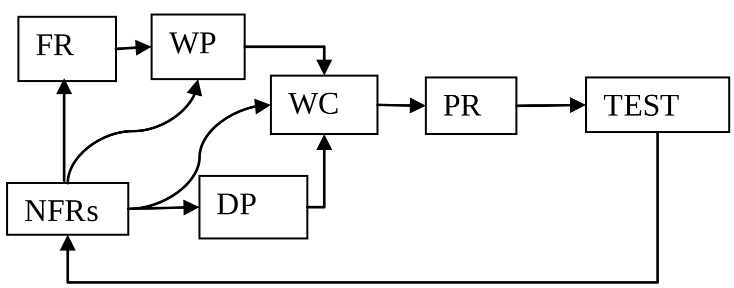


Figure 7.7 Overall Information Flow of the Design Project

In order to explicitly capture the relationship between NFRs and WC domain, the DP domain can be sequenced after WC. It is because not every relationship between NFRs and WC domain can be captured through DP domain. For example, a manufacturing requirement may not have a well-defined design parameter, but it may be directly related to the component. In such instances, sequencing DP domain before WC will not enable the designers to capture the design information. However, NFRs influence the selection of working principle but also influences the FR domain, thereby providing an opportunity to sequence either between FRs and WP domain or after WP domain. Since WPs and FRs domain are directly related to each other, it is best to leave these domains adjacent to each other. By doing so, designers can map the information between these domains as the design progresses. Based on the observations from this case study, only after preliminary design review working principle are selected based on some NFRs elicited by experienced engineers. Thus, sequencing NFRs after WP domain will still enable designers to capture the relationship between these two domains whereas sequencing them between FRs and WP will not aid in capturing the relationship between these two domains. Therefore, the NFRs domain is sequenced between WP and WC domain. Although NFRs feedback information to FRs when new NFRs are created, they are eventually related through one or more working principle, thereby preventing loss of information.

The DR domain is not included in this modeling scheme because the information within this domain is more conversational than recordable in a matrix format. Nevertheless, the author is by no means suggesting to not document the design reviews in a conversational format for future reference.

7.5 Proposed Modeling Scheme

The hypothesis for the research questions, RQ 2.1 and RQ 2.2, is tested using case study research method, and the results confirm both the hypothesis; that is, NFRs drive design changes during the design process, and they can be sequenced between WP and WC domain, as summarized below.

RQ 2.1	**:**	*How do non-functional requirements (NFRs) contribute to the design process in mechanical system?*
Hypothesis 2.1	**:**	*NFRs drive design change*
Status	**:**	*Confirmed*
RQ 2.2	**:**	*Where in the sequence of domains, as presented in the existing modeling scheme, should the NFRs domain be incorporated?*
Hypothesis 2.2	**:**	*NFRs can be sequenced after working principle domain*
Status	**:**	*Confirmed*

The findings that non-functional requirements play a crucial role in the realization of the product artifact suggest the assumption of the benchmark-modeling scheme is true. Therefore, a modeling scheme that includes NFRs domain is proposed in this dissertation in order to aid in identifying the affected system level requirements due to a change in the component. The proposed sequence of domains that includes NFRs is presented in Figure 7.8. This sequence of domain addresses the limitations in the existing- modeling scheme. Additionally, the domains, WS and CV, associated in STEPS (III) and (IV) of the systematic design process are not included in the proposed model because the need to include these domains is not in the scope of this dissertation.

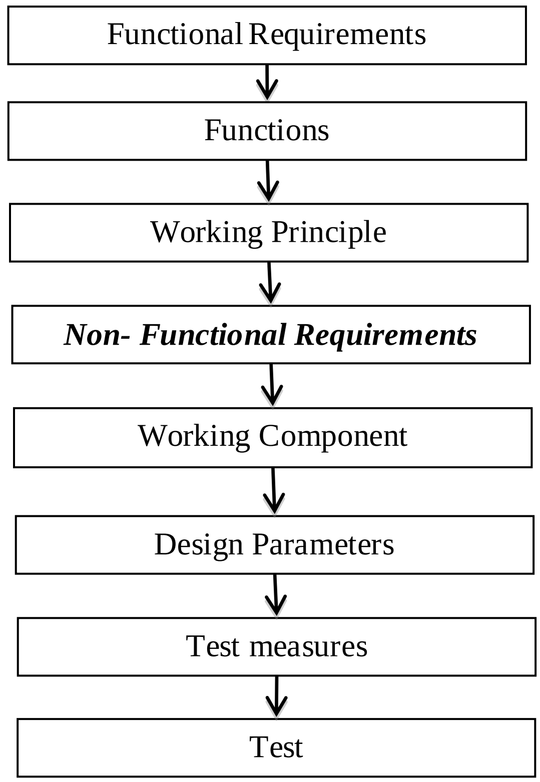


Figure 7.8 Proposed Sequence of Domains To Capture Conceptual Design

A hierarchical requirement-modeling scheme that includes NFRs domain, which is highlighted in yellow color, is presented in Figure 7.9. This is similar to the benchmark modeling scheme but for the NFRs domain. The information between two successive domains is captured using matrix-based representation (Danilovic 2003; Danilovic and Browning 2007). Such representation is used because they are easy to visualize, easy to interpret (Ghoniem 2005; Keller 2006), and easy to automate

The relationship between entities of one domain to the other domain is identified with binary numbering scheme, such as 0's and 1's, where "1" indicates the existence of a relationship while "0" indicates otherwise. This numbering scheme will facilitate matrix multiplication between domains and thereby conduct analyses. Any two domain of interest can be analyzed by a series of matrix multiplication operation.

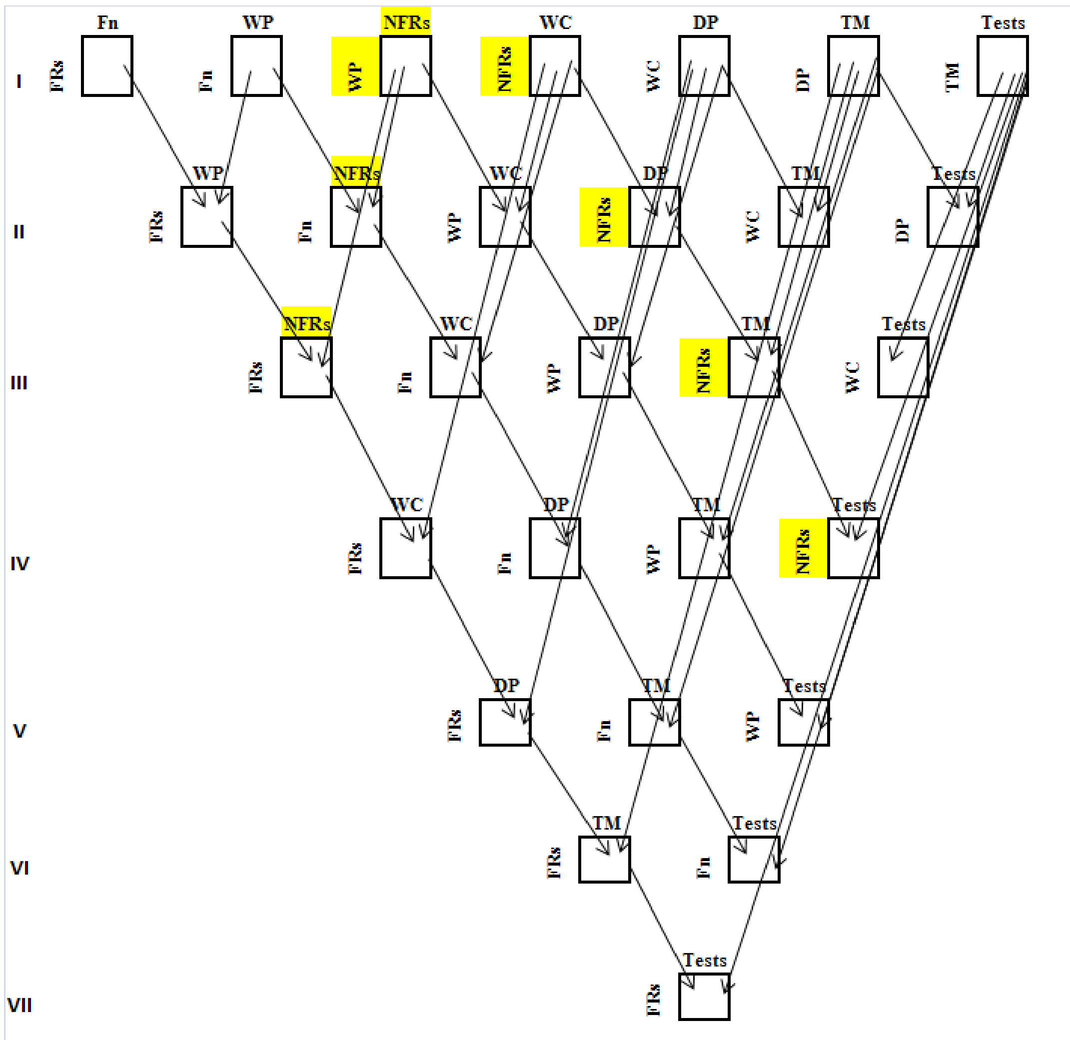


Figure 7.9 Proposed Hierarchical Modeling Scheme with NFRs Domain

This tool is proposed as a support tool that can be used in Step-1 of the proposed VV&T method in the Chapter Six for identifying the system level requirements, as shown in Figure 7.10. In addition, with a series of matrix multiplication, it is also possible to identify the test measurable and the tests associated with different system level requirements.

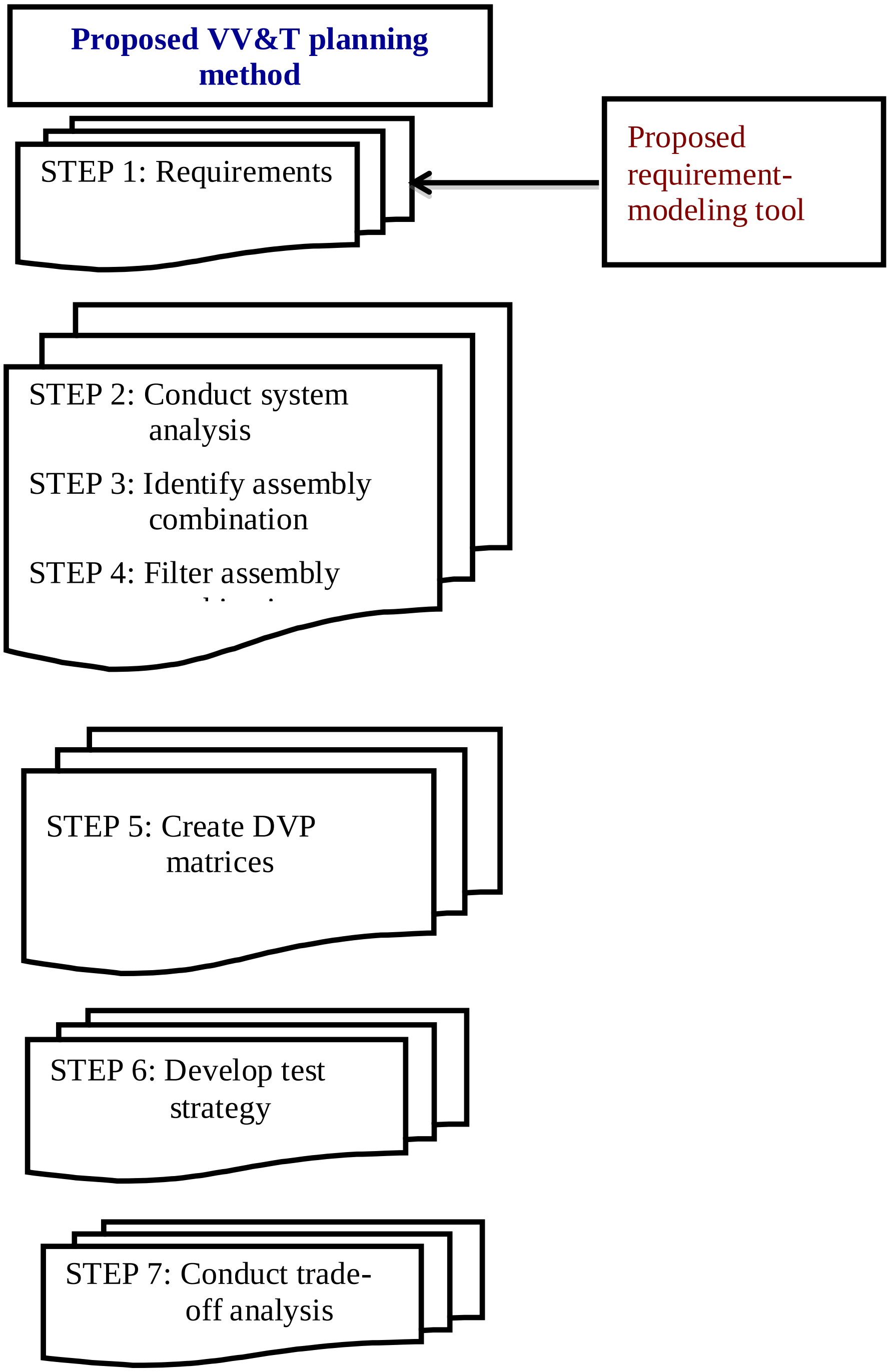


Figure 7.10 Use of the Proposed Requirement-Modeling Tool in the Proposed VV&T Method

7.5.1 Validation of the Case Study Results

The hypothesis that is tested for this research question 'RQ2.1' is if NFRs drive the design changes for which the result confirmed this hypothesis. Validation of qualitative research is classified into two: (i) internal validity, and (ii) external validity or generalization (Yin 2003). The use of data triangulation approach ensures the internal validity of the data collected — an approach in the case study research method that do not follow the replication logic as in the survey based research technique to establish a statistical sample (Stowe 2008; Teegavarapu et al. 2008; Teegavarapu 2009) . External validation of the results for the research question 'RQ2.1' is achieved by comparing the results of this case study with another case study in Chapter Four. Let the former case study be called as 'case study-B' and the latter 'case study-A'. It is observed from 'case study-B' that the NFRs — manufacturing requirements, marketing requirements, and assembly line requirements — have influenced the design change decisions while a similar set of requirements has initiated design changes, as observed in 'case study-A', thereby corroborating the importance of NFRs in the design.

The internal validity of the findings for the research question 'RQ 2.2' is also based on the data triangulation approach. Since the sequencing is determined based on a single case study, the results are presented as "user generalizable". The justification for presenting the results in such a manner has been discussed in Section 4.6.2, hence, not discussed here. However, in order to present the result as 'user generalizable', the attributes describing the case has to be presented in detail, which is also presented in Section 4.6.2

since both case studies are conducted in the same organization — but with different objectives though.

7.6 Dissertation Roadmap

In this chapter, a requirement-modeling scheme is proposed to capture and map the conceptual design information. Including non-functional requirements because of the following reasons advances the state-of-the-art of this model:

1. NFRs influence design changes early in the design process,
2. NFRs act as goals and constraints, and
3. NFRs modify the way the functionality is realized.

Capturing these NFRs early in the design process, such as conceptual design stage, will enable identifying the affected requirements when a component is changed during the production phase, which is the focus of this dissertation. Hence, this tool is also integrated into the VV&T method proposed in Chapter Six as a support tool. In the next chapter, verification and validation of the VV&T method conducted in multiple industries will be presented. The progress of this dissertation is presented in Figure 7.11.

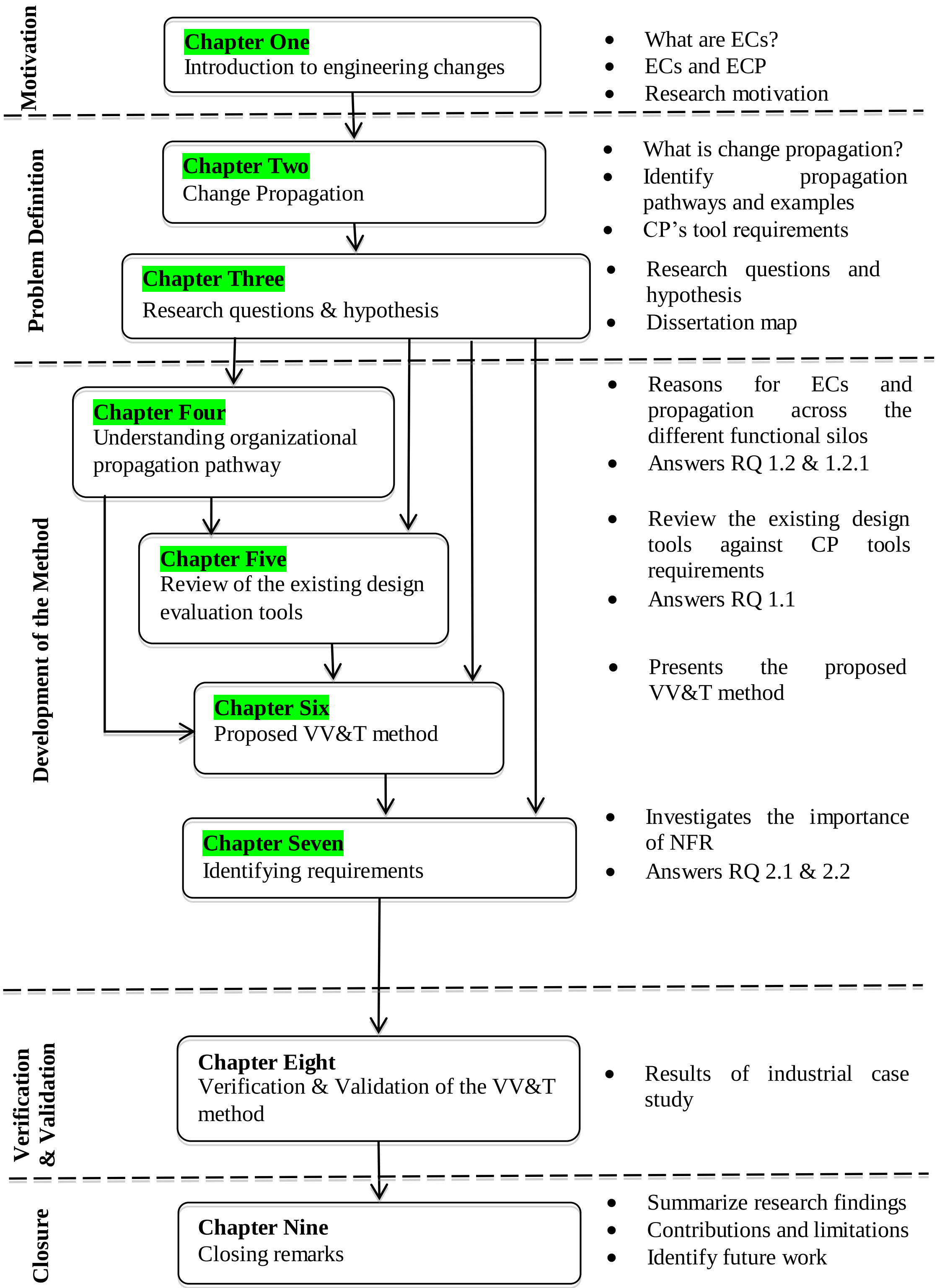


Figure 7.11 Dissertation Roadmap

CHAPTER EIGHT : VALIDATION OF THE PROPOSED VV&T METHOD

The proposed VV&T method in Chapter Six is validated in two manufacturing companies—a commercial vehicle and an automatic fire sprinkler manufacturer— using case study research method. In addition, Delphi validation technique is also used in both of these companies, but it includes two additional manufacturing companies — a passenger vehicle and a rolling mill manufacturer. The status of the hypothesis ‘H1’, whether it is confirmed or not, will be concluded only after triangulating the results obtained from the multiple case studies and Delphi validation technique, which is shown in Figure 8.1.

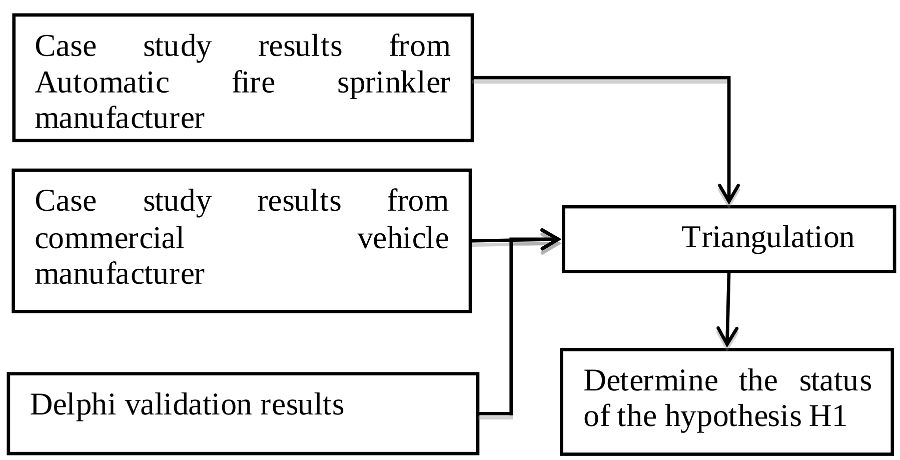


Figure 8.1 Scheme to Determine the Status of the Hypothesis 'H1'

8.1 Case Study Research Method

As recommended by (Yin 2003), the choice of case study research method is driven by the answers to the questions listed in Table 8.1.

Table 8.1 Justification for Case Study Research Method

Research Question	Question	Answer	Justification
RQ1	Form of the research question – is it exploratory or explanatory?	Explanatory	The research question ***explains*** how design changes can be reduced
	Does the researcher require control over the behavioral events?	No	The goal is to understand if VV&T process can reduce propagation effect. Hence, no control over the events is required
	Is the phenomenon under study a contemporary or a historical event?	Contemporary	A contemporary EC event is required to meet the objective of this research question.
	Is the phenomenon under study requires a real-life context?	Yes	A contextual understanding of the phenomenon is required

First, the research question 'RQ1' is of "how" type of a question, which indicates its explanatory nature, as it explains how design changes due to propagation can be reduced. Second, the researcher need not exercise control over the behavioral events to study if the proposed VV&T process possess the ability to reduce design changes due to change propagation effects as it is a electro-mechanical phenomena. Third, as the proposed VV&T method is intended to reduce design changes, studying a contemporary EC under real-life context will enable the researcher to study the contextual information used by the designer, such as rationale for selecting a supplier-variant combination, while applying the VV&T method. Thus, the above factors drive the selection of a case study research method.

Two case studies conducted in an automatic fire sprinkler manufacturer — termed as 'Case-A' — and a commercial vehicle manufacturer— termed as 'Case-B'— is presented in this section. The project requirements, the company information, the data collection method, the observation, and the inference are presented for each of these case studies in Section 8.2and Section8.3.

8.2 Case-A

This section presents the case study results conducted in an automatic fire sprinkler manufacturer located in southeastern part of the USA (United States of America). They manufacture sprinklers and valves in large proportion, which are supplied worldwide, and hence, there are several variants developed to suit different market and customer needs. In addition, some of the components assembled in the product are purchased from multiple suppliers, which includes product variants. Sprinklers consist of fifteen to twenty components whereas valve contains forty to sixty components. Thus, based on the number of parts, they can be classified as medium complex products. The average cost of these sprinklers and fully assembled valves are $30-50 and $3500-4500 respectively.

The requirements for an EC project to conduct this case is described in Section 8.2.1, the details about the project is presented in Section 8.2.2, the data collection method is presented in Section 8.2.3, the findings from this case study in Section 8.2.4, and finally, the observations and inferences are presented in Section 8.2.5.

8.2.1 Project Requirement

Two different types of project can be used to conduct this case study. The requirements for the first type of project, termed as ‘Type-I’, is described in this section as it is associated with ‘Case-A’ while the second type of project, termed as ‘Type-II’, is described in Section 8.3 when discussing the second case, that is, ‘Case-B’.

As the proposed VV&T method is intended for the production phase, an engineering change project in this phase is required. In addition, the project selected should involve interactions of the change component with product variants and multiple suppliers as the hypothesis tested is whether this method can prevent propagation due to variant and organizational pathways or not. An engineering change should have been completed, and the changed component/assembly should be in the testing phase. These requirements are formalized in Table 8.2. These requirements, specifically requirement T1-R3 provides an opportunity for the researcher to draw a logical conclusion about the status of the hypothesis, which is discussed next.

Table 8.2 Project Requirement for Validating VV&T Method

Requirement index	Requirement
T1-R1	Engineering change in the production phase
T1-R2	Product's components contains multiple variants and multiple suppliers
T1-R3	EC completed, change component in the testing phase

When the proposed VV&T method is applied to the project meeting these requirements, it is possible to determine whether or not the design engineer identifies one or more tests that was not previously planned, specifically related to variant combinations. This implies the designer will be able to identify if a change mode is active or inactive by conducting the tests that are previously not planned. If the testing results indicate non-conformance to the design requirements then they can take necessary steps to address the identified problem, thereby converting an active change mode to an inactive one; in other words, ***preventing what could have been an impending design change.***

On the other side, if the result of the tests meets the design requirement then the variant pathway initiated due to the change mode, which was not previously evaluated, is confirmed to be an inactive one, thereby reducing the change risk. This implies the designer has evaluated a propagation pathway that was previously overlooked when they did not adhere to the steps in the proposed VV&T method for developing a validation plan.

Thus, in either scenario, it can be logically deduced that if designers identify tests that were not previously planned, especially those tests that are relevant to variant and organization pathway, then the hypothesis can be confirmed.

8.2.2 EC Project Details

A valve is selected as it met the project requirements described in Table 8.2. This valve is used to prevent fire hazards in industries. In the event of a fire, this valve trips off and releases gushing water in the area of fire thereby reducing the impact of the hazardous event. Thus, it is a safety critical product. A cross-sectional view is shown in Figure 8.2 with the labeled parts.

8.2.2.1 Brief Description of the Valve and its Operation

The valve is called as DDX Deluge valve (Reliablesprinkler 2010). It is hydraulically operated and a differential-type valve used to control the water supply to the Deluge systems, which uses sprinklers as discharge outlets in the area under fire. Different detection systems are used to control its operation, such as hydraulic, manual, and pneumatic. This valve can be reset to its initial state by a push and turn type external knob, as shown in Figure 8.2.

This valve's operation can be described based on the clapper's open and closed position. In its closed position, the supply pressure of the water acts on the underside of the clapper and the push rod through the inlet chamber. When a fire is detected, the pressure in the push rod chamber is vented through its outlet. As soon as the pressure reduces to one-third of the supply pressure, the force under the clapper exceeds the clamping force applied by the lever thereby swinging open the clapper and allowing the water beneath it to pass through the Deluge systems for retarding the fire. As soon as the clapper opens, the lever acts as a latch preventing the clapper from returning to its closed position.

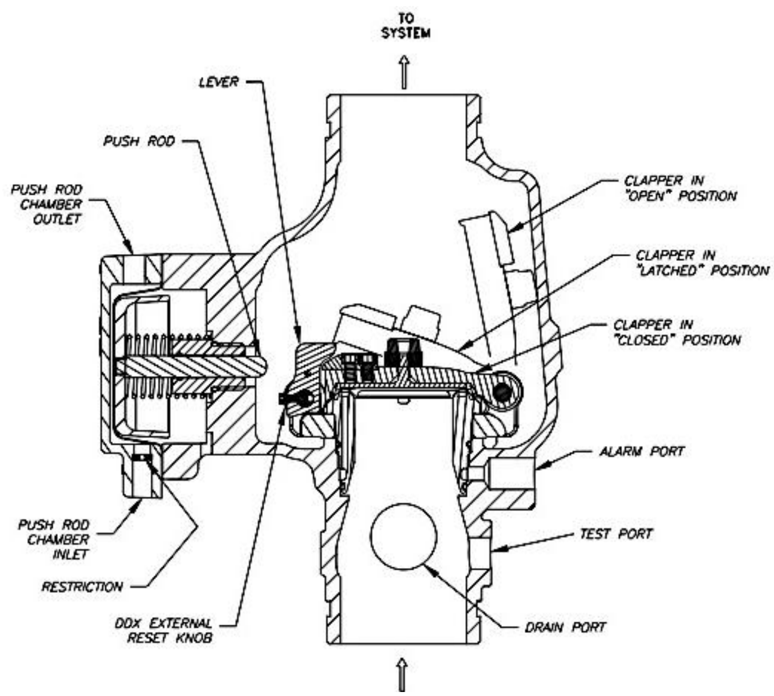


Figure 8.2 Cross-Sectional View of the DDX Deluge Valve

This product is expected to be in the field for 50 years such that it is in a 'ready-to-perform' state should a fire accident occur any time during this time. However, yearly maintenance schedules are in place to ensure if the valve is functional.

The EC conducted in this valve was to modify the clapper assembly to improve the manufacturability. In this process, five different components are changed in the assembly with six different change modes. They are:

1. Part addition
2. Part deletion
3. Material change
4. Feature addition and deletion in the same part
5. Feature modification

Each of these change modes was related to different components in the assembly except for the ones where both feature addition and deletion were conducted on the same part. The lead-time for this change, from initiation to implementation, is targeted between six to nine months.

A team of engineers from different departments that includes engineering, manufacturing, testing, marketing and service, and packaging conducted this EC. The product experience of these engineers, within and outside the investigation site, and their responsibility are presented in Table 8.3.

Table 8.3 Information about the Team Who are Involved in the DDX Valve EC Project

Engineer ID	Experience in this company (in years)	Experience outside this company (in years)	Responsibility
Engineer #1	10		Design and development of valves
Engineer #2	5	26	Project manager
Engineer #3	10		Manufacturing engineer
Engineer #4	15	5	Packaging engineer
Engineer #5	10		Testing engineer
Engineer #6	19	21	Service engineer
Engineer #7	19	21	Marketing engineer

8.2.3 Data collection

The data collection scheme for ‘Type-I’ project is described in this section. In order to obtain the data, the team involved in the EC of the DDX valve project has to apply the proposed VV&T method. In order to achieve this task, six meetings were held with the essential members of the team where each meeting consumed an average of 2.5 hours of time in a single sitting without any major interruptions. In the first two meetings, the VV&T process is applied to a sprinkler project as a pilot run to facilitate the engineers acclimatize the new process’ terminologies. Subsequently, four meetings were held to complete the seven steps in the VV&T process for the valve project. The break down of the time consumed for completing each step is presented in Figure 8.3, which will be discussed in detail in Section 8.2.5.

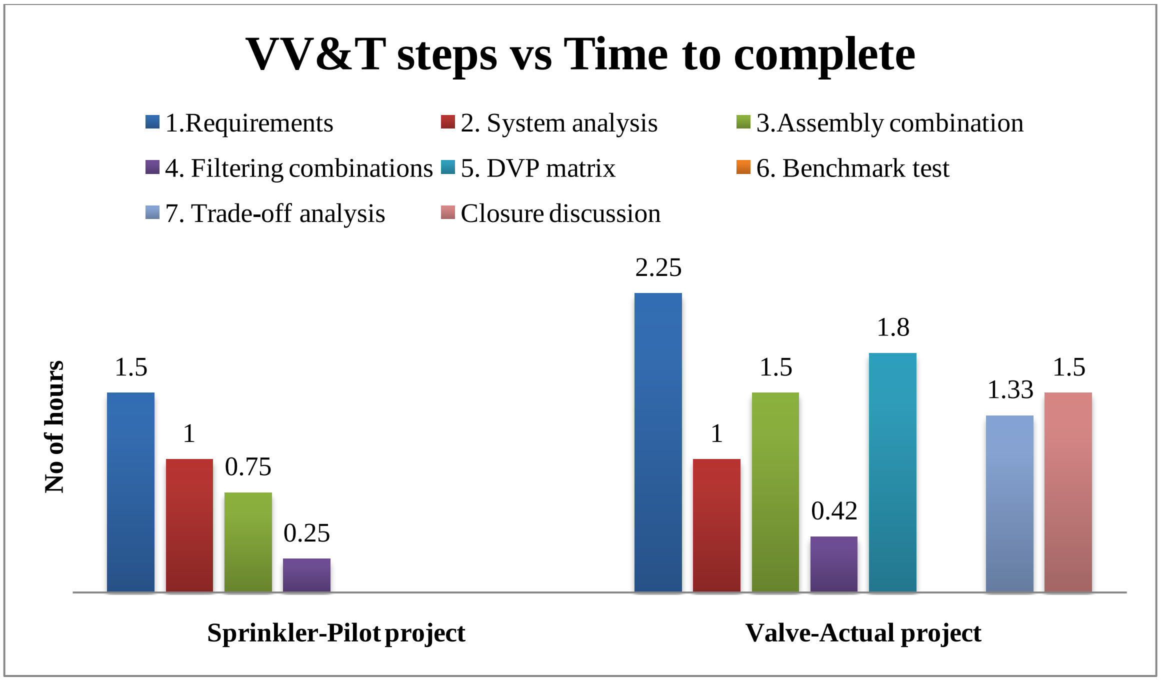


Figure 8.3 Time Taken to Complete Each Step in the Proposed VV&T Process

In order to identify if the designer has identified a new test that was unplanned earlier, the tests identified in the 'Test' column and the associated 'combination vectors' in the DVP matrix (from Step-5 of the proposed VV&T method) are collected. This is necessary because there can be instances where new assembly combinations may be identified for certain previously planned tests thereby resulting in additional testing. For instance, one of the assembly combinations may be tested for corrosion resistance while one more assembly combination may also have to be tested based on the number of combination vector identified in the DVP matrix. Subsequently, each of these tests is compared with the test plan previously developed by the team using the best practices in their company for making a decision whether or not they are planned earlier. To this end, there are two possible scenarios: (i) Tests may not have been previously planned; or (ii) Tests may be previously planned but the combination vectors identified from the DVP matrix is not tested. In either scenario, there are additional tests to be conducted. However, in situation similar to second scenario, it is also identified if the combination vectors are a result of variant or organization pathway, as shown in Table 8.4, which can be determined from the 'combination vector' description in Step-3.

The information discussed above is collected individually from the designer and the test engineer by the author. Subsequently, they are compared to identify any difference of opinion between them, thereby triangulating the data. Triangulation is an approach in case study research method to improve the strength of the data, thereby improving the reliability of the findings (Yin 2003; George and Bennett. 2005).

Table 8.4 Test Status Determination

Tests	Is this test planned earlier? (Yes/No)	Is the assembly combinations identified for this test planned earlier? (Yes/ No)	If the answer to the column I or column II is no, is the test related to variant / organization pathway? (Yes/No)
	I	II	III
T1	Yes	No	Yes

8.2.4 Findings from 'Case-A'

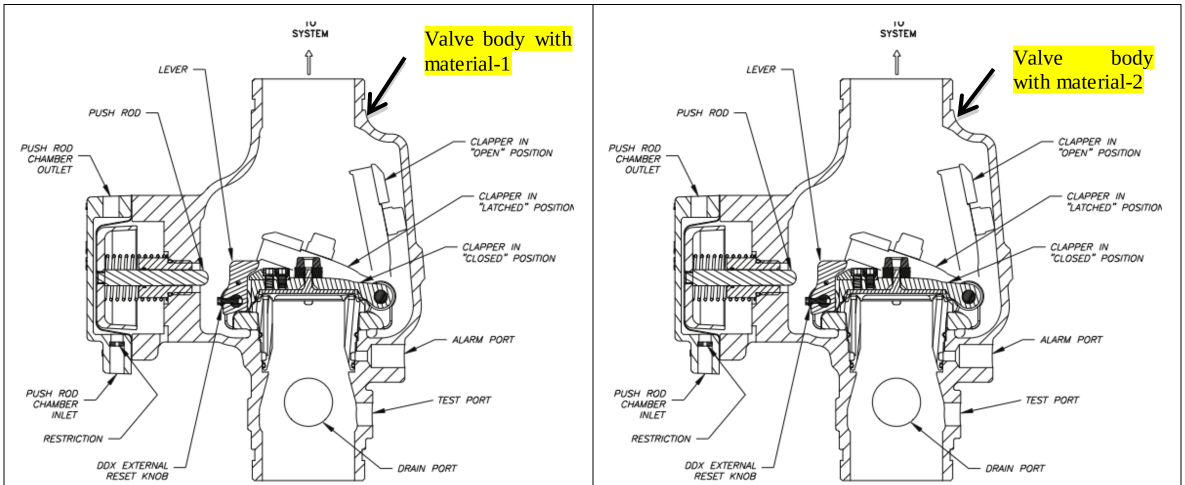
This section presents the observations, inferences, and conclusions from this case study. As the subject of interest is to test the hypothesis, the information relevant to it is discussed first, and subsequently, the observations and inferences from each step are presented.

The steps in the VV&T process, as followed by the team of engineers, are presented in Appendix H. As discussed in the Section 8.2.3, the information about the tests obtained from the DVP matrix is verified with the design and test engineer. However, those tests identified by the engineers as unplanned ones are only presented in Table 8.5 for further discussion. Five tests are identified as unplanned tests out of which three were related to variant pathways, which will be discussed next.

Table 8.5 Planned vs. Unplanned Tests: Status Determination

Tests	Is this test planned earlier? (Yes/No)	Is the assembly combinations identified for this test planned earlier? (Yes/ No)	If the answer to the column I or column II is no, is the test related to variant / organization pathway? (Yes/No)
	I	II	III
Impact test – Test #5 (T5)	Yes	**No**	**Yes – Variant and organization pathway**
Endurance test – Test #6 (T6)	Yes	**No**	**Yes – Variant and organization pathway**
Corrosion test – Test #8 (T8)	Yes	**No**	**Yes – Variant and organization pathway**
Cycle test – Test #11 (T11)	Yes	**No**	**Yes – Variant and organization pathway**
Disassembly test – Test #17 (T17)	**No**	**No**	**Yes – Organization pathway**
Vibration test – Test #18 (T18)	**No**	**No**	**Yes – Organization pathway**

The test ‘T5’, which validates requirement ‘DV-R1.5’, is a test to determine the valve body’s strength to resist the impact of the clapper assembly after it is swung open when the fire is detected. From Step-3 of the proposed VV&T process, it is determined that the clapper assembly interacts with valve body made of different materials, which lead to two different assembly combinations, and from Step-4, it is determined that the requirement ‘DV-R1.5’ is affected by both materials. Thus, this requirement has to be tested with two different assembly combinations, as shown in Figure 8.4.



Assembly combination-1 (C1)	Assembly combination-2 (C2)

Figure 8.4 Assembly Combinations

Combination 'C1' was planned for testing prior to application of this proposed VV&T method while combination 'C2' is identified only after applying this method, which enabled the engineers to analyze the variant interaction effect or variant propagation pathway. Analysis, based on the engineers' experience, revealed that 'material-2' has higher strength than the 'material-1', and hence, the impact of the clapper assembly will not initiate a failure mode —either deformation or crack type of failure— thereby eliminating the need to test the combination 'C2', which is formally recorded in the DVP matrix. Thus, by following this VV&T method, engineers are enabled with an opportunity to analytically evaluate the interaction of the change element with a variant element, which was outside the system boundary, and conclude that the change mode, which is 'material change', in the clapper is inactive. Such evaluation of variant interaction can potentially prevent a propagation effect through variant pathways. Step-3 through Step-5 enabled engineers' to analyze such variant interactions that were otherwise overlooked[5].

The test 'T6', which validates requirement 'DV-R1.6', is an endurance test. From Step-4, it is identified that both assembly combinations 'C1' and 'C2' have to be tested. The test 'T8', which validates requirement 'DV-R1.8', is a corrosion resistant test to ensure the valve operation in salt-water environment. Similar to the previous test 'T5', it is identified from step-4 that assembly combination 'C2' has to be tested against this requirement also. Although engineer-#1 felt confident about this test passing the requirement, he felt a need to conduct this test as it has two benefits. First, the test results will add to their product knowledge and as a reference material for future design, and second, the test results, when documented in the DVP matrix, will act as an evidence to provide the legal authorities should any law suit be filed against the company in the event of an unforeseen failure. Thus, conducting tests with assembly combination 'C2' and systematically documenting it is deemed necessary among the team.

The test 'T11', which validates requirement 'DV-R1.11', is another form of endurance test, which is termed as 'cycle test' by the engineers in the company. Only combination 'C1' was identified for testing before applying this VV&T method. However,

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[5] Note: The author, by using the term 'overlooking', does not negatively reflect on the intellectual merit of the design engineer; it is just the complexity of the product and its interaction with several product variants causes this tendency in the designer's mind to overlook.

after applying this method, it is identified that combination ‘C2’ should also be tested against this requirement. ***After conducting endurance tests for three weeks, a failure is identified in both of the assembly combination ‘C1’ and ‘C2’.*** However, corrective actions are subsequently determined for addressing the failure cause. ***The team realized they have saved $2000-$4000 of money and one to three months of product development lead-time*** (e-mail from the engineer has been presented in Appendix J). If this company had not used this VV&T method, they would have identified a failure in the assembly combination ‘C1’ but not ‘C2’. The constructs in this method have enabled engineers to think about the different variants and eventually identify the assembly combinations for testing. As the combinations involved variants from a single and multiple suppliers, it is concluded that variant and organization pathway of propagation has been identified, thus addressing the limitation in the existing VV&T method. In addition, the failure is identified before an engineering change note (ECN) is released, which indicates the company has prevented a forthcoming change, thereby saving the hassles of addressing customer complaint and associated warranty costs in future. ***This result provides strong and explicit evidence of how the proposed VV&T method can reduce design changes due to propagation effects.***

In both of the tests ‘T5’ and ‘T8’ discussed above, the evaluated assembly combinations are related to both variant and organizational pathways. In Step-3, the product variants supplied by multiple suppliers are evaluated, and a particular supplier is selected rationally, which is discussed next. A snap shot of the element-supplier-variant selection matrix (Step-3) for the element 'lever', as developed by the engineers, is presented in Table 8.6.

Table 8.6 Snap-Shot of Element-Supplier-Variant Combination Identification Matrix

<table>
<tr><th>Affected Elements</th><th>Supplier</th><th>Variants</th><th>E-S-V identifier</th><th>Element-supplier-variant combination selection (Yes /No)</th><th>Reason for selection/ rejection</th><th>No of E-S-V's identified per element</th></tr>
<tr><td rowspan="6">Lever (P2)</td><td rowspan="2">S1</td><td>V1 (Material-3)</td><td>P2. S1.V1</td><td>Yes</td><td rowspan="2">To verify galling is not an issue</td><td rowspan="6">2</td></tr>
<tr><td>V2 (Material-4)</td><td>P2.S1.V2</td><td>Yes</td></tr>
<tr><td rowspan="2">S2</td><td>V1</td><td>P2.S2.V1</td><td>No</td><td rowspan="4">No significant variability between suppliers because it is machined from a plate, and the quantity is around 20 per year</td></tr>
<tr><td>V2</td><td>P2.S2.V2</td><td>No</td></tr>
<tr><td rowspan="2">S3</td><td>V1</td><td>P2.S3.V1</td><td>No</td></tr>
<tr><td>V2</td><td>P2.S3.V2</td><td>No</td></tr>
</table>

There are three different suppliers supplying two variants each with different materials. Since there is only a material difference between the variants, these suppliers are evaluated based on the quality of the material and the quantity they supplied. The variability in the material's property is determined to be insignificant based on the manufacturing engineer's previous experience. In addition, the quantity supplied by the suppliers 'S2' and 'S3' is only twenty per year. Therefore, the variants 'V1' and 'V2' manufactured by both of these suppliers are eliminated from further analysis. However, this matrix provided an opportunity for the engineers to consider the interaction of the change element with variant elements manufactured by different suppliers and subsequently, rationalize the selection of the two 'E-S-V' combinations, thereby evaluating the change effects that may propagate through a combination of both organizational and variant pathway.

A disassembly test 'T17', which validates the serviceability requirement 'DV-R3.1', is a new test that is not identified in the test plan developed by the engineers before the application of this VV&T method. From Step-4, it is identified that assembly combinations stemming from different variants has no impact in this requirement, therefore, any of the two combinations can be selected for testing; engineers selected combination 'C1' for the test.

A vibration test 'T18', which validates shipping requirement 'DV-R5.0', is previously unplanned. Elicitation of shipping requirements necessitated the identification of this new test. Vibration test was conducted in the past, but the vibration level was determined only with the road transportation in mind. However, this company is flexible to ship their products in any form of transportation, such as seaways, roadways, railways, and airways. Thus, after reviewing the requirements, the vibration level required for the test has been modified, and subsequently, the test has been scheduled.

The two tests 'T17' and 'T18' discussed above are related to organizational pathway of propagation because the disassembly test evaluates how the design affects the service department, and the vibration test evaluates if the mode of shipping could affect the product integrity. As discussed in Chapter Four, changes can propagate across the departments in the organization if those changes are not validated against the requirements set-forth by them. Thus, identifying and evaluating these tests has provided the design engineer to foresee any potential problem that might have stemmed after releasing the drawing for production, thereby preventing an impending design change due to organizational pathway of propagation.

These four tests discussed above confirm that the proposed VV&T method has the ability to enable engineers identify tests that are related to variant and organization pathways. However, the tests identified in the DVP matrix also evaluate other pathways, such as behavior and geometric pathways, which is presented in Table 8.7. These tests are grouped under different propagation pathway based on the nature of the test, and the number of combination vectors. For instance, 'Test #1' is a functional-performance test; hence, it is grouped under behavior pathway. In addition, two assembly combinations are evaluated which is why it is also grouped under variant and organizational pathway.

Table 8.7 Pathways Evaluated by the Different Tests Identified in the DVP Matrix

Test number (From the DVP matrix presented in Chapter Six)	Behavior pathway	Geometric pathway	Ambient pathway	Variant pathway	Organization pathway
Test #1	✓			✓	✓
Test #2	✓				
Test #3	✓			✓	✓
Test #4	✓				
Test #5	✓			✓	✓
Test #6	✓			✓	✓
Test #7		✓			
Test #8	✓			✓	✓
Test #9		✓			

Test number (From the DVP matrix presented in Chapter Six)	Behavior pathway	Geometric pathway	Ambient pathway	Variant pathway	Organization pathway
Test #10		✓			
Test #11	✓			✓	✓
Test #12		✓		✓	✓
Test #13				✓	✓
Test #14					✓
Test #15					✓
Test #16					✓
Test #17					✓
Test #18					✓

Grouping these tests based on the pathways evaluated presents additional evidence supporting the proposed VV&T method. Observing the pathways evaluated by these tests, engineers do evaluate variant and/or organization pathways based on their experience. For instance, observing the pathways 'Test #1' and 'Test #3' evaluates, it is inferred that engineers have previously planned tests with different combinations, which addresses variant and organization pathways, based on their experience **before** applying this VV&T method. However, ***after applying the proposed VV&T method presented in this dissertation, engineers are able to identify two previously planned tests, which are 'Test #5' and 'Test #8', for which additional assembly combination has to be evaluated.*** This inference indicates that the construct in Step-3 through Step-5 is valid and effective.

New tests, such as 'Test #17' and 'Test #18', are considered necessary by the team of engineers. The reason these tests are identified is due to Step-1, which is the identification of requirements that include functional-performance, manufacturing, service, and shipping requirements. These new tests are validation tests for service and shipping requirements respectively. Thus, Step-1 is also valid and proven to be effective.

8.2.5 Observations and Inferences from Each Step

This section discusses the observation and inferences (if any) from each step while developing the DVP in the company where this case study is conducted. In the first step, while identifying the system level requirements, the most important observation is the type of requirement that is elicited by the engineers. As the author requested them to elicit the requirements, engineers provided the ‘verification requirements’ in some instances rather than the product requirements. Hence, these verification requirements are moved to the ‘test’ column in the DVP matrix, and subsequently, they are asked to elicit the product requirement for the corresponding verification requirement. This is critical because one product requirement may have multiple verification requirements. For instance, a product requirement, such as ‘the vehicle should be durable’, can have a corrosion resistant test and a torture-track test as their corresponding verification requirements. Hence, if verification requirements are written in the ‘requirements’ column of the DVP matrix, it is highly likely that some of the important tests may never be considered.

As the requirements are collected from the engineers from different departments, the time taken to complete this step is 2.25 hours, which is the longest in comparison to the other steps. This time can be significantly reduced for those companies using requirements management software such as DOORS. However, for those companies without such software, as the one discussed in this case study, it is an opportunity for the team to meet together and discuss the product requirements, thereby reducing the chances of not considering any requirement that might be of interest for any other department.

The second step, where system analysis is conducted, consumed one hour out of which fifteen minutes are lost in creating the DSM rather than mapping the component relationships. Hence, automating it can save this time. The system consists of 25 elements, both internal and external, which implies that engineers evaluated nearly 300 cells in the matrix (625 cells minus diagonal elements minus symmetry) and identified their interaction. This process alone consumed nearly thirty minutes. In addition, elements such as water, air, and grease are also considered unlike the traditional component DSM. This is to consider the interaction of the change component with the variants of these elements. This company has experienced a problem in the past because of not considering the different variants of the water. Engineer #2 said:

> *"We supplied our valves to overseas. Seats in some valves (...of the sprinklers) started breaking because of corrosion. When we investigated we found that the water was too pure and caused corrosion. It was because the water was produced by reverse osmosis method…"*

After completing the DSM, engineers are asked to identify the change components in the DSM and have them read column-wise to understand the interactions. Subsequently, the following questions are asked:

1. Does the change mode have an impact on the property of the working surface pair?

2. Does the change mode have an impact on the channel and support structure?

These questions led engineers to analyze and evaluate the change modes. ***During this process, one instance is noted where engineer - #1 identified the need for further analysis in the interaction property between the change and the interacting element.*** Although the results of this analysis indicated no potential problem, the fact that this process of questioning drives engineers to conduct analysis specific to the change mode justifies the construct built in this step to prevent propagation.

The important observation in this step is the team, as a unit, started thinking about the interactions and their effects. This is considered as a positive aspect among the team while the design engineer (engineer #1) said:

" I see this method being implemented as a requirement for future design changes"

In the third step, four observations are made. First, the formula to compute the number of assembly combinations needed modification because the underlying assumption in the formula presented in Section 6.3.4 assumes that the number of supplier-variant combination identified per element is independent of the variants of other element.

Table 8.8 Element -Supplier-Variant Combination Identification Matrix

Affected elements	Supplier	Variants	E-S-V identifier	Element- supplier-variant combination selection	Reason for selection/ rejection	No of E-S-V's identified per element
Lever (P2)	S1	V1 (Material-1)	**P2.S1.V1**	**Y**	To verify galling is not an issue	2
		V2 (Material-2)	**P2.S1.V2**	**Y**		
	S2	V1	**P2.S2.V1**	N	No significant variability between suppliers, and the quantity is around 20 per year	
		V2	**P2.S2.V2**	N		
	S3	V1	**P2.S3.V1**	N		
		V2	**P2.S3.V2**	N		
Valve body (P3)	S1	V1 (Material-3)	**P3.S1.V1**	**Y**	Different material; one with ductile iron and the other stainless steel	2
	S2	V2 (Material-4)	**P3.S2.V2**	**Y**		
Push rod (P4)	S1	V1 (Material-5)	**P4.S1.V1**	**Y**	Two different materials; 300 series stainless steel and Aluminum Bronze	2
		V2 (Material-6)	**P4.S1.V2**	**Y**		
	S2	V1	**P4.S2.V1**	N	No significant variability between suppliers, and the quantity is around 20 per year	
		V2	**P4.S2.V2**	N		
	S3	V1	**P4.S3.V1**	N		
		V2	**P4.S3.V2**	N		
Reset handle (P5)	S1	V1 (Material-7)	**P5.S1.V1**	**Y**	Different material; one with Brass, the other one is Stainless Steel	2
	S2	V2 (Material-8)	**P5.S2.V2**	**Y**		
Water (P6)	S1	V1	**P6.S1.V1**	**Y**		1
Air (P7)	S1	V1	**P7.S1.V1**	**Y**		1
Lever spring (P8)	S1	V1	**P8.S1.V1**	**Y**	Different sizes and different input force	2
		V2	**P8.S1.V2**	**Y**		

The E-S-V identification matrix, as shown in Table 8.8, is used to discuss the limitation of the underlying assumption in this formula. The number of assembly combinations is 32, as per the formula (product of the E-S-V's identified in the last column in Table 8.8). However, this is not possible because some variant elements are used only in combination with a specific element; in other words, ***there exist a parent-child relationship between the selected E-S-Vs***. Thus, it is essential to identify the number of independent E-S-Vs, as shown in Table 8.9. In this example, the valve body is the parent element (independent element) while the lever, the push rod, the reset handle, and the lever spring are child elements (dependent element). Thus, the number of assembly combinations reduces to just two instead of 32.

Table 8.9 Parent-Child Relationship Table

Parent	Valve body – P3.S1.V1	Valve body – P3.S2.V2
Child	Lever : P2.S1.V1	Lever : P2.S1.V2
	Push rod : P4.S1.V1	Push rod : P4.S1.V2
	Reset handle: P5.S1.V1	Reset handle: P5.S2.V2
	Lever spring: P8.S1.V1	Lever spring: P8.S1.V2

Based on this observation, the following two questions should be asked immediately after creating the E-S-V matrix:

1. **Does any element variant dependent on other element variant (yes/no)?**
2. **Which element(s) is/are dependent on parent element?**

The elements in these questions refer only to those that are in the E-S-V matrix.

If the answer to the first question is in the affirmative then the formula presented in Section 6.3.5 is invalid, and hence, the formula, as shown in Equation 5, should be used to calculate the number of assembly combinations.

Equation 5

The second observation in this step is the rationale used by the engineers to select one out of multiple suppliers. For instance, the element 'lever' has three suppliers 'S1', 'S2', and 'S3' out of which two suppliers 'S2' and 'S3' are eliminated. Since the difference between the variants is only material, the team discussed the variation in the material property between these suppliers in the past, which is considered insignificant. In addition, the quantity supplied by the suppliers 'S2' and 'S3' is just twenty numbers per year. Thus, the possibility of E-S-Vs stemming from these two suppliers having an impact is remote, and it is not worth investing in verification and validation for a low supply quantity; therefore, they are eliminated from further analysis. A similar argument is made for push rod also. On the contrary, for the elements 'valve body' and ' reset handle', both suppliers are selected because each one of them is supplying a different variant. However, further research is required to understand the different strategies with which multiple suppliers can be eliminated. With a detailed understanding, it is possible to develop a questionnaire that can be used to guide novice designers in eliminating E-S-Vs. Nonetheless, experienced engineers are comfortable in eliminating these E-S-Vs based on the team's experiential knowledge.

Third, the time consumed for this step is about 1.5 hours. There are seven affected elements and twenty E-S-Vs. Approximately, thirty minutes is utilized to identify the suppliers and their corresponding variants, and documenting the identifiers. It is interesting to note that the manufacturing engineer, which one will normally expect design engineer to elicit — an additional evidence of why this method should be a team-based effort, identifies some of the variants. However, the remaining one-hour time is utilized to discuss whether each E-S-V should be selected or not. This implies the degree of thinking process and the rigor the team undergoes in understanding the supplier-variant interactions.

Finally, the construct in the matrix either did not create any confusion among engineers or did suffer from any lack of information during its development, but the formula used to calculate the combination vector required a modification. However, this limitation in the construct is addressed by modifying the formula. Subsequently, the information flow from this step to the next one is not hindered.

In the fourth step, when engineers are asked to identify the design parameters of the affected variant elements, they classified into two broad categories:

1. Geometrical property; and
2. Material property

They used their experience to identify if the variant's geometrical or material property will have an influence on the design requirements. This step is completed just under 3/4th of an hour in which ten minutes is utilized to copy the requirements from the first step to the requirements-design parameters matrix and to generate the list of design parameters. Even in this step, engineers either did not notice any lack of information to complete the matrix or did raise any red flags on the information within this matrix, which validates the information flow between the steps and the construct validity of this step.

In the fifth step, where the DVP matrix is created, there are three observations that are necessary to discuss here. First, engineers found the rudiments of the matrix essential. Engineer #1 said:

" *A matrix of this nature will be extremely useful to show it to the legal authorities should any law suit be filed against us. It contains necessary information that they may want to see*."

Second, engineers did not find any lack of information to complete the matrix —necessary information is easily available to them from the earlier steps. Thus, the construct validity of this step and the information flow sequence is validated. The time taken to complete this step is approximately 1.8 hours, which is also an indicator of the rigor that engineers go through to identify and schedule the tests. The matrix was already created before starting this exercise, so no time is lost in creating this matrix. Thus, the total approximate time reported here is directly utilized to complete the matrix. It should be noted that most of the tests are previously planned and completed; hence, the 'start date', 'end date', and 'responsibility' columns are not completed, so the time consumption may be higher for a new EC project. On an average, it took around 6.4 minutes to complete the necessary columns corresponding to a requirement. This information is provided as an indicator for the readers, who are willing to implement this method in their company, on the time they may need to allocate their resources. Third, as several members are involved in developing this matrix, information in each column is debated in length among them to ensure accuracy.

The EC project discussed here did not present an opportunity to use Step-6 for developing acceptance criteria, so there was no opportunity to observe, infer, and report any findings here.

There are several observations in the seventh step that are essential to be discussed. First, the protocol used by the team to classify the cost and lead-time per test into low (1), medium (3), and high (9) will be discussed. The team indicated the spread of the testing cost data is not wide enough in order to clearly demarcate those values into three levels. However, there is an exception with a single test being extremely expensive in comparison to the others, which can be termed as an outlier. Thus, this outlier value cannot be used as a high value and subsequently rank other cost data in a relative sense. In this context, it is decided to classify the tests based on where the testing is conducted, that is, internal, external, or both. Tests conducted by an external agency are considered very expensive by the team, so such tests are assigned a numerical value of nine. There are tests conducted by both an internal and an external agency. Based on the team's experience, certain tests of this nature is as expensive as the tests conducted only by an external agency while in some instances, it is not as expensive. So, a relative ranking scheme is introduced for such situation. However, these two situations take the numerical value '9' and '3' respectively.

Tests conducted by an internal testing department are relatively ranked for the next two levels, which are'3' (medium) and '1' (low). For instance, tolerance analysis is relatively less expensive than conducting an endurance test in the rig. In such instance, tolerance analysis will be assigned a numerical value of ‘1’ while endurance test with a numerical value of ‘3’.

However, this approach will not make sense if it is applied for lead-time/test. It is because some internal test can be nearly as time consuming as an external test. Hence, external tests or tests requiring both internal and external are considered highly time consuming and assigned a numerical value of ‘9’. The other two lower levels, which is ‘3’ (medium) or’1’ (low), are identified using a relative ranking scheme. This protocol for grading the cost/test and lead-time/test is summarized in the Table 8.10.

Table 8.10 Protocol for Grading Cost/Test and Lead-Time/Test

Factors	Numbering scheme	Criteria		
		Only external test	Both internal and external test	Only internal test
Cost/test	9	✓		
	9		As expensive as the external test	
	3		Cost is significantly less than the external test	
	3			✓
	1			Cost is significantly less than the cost equivalent to above cell or ‘3’
Lead time/test	9	✓		
	9		✓	
	9			If tests are as time consuming as external test
	3			If tests consume significant less time than the external tests
	1			If tests consume significantly less time than the one equivalent to ‘3’

The severity of the requirements are also rated using 1-3-9 numbering scheme. The legal requirements are assigned the highest value while the other requirements are relatively ranked. However, the team rated some requirements based on the impact of loss of functionality, which is conceptually equivalent to the FMEA type severity rating. For instance, in the requirement 'DV-R1.8: The valve assembly should be operational in salt-water environment' is rated '9' by the team even though it is not a legal requirement. This indicates the need to develop a different numbering scheme to clearly highlight the legal requirements and subsequently, rate others in a relative sense. For instance, a 1-3-9-27 scheme may bring out the required difference, but testing the validity of this scheme is out of scope of this dissertation. Engineers rated most requirements either '9' or '3'; only one requirement is rated as low severity '1', which is a serviceability requirement. This makes sense for this type of product where the valve, after installation, is maintained only once a year. However, this severity may not be true for a product such as brake where brake lining has to be replaced once in six months or so. Thus, it is recommended for the readers to follow only the principle behind the severity-rating scheme rather than drawing parallels between the severity and the associated requirement.

As several of these tests are repeated by both an internal and an external agency, the construct in the trade-off analysis matrix did not support to capture this classification. The author infers this limitation when the team had difficulty in prioritizing the tests, as they were not clear whether the number in the cell indicated only internal or external tests.

		Tests																				
Requirement	Severity	Clapper strength test **(Test #1)**	Inlet pressure test **(Test #2)**	Wear test **(Test #3)**	Reverse flow test **(Test #4)**	Shot gun test **(Test #5)**	Endurance test **(Test #6)**	Corrosion test **(Test #7)**	Screw - seal Tolerance analysis **(Test #8)**	Screw- seal/ CAD packaging **(Test #9)**	Seat - mounting ring Tolerance analysis **(Test #10)**	Cycle test **(Test #11)**	Seat body tolerance analysis **(Test #12)**	Machining stock analysis **(Test #13)**	Machining process test **(Test #14)**	Assembly test **(Test #15)**	RASCO Spec 10141 test **(Test #16)**	Disassembly test **(Test #17)**	Vibration testing **(Test #18)**	Low pressure operation test **(Test #19)**	Verification complexity index (VCI)	Rank
The product should not fatigue at the rated pressure	9	4																		4	648	2

Figure 8.5 Snap Shot of the Trade-Off Analysis Matrix

For instance, it is inferred from Figure 8.5 the clapper strength test and the low-pressure operation test is repeated four times. However, when engineers started prioritizing these tests, there was a lack of clarity in the matrix to identify whether or not these tests should be repeated internally four times or externally. Although it is possible to clarify mentally, an explicit way of identifying them will be preferable.

The sequence of the tests is also not clear from this row: Which of the following tests should be conducted first: clapper strength test or low-pressure test? As per the legal requirements, low-pressure test is always followed by a clapper strength test. Either the sequence can be changed or the former can be omitted. Such test dependency information is not captured in the matrix, which can lead to inappropriate test prioritization.

After the completion of the test prioritization, manufacturing engineer raised a concern about its validity. It is because tests such as ‘cast machining stock analysis’ is prioritized last whereas wear test is prioritized first. This does not make sense because the former is conducted prior to the prototype drawing release while the latter is conducted before the production drawing release. Hence, in order to overcome this glaring limitation, it is suggested to identify tests with respect to the different stages of the drawing release: before prototype and before production.

The ranking of the requirements based on VCI metric aligned with the test engineer's (Engineer #5) best practice of ranking and prioritizing the tests. He said:

> *" I have created this type of matrix on my own and have prioritized the tests based on my knowledge on the valve, its failure criticality, length of testing, and from the opinion of design engineers.... But doing this prioritization as a team using standardized method, I am going to follow the procedure...it is going to help the process a lot."*

Engineer #1 discussed on how this matrix could help him to order the right quantity of parts, as he has experienced problems in the past because of incorrect part quantity and resulting in significant increase in the testing lead time. He said:

> *" I have experienced problems in the past where I order a quantity of 200 parts, but later I realize the parts are short. This slows down the process. With this matrix, I can find out the correct quantity of parts in the first place, and save time."*

The trade-off analysis matrix presented in this dissertation is not designed to determine the number of samples. However, as there is a need to incorporate such feature in this matrix, it may be researched and implemented in future.

Finally, the time taken to complete the seventh step is approximately 1.33 hours. The information in the rows and columns were completed before starting the work in this step. However, approximately 15 minutes is lost to compute the VCI. For each requirement, its corresponding VCI is computed in excel without using its automation feature. The reason is to help the team understand the formula that is being used, which will be useful when they create the matrix for some other project. Subtracting this time, approximately one hour is utilized to complete this matrix containing 18 requirements and 19 tests. Thus, on an average 3.3 minutes is required to compute VCI per requirement, which is an indication of the rigor the team has undertaken in completing the various aspects in this matrix.

Based on the observations from each step discussed earlier, the proposed VV&T method confirms the hypothesis ‘H1’. It is also inferred this method is valid on both aspects: logic and construct. Also, limitations in the formula used in Step-3 is identified and addressed. Similarly, other limitations in Step-7 are inferred, but they are identified for future work. Since, the individual steps are discussed thus far, the value of this method, as a whole, as perceived by the engineers will be discussed next.

The excerpts of the engineers are obtained from the concluding session — a 1.5 hour-long session — of this process. Their points of discussion were noted down and presented here. In order to ensure accuracy of their statements, this chapter was shared with the project manager for him to review, verify among the team, and comment on sections where they meant otherwise (if any). Thus, a separate interview is not held with these engineers.

First, the time required for developing this method is discussed because the time utilized by the team to complete all seven steps is approximately 8.5 hrs. This implies that the company has to allocate their resource for so long, but the question is: Is the time investment valuable? When asked to the team, engineer #1 said:

> *" The nature of the product development speed in this industry is slow, as it takes a long time, up to six months, for conducting the tests. If we can start the tests with better probability of passing the tests by figuring out the problem earlier and correcting it, we can save significant amount of time…. Our sprinklers take three months for testing. If we can prevent three iterations, we can save six months of time… So, it doesn't matter if it takes ten or forty hours, but if we are able to prevent running several tests, I think it will be extremely beneficial…"*

He also added:

> *" The time scope with which we did was around about two weeks. But if we can spread it up to a month then there will no problem whatsoever…time is not an issue."*

However, the project manager (engineer #2) acknowledge the value built in this process, but he felt the creation of the various matrix manually is time-consuming and he needed computer support:

> *"The creation of matrices in every step, copying same information from one step to the other is extremely time consuming. We need that to be reduced."*

Thus, 'Case-A' discussion is completed, yet the results will be used to triangulate with Delphi validation results and the results of 'Case-B', which is discussed next.

8.3 Case-B

This case study is conducted in a commercial vehicle manufacturer. The company in which this study is conducted is the same as where the reasons for change propagation are studied. Hence, readers can consult Section 4.2.1 for details about the company.

The project requirements for studying this case study are different than the one used for 'Case-A', which is discussed next.

8.3.1 Type-II Project Requirements

In this type, in addition to T1-R1 and T1-R2 requirements in Table 8.2, a project that is planned for an engineering change is necessary in which the reason for the change should be related to address a problem caused due to variant pathway of propagation. The rationale for this requirement is discussed after presenting the formalized requirements in Table 8.11.

Table 8.11 Type-II Project Requirements

Requirement index	Requirement
T2-R1	Engineering change in the production phase
T2-R2	Product's components contains multiple variants and multiple suppliers
T2-R3	EC to be conducted
T2-R4	Change reason is to address a problem due to variant pathway of propagation

The rationale for the requirement 'T2-R3' and 'T2-R4' is to provide the designer an opportunity to apply the proposed VV&T method for an EC, which is planned to address a problem caused due to variant and organization propagation pathway, and evaluate if this method could have avoided such problem had it been applied in the earlier EC release. If the opinion of the designer is affirmative then the hypothesis is confirmed, or if the opinion is dissenting then the hypothesis is disconfirmed. Similar approach — that is, obtaining designer's opinion on a new method for a problem they have experienced in the past— have been adopted for validating methods such as AFMEA (Eubanks et al. 1997), CPM (Clarkson et al. 2004), CPM integrated with C&CM (Keller et al. 2007). However, the fundamental advantage in the validation approach followed in this dissertation over the others is ***the validation is conducted systematically, and the feedback is obtained from the designers after having them apply the proposed method to a design problem in a real time environment***. In other methods — such as AFMEA, CPM, and CPM with C&CM — conclusions are drawn hypothetically based on the solution obtained from these methods when applied for a historical problem by the researchers themselves, which is also not based on any systematic process, thereby lacking rigor. Therefore, the process followed by the author to obtain the designer's opinion is rigorous, thereby increasing the reliability of the findings.

8.3.2 EC Project Description

The selected EC project's intent is to address a product failure that resulted in a major product recall. On careful investigation of the failure cause, it is identified that a variant and organization propagation pathway has initiated this propagation effect. Hence, this project is selected for the case study.

Figure 8.6 shows the cross-sectional view of the sub-system that is relevant for this discussion. It shows a seat resting on a seat track that in turn is attached to a plywood floor.

A bolt and a nut, which has three variants, the only difference being the material coating, hold these components together; also, each of these variants are supplied from multiple suppliers.

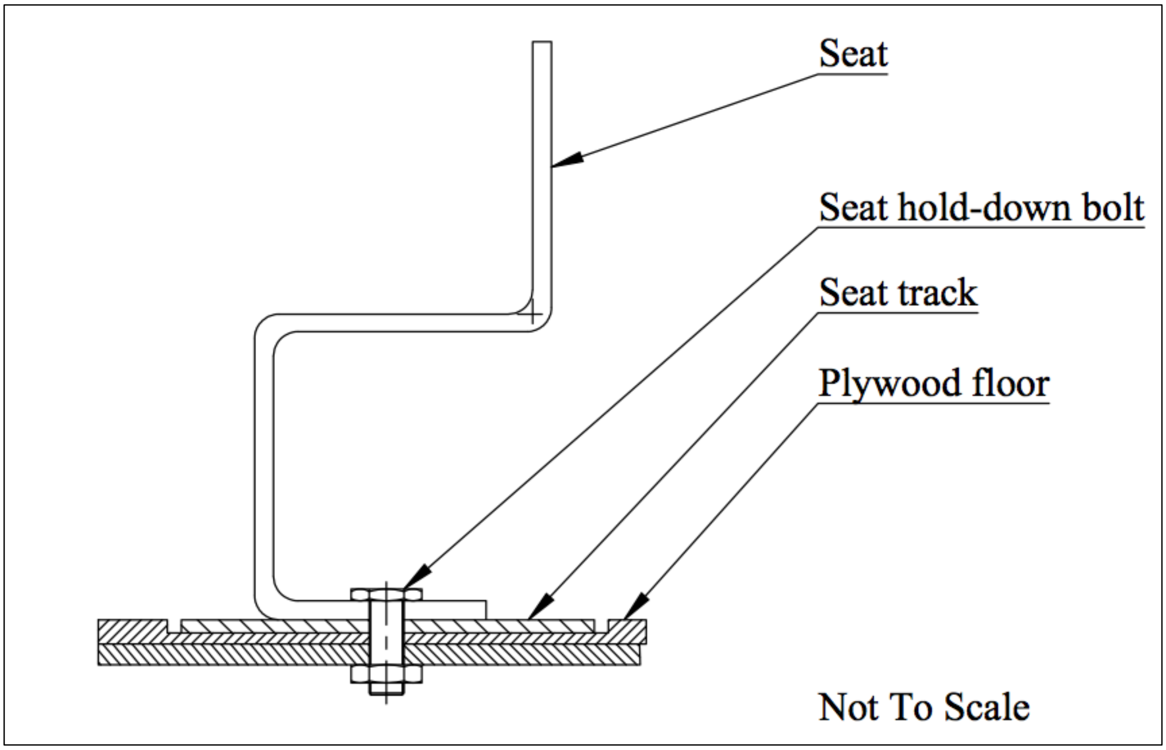

Figure 8.6 Seat Assembled to the Bus-Floor

In a previous EC release, which caused the product recall, the plywood floor material was changed from grade ‘x’ to grade ‘y’. The new grade was tested for corrosion resistance with one of the three bolt variants. However, when one of the other two bolt variants was used in the field, the plywood material chemically interacted with its material coating and acted as a nucleation site for corrosion, which eventually corroded the floor. Thus, the change mode in the plywood was an active change mode in one of the assembly combinations that was not evaluated during the validation phase.

8.3.3 Data Collection

The project engineer who dealt with the EC project, discussed in Section8.3.2, is the primary source of data collection. Another source of data is the ‘Chief Engineer’ with whom the project engineer is associated. The experience of these engineers is eight and fifteen years respectively in this company.

During the author’s internship, the project engineer (Pr.E) is provided with hands-on training on how to use this method in another on-going project in which the author was a part of the design team. Subsequently, the Pr.E applied the proposed VV&T method to the EC project for developing a test plan. Later on, a meeting was held among the author, the project engineer, and the chief engineer in which the project engineer provided his opinion on the value of this method, and how it could have avoided the product recall problem.

The project engineer’s opinion is transcribed and presented to him for verifying the accuracy of his statements. In addition, the chief engineer has also provided his opinion on the value of the developed method via e-mail to the author’s advisory committee chair. Since, this method has been developed in 2009, which is two years before the time of writing this dissertation, the author has also obtained additional feedback in September 2011 to verify if this method is still being used by them in any other projects; the implication being to identify the degree the company has valued the developed VV&T method.

8.3.4 Engineers' Feedback

This section presents the feedback information from the engineers in a chronological order.

In the meeting held among the author, chief engineer, and the project engineer in November 2009, the project engineer said:

> *"The method developed by Prabhu is helpful to develop the validation plan. When I applied this method to the bus-floor project, I found it very useful to identify the mix of assembly. I think a tool like this could have prevented the recall… when I look it into this project…we didn't test certain assembly combinations, but this tool at least helps us identify the product mix —variants and suppliers, identify these different assembly combination. If we know what to test with, testing is not a problem…and if it can prevent a failure of this magnitude —I think it can —this can be extremely beneficial…."*

The above statement implies the method can enable engineers in identifying the variant and organization propagation pathways. In this case, the project engineer has a direct reference to a problem while applying the proposed method, and during this process, the method's potential to identify such problem is constantly evaluated in their mind. As a result, the value of the method has been explicitly qualified, which can be considered as an evidence of how the engineer has positively felt about this method. Such positive feeling is not normally expressed by engineers had the method not been beneficial.

The Pr.E added:

"DVP matrix does help to plan the validation program and follow up with various agency including suppliers…. We conducted weekly scheduled meetings including supplier for developing this matrix …it was easy to follow up with what they have to do, and what we have to do…the resource availability for tests and scheduling them was organized…put it simple, it was easy to track the program progress…"

The indirect implication of the above statement is the matrix developed as a team enables to overcome the communication issues associated with test resource allocation, scheduling, and planning with the team located both internal and external to the organization; hence, the associated time delays.

The time required to develop this matrix is not explicitly captured in this case study. However, the DVP was developed in a two-week span. The project engineer discussed this important aspect of time:

" I was able to create this matrix over a two-week span, but I did skip the trade-off analysis matrix…. As I realize this tool can prevent failures and save cost…I don't think time should be a constraint."

Later, in December 2009, the chief engineer sent an e-mail to the author's advisory committee chair. It read:

"He (Prabhu) helped our team develop a formal process for developing Design Validation Plans that will continue to be used after he returns to Clemson…."

The above statement is an evidence of the method's value realized at the senior executive level. In addition, the statement indicates this method will be used even after the end of author's internship. Hence, in order to verify this fact the project engineer was again contacted on September 2011 via telephone— nearly two years after introducing the method. He said:

> *"Yes, I have been using this method with my team. I am giving the pro-flex project (the one in which you worked with after developing the DVP method) as a reference to develop DVP's for other projects; we are still using this method. We have three more projects that are coming up for which we will be using it."*

As a concluding remark of this case study, the evidence collected confirms the hypothesis 'H1'. Thus, so far, two case studies have confirmed the hypothesis. Based on the observation from Case-A and Case-B, an inference about the system boundary definition is made, which is discussed next.

8.4 System Boundary Definition

The definition for the system boundary to identify the elements that should be considered for the system analysis in the proposed VV&T method is reviewed in this section. In Chapter Six, it is proposed to leave the identification of the system boundary to the discretion of the engineers or per the current best practice followed in one's company. However, it raises question on the consistency of the combination vectors that will be determined in Step-3 if a different engineer did the same EC. In other words, this section reviews the sensitivity of the subjective selection of the system boundary on the outcome of the combination vectors and proposes an objective way of identifying elements for the system analysis by studying the results in Case-A, Case-B, and the brake drum example presented in Chapter Six.

Observing the combinations obtained from the EC examples: the brake drum (presented in Chapter Six), the valve (presented in Section 8.2), and the plywood material change (presented in Section 8.3), it is inferred that the combinations are primarily obtained from the variants of the affected elements that are directly interacting with the change element. For instance, the combination vectors identified for the brake drum example stems from the direct interaction of the change element, which is brake drum, with the affected elements' variants, which is brake lining and wheel rim. A similar observation is found in the DDX valve and school bus seat example. Therefore, **in a system/sub-system where the change is initiated, as a conditional requirement, the change components and the components that are directly interacting with them must be identified within the system boundary**. If the interacting elements are not owned by the functional group then they are considered as external elements. Thus, the identification of combination vectors, which is objective, will not be dependent on the subjective selection of the system boundary. In addition, considering other elements of the system/sub-system, where the change is initiated, within the system boundary and subsequently constructing a DSM using these elements will only provide an opportunity for the designer to enhance the understanding about the system, but it will not impact the outcome of the combination vectors. This process of defining system boundary is illustrated with the brake drum example discussed in Chapter Six for simplicity.

The change element, which is the brake drum, belongs to the sub-system 'brakes'. Hence, the change element and its direct interaction elements are identified in the system boundary. Even though the elements 'hub' and 'wheel rim' are directly interacting with the change element, they are identified as external elements, for the braking system group does not own them. The modified system boundary diagram is shown in Figure 8.7.

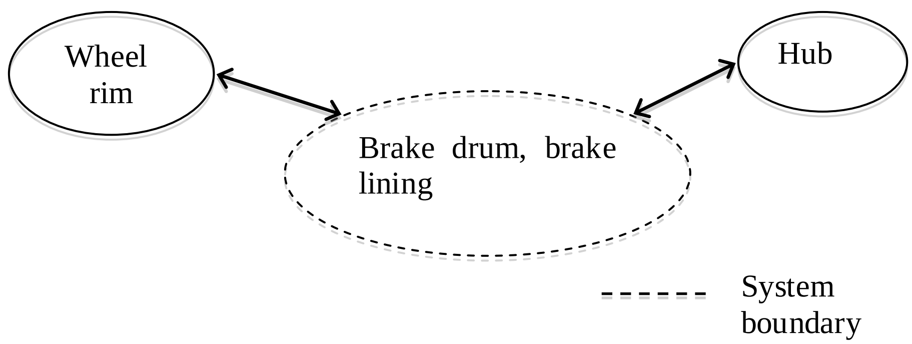

Figure 8.7 Modified system boundary for the brake drum example

Subsequently, as shown in Table 8.12, DSM for these elements can be constructed for system analysis. This DSM is a reduced version of the one presented in Figure 6.7, so the elements' alphabetical reference is preserved. As a next step, the E-S-V matrix is developed based on the procedure described in Step-3 of the proposed VV&T method in Chapter Six, which would be exactly the same as presented in Table 6.1 and Table 6.2.

Table 8.12 Modified DSM based on modified system boundary

		B	**E**	**M**	**N**
Brake drum	**B**		1	1	1
Brake lining	**E**	1			
Hub	**M**	1			
Wheel rim	**N**	1			

Comparing the E-S-V matrix with the reduced number of elements in the system boundary as against the elements considered in Chapter Six, it is inferred **there is no**

difference in the identified combination vectors. This is also true for the DDX valve, which is not shown here for simplicity. Hence, if the elements in the system boundary are identified as recommended in this section then the combination vectors will be determined consistently irrespective of the engineer who is conducting the change. An inconsistency existed earlier because the selection of the system boundary, as presented in Chapter Six, is left to the discretion of the engineer. This implies that they may or may not include the elements that are directly interacting with the change element, such as elements owned by other functional group even though it is a direct interaction element, thereby leading to a possibility of determining a different set of combination vectors. Nonetheless, this issue of sensitivity of combination vectors to the system boundary is eliminated if it is defined as described in this section.

8.5 Case-C

This section presents the validation of the proposed VV&T method using Delphi method of validation. A brief description of this method is discussed before presenting the findings using this technique.

8.5.1 Delphi Method

The Delphi method has been established as a research method in 1963 by RAND Corporation when it initially conducted experiments to identify the possible outcomes of the nuclear attacks on the US by the Soviet Union. After this application, it has become widely used world wide in different industries. It is a technique used in situations, but not limited to, when the problem does not lend itself to precise analytical techniques but can benefit from the consensus of subjective judgments from a panel of experts (Clayton 1997). Such use of expert panels is desirable because of the following reasons (Moore 1987):

1. It provides the researcher an opportunity to combine the experts' opinion and evaluate the results, thereby maximizing the chances of getting closer to the truth.
2. If the research is about solving a problem pertaining to a specific group then involving them in the research will increase the likelihood of accepting the solution the researcher develops.
3. Complex problems often times can be addressed using intelligence pooling.

This method is essentially a group decision-making process; however, the technique involved in obtaining the consensus from the team of experts is where the strength of this method rests. The researcher sends out a questionnaire, electronically or mail, to the known respondents who accepted to participate in the research program. The questionnaire is modified after receiving the responses and sent back to them. This process is termed as 'rounds', which is continued until a consensus is achieved among the respondents. The notable factor here is the respondents do not know the opinion provided by the other respondents. This is a critical factor because it removes the social-emotional behaviors. For example, in a face-to-face meeting among experts, an outspoken person within the team may dominate the meeting that may force others to conform to his/her decision even though they might have valid objections about the decision being made. In addition, this technique can also eliminate 'halo' effect; that is, tendency of the team to incline towards a decision made either by a ‘well-respected’ member or by a member holding a high rank in the organization. These social difficulties are eliminated by using this technique, thereby creating an environment for the experts to express their opinion freely without having to worry about other social factors (Moore 1987; Clayton 1997; Beverly 2004; Okoli and Pawlowski 2004; Skulmoski et al. 2007).

The other major advantage of using this technique is the flexibility it provides in terms of the number of panel members. Unlike the traditional surveying technique, where a statistical sample size is sought for achieving a statistical generalization, the number of members in the panel, with whom the interviews are conducted, is independent of any statistical basis (Okoli and Pawlowski 2004), as the goal is not to obtain a universal generalization but an analytic generalization. However, there is a recommended number of panel members identified in the literature that vary based on the characteristics of experts: Homogenous or Heterogeneous. Fifteen to thirty experts are recommended for a homogenous panel of expert — that is, from the same discipline such as astrophysicists— while five to ten members are recommended for heterogeneous — that is, from multiple discipline such as astrophysicists, university professors, and government research organizations (Delbecq et al. 1975; Clayton 1997; Beverly 2004).

One critical limitation of using this method is the selection of right experts, as the results of the study are dependent on the knowledge of the panel. To this point, experts are defined as:

> *“An expert is someone who possesses the knowledge and experience in a specific domain— (Clayton 1997)”*

The expert selection for validating the proposed VV&T method will be based on this definition. Thus, engineers who are directly involved in conducting engineering changes, managing engineering changes, or involving in addressing product reliability issues are selected. It is assumed that engineers with experience in the aforementioned roles for more than five years are experts.

This method is extensively used to develop theories, identify critical factors in a unknown phenomenon, or validate methods or processes in information systems theories (Okoli and Pawlowski 2004), and in academic setup, it is used in both masters and Ph.D. dissertation for data collection and research validation (Skulmoski et al. 2007). This method is also used in several industries including health care, defense, business, education, and engineering (Skulmoski et al. 2007). With this brief background about the Delphi method, the next section describes how this method is used to validate the proposed VV&T method.

8.5.2 Validation of VV&T Method

As described in the earlier section, the Delphi method uses questionnaires to obtain opinions from the panel of experts. Four different industries are used to form the panel such that it forms a heterogeneous group; thus, five to ten members are required. The expert's experience and the type of industry they work in are presented in Table 8.13.

Table 8.13 Experts' Background Information

Expert #ID	Industry	Years of experience	Years of experience in previous employment (Only if it is in the same industry)	Qualification	Post
#1	Commercial vehicle industry	8		B.S.	Product support engineer
#2	Commercial vehicle industry	10		B.S. P.E.	Sr. Product development Engineer
#3	Commercial vehicle industry	10		B.S.	Sr. Product development engineer
#4	Passenger vehicle	15		Ph.D.	Manager-Reliability and quality
#5	Passenger vehicle	14		M.S.	Customer satisfaction team lead
#6	Fire sprinkler	10		M.S.	Design and development engineer
#7	Fire sprinkler	10		M.S.	Manufacturing engineer
#8	Fire sprinkler	5	26	M.S.	Project Manager
#9	Fire sprinkler	10		M.S.	Test engineer
#10	Rolling mill	3		Ph.D	Sr. Design engineer

For the experts #2 and expert #3, a tutorial of the proposed VV&T method is conducted in November 2009 after a positive report to the Engineering department's chief engineer by the project engineer (refer Section 8.3.4). There were two additional experts, but they are no longer associated with this organization, hence not included in the research. In October 2010, a MS Power Point presentation is sent to those engineers along with the questionnaire form who are currently on-roll in the organization.

Experts #4 and #5, who were part of one of the three giants in a passenger car manufacturing industry, were willing to participate in this research via teleconference to provide feedback rather than working on the questionnaire. Thanks to the flexibility in the Delphi method, their request was accommodated. Since questionnaire is not used, a line of inquiry is maintained to obtain information about the specific aspects in the questionnaire form, which is presented in Figure 8.8, and the degree of agreement is judged based on their tone of expression. As an alternative to the questionnaire, a power-point presentation is sent to them couple of hours before the presentation. The time allotted by the experts for the presentation is only fifteen minutes and another fifteen to twenty minutes for discussion. After presentation and discussion, the meeting summary is immediately prepared after the meeting, which is presented in Appendix I.

Experts #6 through #9 have participated in applying the proposed VV&T method in real time setting (refer Section 8.2). However, in addition to the opinion they provided during the closure meeting, this survey questionnaire is also sent to them. It is because they can provide answers to the specific questions that are relevant to the hypothesis being tested. Finally, expert #11, who is working in a rolling-mill industry, was willing to participate in the survey. So, the proposed VV&T method was presented over the telephone along with a write-up. Two months later, this respondent completed the questionnaire form.

The questionnaire sent to this panel of experts is presented in Figure 8.8. In this set of questions, the essential questions that can help answer the hypothesis are the fifth and the tenth question, which are internally triangulated. If the respondents agree to this question then the hypothesis is confirmed else disconfirmed. If 60% of the respondents agree then it is declared that the consensus is established, or the rounds are continued after modifying the questionnaire until this percentage of agreement is achieved. Studies of this nature uses 50% agreement rate as an indication of attainment of consensus (Paul 2008); however, a 60% agreement rate is identified by the author for achieving better quality.

QUESTIONNAIRE FORM

Description:

The purpose of this questionnaire is to gather your opinion about the proposed verification and validation (V&V) strategy. The intent of the V&V strategy is to aid engineers in preparing a design validation plan (DVP). One of the benefits of using this DVP is to reduce the number of engineering changes that may follow a redesign for cost reduction purpose or introduction of new products. Each step in this strategy addresses specific issues in change propagation that are identified from previous research – change propagation is one engineering change leading to other. The proposed V&V strategy is one of the many ways to address change propagation. From an academic standpoint, we are evaluating this proposed strategy to determine its potential to minimize change propagation. We sincerely appreciate your support in this effort.

Questions:

1. In how many projects have you used this strategy to develop the validation plan?
   a) None b) 1 c) 2-3 d) 4 or more

2. Considering this strategy and other current best practice with which you are familiar, to what degree this V&V strategy can be effective in minimizing change propagation?
   a) Excellent b) Good c) Medium d) Low e) Very low

3. Does the first step (*identify requirements*) in the V&V strategy help designer address the factors listed below in identifying system level requirements?

   (You may select more than one)

   a)Aids as a guide to gather requirements

   b)Aids in thinking

   c)Assist in developing new requirements

   d)Saw no benefit

4. Does the study of system interaction in Step-2 (System interaction analysis) of the V&V strategy

help designer in one or all of the following?
(You may select more than one)

a) Aids in understanding of the system

b) Aids in identifying parts of the system that are affected

c) Minimize change time

d) All of the above

e) Does not help

5. The business strategy of using multiple suppliers and variants from each supplier presents a challenge to designers in filtering the necessary supplier variant combinations when considering an engineering change. Do you think Step 3 in the proposed strategy assists in this process?

a) Strongly agree b) Agree c) Neutral d) Disagree e) Strongly disagree

6. The design validation plan sheet is a formal document for recording the various tests needed to validate or verify a change. As most systems in the OEM are developed with a high mixture of supplier parts, communication breakdown between supplier and OEM is common. Do you think the use of this document, in addition to the current best practices, will further enhance the communication between the suppliers and the OEM?

a) Strongly agree b) Agree c) Neutral d) Disagree e) Strongly disagree

7. Developing a validation plan for cost reduction ideas proposed by vendors in a collaborative fashion can minimize subsequent engineering changes/ deviations. We believe it is possible to minimize the number of deviations because the plan is developed in a collaborative environment, and it drives the designers to think about developing suitable tests. To what extent do you agree with this statement?

a) Strongly agree b) Agree c) Neutral d) Disagree e) Strongly disagree

8. Do you agree that this seven-step process will help designers to aid in thinking and understanding of the system?

a) Strongly agree b) Agree c) Neutral d) Disagree e) Strongly disagree

9. To what degree will this V&V strategy enhance the communication between different departments in a manufacturing firm such as manufacturing, marketing, materials, and service?

a) Strongly agree b) Agree c) Neutral d) Disagree e) Strongly disagree

10. To what degree does Step-3 in V&V strategy aid designer in considering part variants from multiple suppliers?

a) Strongly agree b) Agree c) Neutral d) Disagree e) Strongly disagree

Figure 8.8 Questionnaire used in the Delphi Method for Validating VV&T Method

In order to increase the reliability of the findings, these questions are internally triangulated whose scheme is presented in Table 8.14. Questions 'Q1' through 'Q3' are preliminary start-up questions, hence not triangulated. Q6, Q7, and Q9 questions whether or not developing this DVP matrix in a collaborative fashion will help improve communication between various departments and suppliers. Q5 and Q10 is the subject of interest, as it is directly related to the hypothesis tested. If the respondents agree to these questions then it can be logically concluded that the construct in the method enables engineers to consider part variants, thereby providing an opportunity to evaluate the variant and organization pathway. Any early evaluation of these pathways can potentially identify propagation effects through these pathways, and hence, they can potentially reduce engineering changes. Finally, Q4 and Q8 questions if this VV&T method aids in thinking and understanding of the system, which are identified as two major reasons for change propagation by (Jarratt et al. 2006).

Table 8.14 Triangulation Scheme for the Questions in the Questionnaire

	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Q4					x		
Q5							x
Q6				x		x	
Q7							
Q8							
Q9							
Q10							

8.5.3 Results of the Interview

This section presents the results of the interview where the respondents' response are computed to verify if they arrive at the consensus. The qualitative degree of agreement is converted to quantitative value using the rating scale shown in Table 8.15. This rating scale has been recommended by (Delbecq et al. 1975; Huck et al. 1996; Clayton 1997). The responses to the questions 'Q5' and 'Q10' are presented in Table 8.16.

Table 8.15 Agreement Rating Scale

Strongly agree	Agree	Neutral	Disagree	Strongly disagree
+2	+1	0	-1	-2

Table 8.16 Experts' Rating for Q5 and Q10

Questions	Expert #1	Expert #2	Expert #3	Expert #4	Expert #5	Expert #6	Expert #7	Expert #8	Expert #9	Expert #10
Q5	+1	+1	0	+1	+1	+2	+2	+1	+1	+1
Q10	+2	+1	0	+1	+1	+2	+2	+1	+1	+1
Average	+1.5	+1	+0	+1	+1	+2	+2	+1	+1	+1

Ninety percent of the respondents, as inferred from Table 8.16, agree to the fact that the proposed VV&T method can enable them to identify the part variants from multiple suppliers. In addition, the distribution of data on the degree of agreement indicates a general trend of agreement while some experts (expert #1 and expert #7) expressing strong agreement. It is because they have applied this method to 2-3 projects, which is identified from Q1, before completing the survey questionnaire. Since Step-3 in the VV&T method helps designers to identify the combination vectors from these variants, which when tested can evaluate variant and organization pathways, **it can be logically concluded that the evidence confirms hypothesis 'H1'**. The results from other questions are discussed next.

Seventy percent of the experts agreed when asked whether or not this method will improve the communication between design and other departments and suppliers as presented in Table 8.17. However, the rest did not express either a disagreement or an agreement.

Table 8.17 Experts' rating on Q6, Q7, and Q9

Questions	Expert #1	Expert #2	Expert #3	Expert #4	Expert #5	Expert #6	Expert #7	Expert #8	Expert #9	Expert #10
Q6	+1	+0	0	+1	+1	+1	+1	+1	+1	+2
Q7	+2	+0	+1	+1	+1	+2	+2	+0	+1	+2
Q9	+1	+0	+0	+1	+1	+1	+1	+1	+1	+1
Average	+1.33	+0	+0.33	+1	+1	+1.33	+1.33	+0.66	+1	+1.67

Finally, experts strongly agreed the VV&T method would aid in designer's thinking and understanding of the system, as inferred from Table 8.18. This aspect has been identified as one of the reasons for change propagation (please refer Chapter Four). As a note, since the question 'Q4' did not have the rating scale, +2 value is assigned if the respondents agree to any of the first two choices in the question.

Table 8.18 Experts' Rating on Q4 and Q8

Questions	Expert #1	Expert #2	Expert #3	Expert #4	Expert #5	Expert #6	Expert #7	Expert #8	Expert #9	Expert #10
Q4	+2	+2	+2	+2	+2	+2	+2	+2	+2	+2
Q8	+2	+0	+2	+2	+2	+2	+1	0	+1	+2
Average	+2	+1	+2	+2	+2	+2	+1.5	+1	+1	+2

One of the experts, expert #3, also sent an e-mail note acknowledging the value of this method to identify assembly combinations. It stated:

" It is a very well thought out process…. We isolate the variant combinations intuitively…Of course to be thorough we have to test all the suppliers unless we can some how use a isolated test to judge that one supplier part is going to lead the

*poorest performance…. **I think when you get into vibration and noise testing, it can be much more difficult to determine, intuitively, which variant combinations are going to be worst case for all parts of the system**…The trade-off analysis matrix in the seventh step would be beneficial to maximize testing resources. "*

8.6 Conclusion

The final status of the hypothesis 'H1' is determined by triangulating the information from two industrial case study results and industrial expert's opinion, as shown in Figure 8.9.

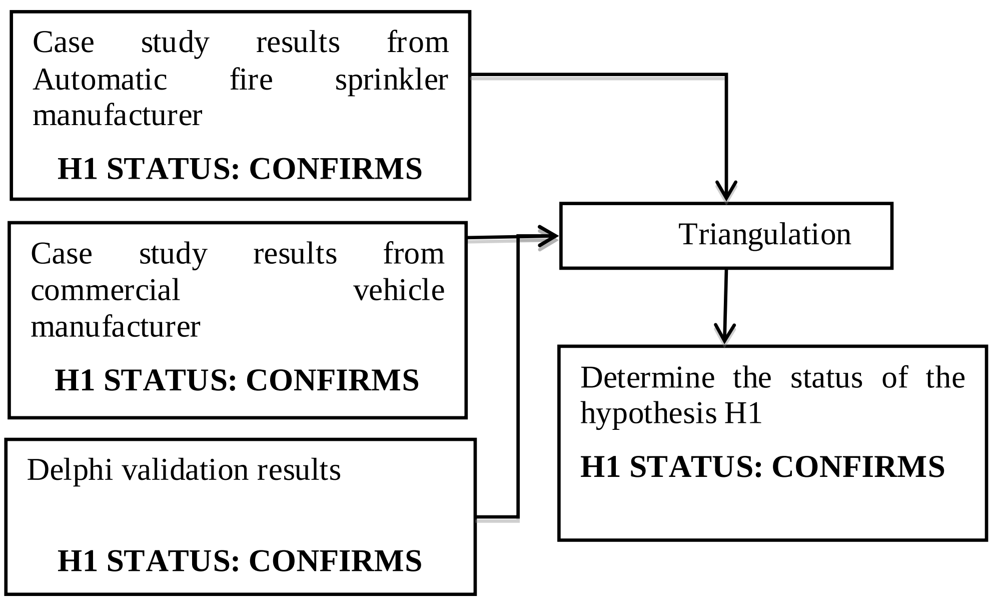

Figure 8.9 Hypothesis Triangulation Result

The results of testing the hypothesis 'H1', using different means are triangulated, that is, verified if the results from one study aligns with the other. As all three results confirms the hypothesis, including a explicit and compelling evidence in Case-A, it is concluded that the proposed VV&T method ***can reduce engineering changes caused due***

to change propagation effects specifically resulting from variant and organization pathways, which is the limitation in the existing VV&T method found in the systems engineering literature.

RQ1	**:**	*How to reduce the engineering changes caused due to change propagation?*
Hypothesis1	**:**	*A systematic planning of verification, validation, and test method can reduce design changes due to change propagation*
Status	**:**	***Confirms***

8.7 Dissertation Roadmap

This chapter presented the validation of the proposed VV&T method, and it is concluded that this method can reduce design changes due to change propagation, which is the overarching goal of this dissertation. Hence, in the next chapter, the concluding remarks are presented along with the future research areas to advance the proposed VV&T method.

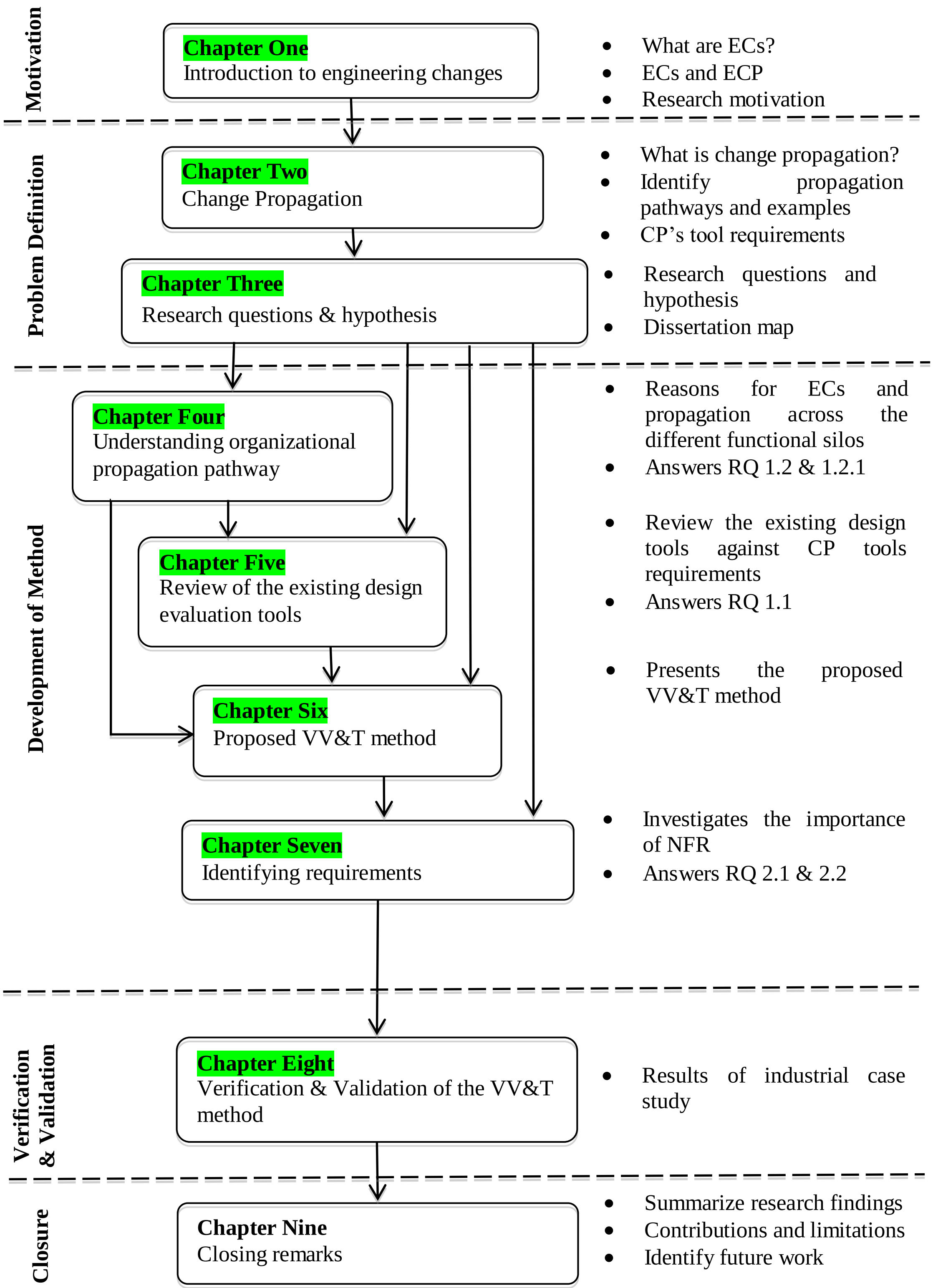

Figure 8.10 Dissertation Roadmap

CHAPTER NINE : CONCLUSION AND FUTURE WORK

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

9.1 Concluding Remarks

This dissertation presented a design method to reduce the engineering changes caused due to change propagation from a VV&T approach. To this point, six research questions have been answered, which added new knowledge to the body of literature in the Engineering Change field. Research questions 'RQ1.2' and 'RQ1.2.1' are addressed in Chapter Four using an industrial case study. In RQ1.2, the reasons for ECs are identified in which 77% of changes are identified as internal while 23% are external changes. Subsequently, in RQ1.2.1, the ones that caused change propagation are identified by isolating these changes into two: genesis and propagated. It is identified that 32.4% of the total changes are propagated changes, which were primarily due to document and design error occurring during the engineering release in addition to the ones caused by design limitations. Industries can perhaps reduce EC time by one-third, and the associated costs by creating sophisticated appropriate controls to provide redundancy in document release to avoid propagated changes in both supply inventories and manufacturing processes. This study confirms that changes can propagate across the functional domain in a manufacturing firm causing unplanned changes, which is in contrary to the canonical concept of change propagation currently restricting the study of propagation within the product. Thus, it is essential to consider this aspect in change propagation research, which will enable the creation of new management tools to support changes in incremental product design.

With this degree of understanding in causes for change propagation, the existing design evaluation tools are analyzed in Chapter Five to determine the limitations in terms of their ability to identify the different propagation pathways, such as behavioral, organizational, variant, and geometric pathways. Research question ‘RQ1.1’ is addressed in the aforementioned chapter. Several design evaluation tools are reviewed using document analysis only to find there are limited tool to determine variant and organizational type of propagation pathways.

Subsequently, after identifying the limitation in the existing design evaluation tools, in Chapter Six, the existing VV&T method is reviewed to determine if it addresses the identified limitation, which indicated a gap in the existing VV&T method as prescribed in the systems engineering domain. So, it is extended to suit electro-mechanical engineering needs such that variant and organizational propagation pathways are considered in the verification and validation planning stage; the idea is if it is considered during planning then it will be evaluated either analytically or physically. A seven-step method is developed and proposed such that it integrates the aspect of the existing VV&T method, yet incorporates new features to identify the variant and organizational pathways.

The proposed VV&T method is validated, as discussed in Chapter Eight, in a leading commercial vehicle manufacturer and a leading automatic fire sprinkler manufacturer in USA. In addition, Delphi method is also used to validate the proposed method in which experts’ opinion are obtained using an online survey questionnaire form and a telephonic interview. The participants are from the aforementioned companies and from one of the three giants in the passenger car manufacturing company. Delphi method indicated a strong consensus among the experts on the ability of the proposed VV&T method to identify variant and propagation pathways. Engineers in automatic fire sprinkler applied the proposed VV&T method to an ongoing engineering change project. As a result, new tests relevant to variant and organization pathways are identified, which was not planned earlier. ***Additionally, when tests were run on one of these tests, propagation effect due to variant and organizational pathway lead to a failure — an explicit and compelling evidence of the benefit of this method***. Similarly, in the commercial vehicle manufacturing company, an engineer applied the proposed method to an on-going engineering change project that rooted because of variant and organization propagation pathway. After applying this method, engineer expressed positive opinion on the ability of this method to address such problems. ***Thus, it is concluded that the proposed VV&T method enable engineers to identify variant and propagation pathways; therefore, it can reduce ECs caused due to change propagation.*** Hence, research question 'RQ1.1' is addressed.

A supporting tool to the proposed VV&T method's first step of identifying system level requirements is also proposed in Chapter Seven. A hierarchical requirements modeling scheme including non-functional requirements is presented, which is advancement from the existing state-of-the art. Two research questions 'RQ2.1' and 'RQ2.2' are addressed using industrial case study where RQ2.1 explores if NFRs drive the design changes, which is confirmed by the findings. In RQ2.2, it is identified where in the sequence of domains NFRs to be incorporated. After analyzing the information flow in a rear-bumper design project of a heavy commercial vehicle, it is decided to sequence after ‘working principle’ domain.

To conclude, the overarching goal of this research to develop a design method for reducing engineering changes caused due to change propagation has been successfully developed and tested. In this process, six research questions are addressed that contribute directly to the body of knowledge in the EC field. However, there are areas where the proposed VV&T method can be improved by further research, which is discussed next.

9.2 Future Work

The limitations in the proposed VV&T method are identified for future research work. First, engineers in automatic sprinkler manufacturing company expressed concern about the manual operation to create the different matrices in the method. Since, the hierarchical requirements modeling scheme is a computer-based tool, it will be beneficial to integrate this tool and the different steps in the method into single software. It is because the system level requirements can be easily identified using such tools without having to rely on engineers’ memory. This software development exercise is a Master’s level research project. The challenges involved in this project are:

1. To enhance the requirements modeling scheme to map components and their associated variants and suppliers.
2. In some companies, requirements management software will already be in place. In such situation, the software should be able to access the

requirements from that software and integrate into the requirements modeling scheme.

3. To develop user-friendly software that seamlessly helps designers to generate the DVP matrix in a collaborative environment.
4. As most companies have 3D models of their product, the DSMs created in the second step of the VV&T method should be generated automatically from these models when user keys in the associated assembly part number. However, it should also have flexibility to add and delete elements in the DSM for considering elements external to the system boundary.

Second, engineers in the passenger car manufacturing company indicated this method lacks functional analysis, as it is necessary to develop the tests by identifying the failure modes of these functions. However, the limitations of using 'functions' have been discussed extensively in Section 5.2.1. Although the goal of the proposed method is not to develop tests, which is verification requirements, it presents an opportunity to conduct a case study in an industry to determine what will be the difference in the type of tests identified when only requirements are used as against identifying tests from functions and their associated failure modes. One obvious advantage of using requirements is tests relevant to NFRs are identified, which will not surface if functions are used. Nonetheless, this hypothesis has to be tested rigorously, which is another Master's level research project.

Third, in evaluating the change modes in Step-2 of the proposed VV&T method, a standard design guideline will help novice designers to ask the right questions. It can be developed with additional knowledge of common change modes and their associated propagation effects. For instance, a material change can initiate a corrosion failure; a BOM change can cause material change. Similarly, what are the most common effects with other change modes has to be explored. Hence, this research question requires exhaustive case studies in multiple industries. Given the nature of the project, it may be completed by multiple Master's level students.

Fourth, the trade-off analysis matrix presented limitations in its representation:

1. Internal and external tests are not explicitly represented. It is essential for the test engineer to develop their schedule; hence, a modified representation of the trade-off analysis matrix is required.
2. A 1-3-9 cardinal ranking scheme is used to identify the severity of the requirements. However, legal and other functionally important requirements are not differentiated as the numbering scheme smears them off into a group of tests with similar priority. Hence, a 1-3-9-27 ranking scheme is proposed to bring out the necessary difference, which needs to be tested.
3. Use of 1-3-9 ranking scheme for testing cost, testing lead-time, and requirement severity, in certain instances, leads to same VCI metric, which implies the importance of requirements are smeared off and presented to the designers as equally important tests. Hence, it has to be explored further if a finer scale is required, such as 1 to 9, to

differentiate individual requirements. If the answer is affirmative then how to develop the scale?

4. Engineers in automatic fire sprinkler manufacturing company expressed the need to identify the number of samples required for testing. Hence, a computation scheme should be introduced in this matrix for identifying the samples required for testing.

Fifth, this research can be extended further to develop a framework for integrating the DVP software, as discussed earlier in this section, into the product data management (PDM) system. As many large-scale companies are migrating their existing data management system to PDM, it will be beneficial for them to develop the validation plan within the PDM environment because documents necessary to ECs are archived in this system. Thus, integration of the DVP module into the PDM system can help companies to organize the DVP matrix associated with each EC in a unified digital location. However, developing and testing this framework is a doctoral level research project.

In this dissertation, the focus was on variant and organization pathways, though aspects to address ambient pathways are considered in system analysis stage. However, new construct should be developed and tested to address ambient pathway of propagation.

Last but not the least, choosing the worst case in Step-3 of the proposed VV&T method may not be as straightforward as described in the brake drum example presented in Chapter Six if the number of affected elements increases. Though the engineer's experience can help identify the worst case for some problems, it may not be feasible to make an engineering judgment simply based on experience for a complex problem because different combination vectors can be a worst case for different requirements. For instance, a short wheelbase vehicle is considered as the worst-case when testing it for braking stability, but a long wheelbase vehicle is considered as the worst-case when testing for turning radius of the vehicle. Hence, a method to identify the worst-case of the combination vectors, which are stemming from the variant elements, for each requirement must be developed to facilitate filtering the combinations, thereby reducing verification cost and time. In addition, a strategy to filter the combination vectors stemming only due to suppliers is also needed. Although supplier selection can be based on the quantity supplied by each supplier and/or the quality history of each supplier, sufficient evidence doesn't exist to include these metrics as a standard guideline in the proposed VV&T method. The filtering strategy is essential in order to arrive at an optimum number of variants and suppliers, as it is not desirable for a company to invest significant portion of time and cost testing different assembly combinations than what they actually benefit from a given EC.

APPENDICES

Appendix A **: INTERVIEW #1**

Name	: Interviewee #1
Title	: Line support Engineer
Years of Experience	: 13 months
Industry	: Automotive
Date of Interview	: 07/10/2009
Location	: Tulsa, OK, USA

Prabhu: What are the sources of EC that you have experienced for a product after it is released for production?

Interviewee #1: The change requests are received from manufacturing as far as putting the vehicle together, making it easier to assemble. Most of the times the requests are for improving the design.

Prabhu: What are the types of EC in product redesign and cost reduction programs?

Interviewee #1: I don't really do cost reduction. I've done more improvement where we find the problems on the line. The changes which I have done involve improving the design to make it better. It didn't involve too much of change but smaller changes that have been overlooked while designing.

Prabhu: What is the age (range) of the product for which product redesign and cost reduction is carried out?

Interviewee #1: That varies a lot from 2 months to 20 years. The parts used in the plant were as it is since the inception of this plant. There was a small change recently and they haven't changed since the initial release, which was in early 90's. Recently, a new B port panel was introduced and we were just trying to make it work. That one was couple of months since its production.

Prabhu: What fundamental difficulty, as a designer, do you face while you start a redesign or cost reduction exercise? To be more specific, with the design requirements.

Interviewee #1: The hardest part to come up with something that would be easy to use, easy to install with regards to the line.

Prabhu: Do you have any difficulty in identifying the design requirements? You are doing the product redesign, so you would be interested to know why it was designed like how it is, what are the design requirements for that product?

Interviewee #1: Usually, when I get involved, I already know what is the problem statement, we know what is going wrong, and sometimes even they have some quick fix solutions on the line. You kind of take that, look at it and sometimes you can run with that or change it.

Prabhu: You have team center, CDMS, requirements document database, International requirement standards. Do you have a software/design tool, which links the requirements to the specific part, which you are working on?

Prabhu: Suppose you are doing a change in a vehicle body window. Do you have any software where you can directly go and look into a part no: xxx and want to know the design requirements while you design it. Can you go and look into it?

Interviewee #1: I don't think there is anything that really does that directly but indirectly, sometimes, by looking into previous releases. Usually, I have to talk to somebody who has the information. There is no straightforward method to identify design requirements from the part no.

Prabhu: Who uses this CDMS tool?

Interviewee #1: I use it and all engineers use it. It is pretty much the bible to build the vehicle.

Prabhu: What information you have in that?

Interviewee #1: Bill of materials (BOM), broken down by feature codes.

Prabhu: Is it any different than team center?

Interviewee #1: I haven't actually got to use it, as I still don't have it. It has some cool features where it can compare the CAD models with the previous revision and the current revision. I don't know how it is better than the existing one.

Prabhu: Do you have any process to identify the affected system requirements by the proposed product redesign or cost reduction?

Interviewee #1: No, we don't have. This is one of the problems we have where parts are inadvertently affected by changing other parts

Prabhu: If you are doing a product change for a system supplied by multiple suppliers. For instance, front axle, tie rod, knuckle are supplied by different suppliers. If you have an example, please add on.

Interviewee #1: I didn't have a chance to work with multiple suppliers till now. I worked with our vendor who receives part from their supplier. That is the closest I have worked with regards to multiple vendors. It was difficult to get both suppliers lined up to solve the problem.

Prabhu: Do you face similar difficulty of identifying the design requirements for EC's risen from manufacturing, service, marketing, etc.? Can you give some examples?

Interviewee #1: Not much with service and marketing but definitely we receive a lot from manufacturing. The closest thing would be working with the Decals.

Prabhu: What types of issues are raised by the assembly line and how that converts as a substitution/ deviation?

Interviewee #1: Part shortages, parts not being to print, wrong assembly is the issues rose from manufacturing line. Part shortages and wrong assembly are more common with this.

Prabhu: In this chart, we have listed possible assembly issues that can go wrong. Can you mark which one has strong dependency between two factors?

Interviewee #1: Material shortages and Logistics. Interference and wrong assembly that two work pretty close together

Prabhu: What about missing parts?

Interviewee #1: I would call that as material shortage.

Prabhu: Can you give an example for the material shortage?

Interviewee #1: Fasteners run into shortage and we have to substitute with equivalent another part that is close to the requirements. If we find and replace then that will be a substitution. Any part that is added, deleted but not replaced will be a deviation.

Prabhu: Which parts you change quite often?

Interviewee #1: Fasteners are the one that we run out of most. It is of different kinds and used at different places. If we cannot find a replacement we have to wait till we get that more in.

Prabhu: If you look into the interference, those are pretty much design issues. Any examples?

Interviewee #1: Yes, interference could be because of wrong assembly/ wrong installation drawing/ operator error. It could be any of those and occasionally design error.

Prabhu: if you have an internal manufacturing division, what types of deviations does manufacturing raise?

Prabhu: There are different type of issues like tool failure, tool maintenance, process change and material shortage. Have you come across any of these types?

Interviewee #1: Tool failure, tool maintenance is taken care by MEI.

Prabhu: Because of that do you have to do any substitution, deviation? Request can be like we have another tool but we will have certain difference in dimensions. Can we use it?

Interviewee #1: I have never seen or heard that come up. It could probably happen.

Prabhu: Anything about tool failure?

Interviewee #1: Usually they have back up tools. I can’t think of a time where they ever not have a tool to use. Depending on what it is for, you may or may not be able to come up with a substitution or deviation.

Prabhu: Operator error?

Interviewee #1: Yes, that happens

Prabhu: Because of that do you issue any deviations?

Interviewee #1: No, they have to fix it usually.

Prabhu: Because of the material shortage in manufacturing, have you ever received deviations?

Interviewee #1: As far as the part shortage, Yes. It will be just like the assembly.

Prabhu: I don't have material for floor pan but I have a different material, can I use that? Have you received any deviation of that type?

Interviewee #1: I could conceive that could happen. But I haven't seen it yet.

Prabhu: I guess this will have an impact on the assembly line because of the material shortage right?

Interviewee #1: Yes, definitely

Prabhu: These two are closely linked

Interviewee #1: Yes

Prabhu: You buy parts from various suppliers and assemble along with the parts manufactured internally. What different issues have you experienced from the supplier parts and therefore lead to deviations/substitutions?

Interviewee #1: We have wrong parts coming in such as small punched holes in various vehicle body skins. As it was low volume, we corrected the part and used it. We also received wrong rear door and frame that did not fit properly where we asked the vendor to correct it. Many a times, the vendor has to fix the parts.

Prabhu: How logistics have affected your assembly line and caused substitutions and deviations?

Interviewee #1: During December or January we switch either our supplier or distributor. We have trouble in managing the requirements (quantity) and we have to do lot of substitutions and identify the equivalent parts.

Prabhu: Was there any deviations/ substitutions caused because of design office errors such as BOM, wrong installation, etc.

Interviewee #1: Yes, we did an improvement to the B-pillar panel to make assembly easier. It was done two months after its introduction in the production line. Sometimes, quantity is wrong in the bill of materials but not quite often.

Prabhu: How much time do you have to react to a deviation/substitution/engineering change?

(Not answered)

Prabhu: What documents/ tools do you use to assess if the change affects other system requirements, requirement for validation, etc.

Interviewee #1: On the installation drawing of vehicle body joints, there will be a note indicating that is FMVSS joint. That is the only way to identify the relation to system requirements.

Prabhu: But for any other requirements?

Interviewee #1: You really have to know what is going on in the vehicle.

Prabhu: Do you have any documents / tool to find this?

Interviewee #1: In Unigraphics assembly, we can find the parts that are affected by the change. I think you just need to know. There is no warning system that denies a change in the software.

Prabhu: How do you know a change has to be validated before release?

Interviewee #1: Lot of them depends on FMVSS, you have to be careful and make sure you validate somehow. Sometimes it is only cosmetic and it really depends on what you are changing. If you are changing upholstery or padding, which is pretty straight forward, no testing is required. If it is anything of compliance, you definitely have to test. I guess you have to know which systems get affected by FMVSS

Prabhu: Therefore it is learned by experience and you don't have any software or tools that can help to do it, right?

Interviewee #1: There is no software/tool available that you can plug-in your part number and tells what you need to verify. Nothing is there to tell you the design requirements, necessarily. You just have to know, talk to people, mostly experience.

Prabhu: What type of tools do you think, if present, could improve the visibility of affected system requirements while doing an engineering change which we talked earlier (documents, CAD based, team center, etc.,)?

As I told you, it would be nice if it can if it can tell that this part is used in a FMVSS joint in the part information. It would make you verify that part without knowing everything about the vehicle.

Prabhu: Will that save lot of your time?

Interviewee #1: Yes, before you go and change your material, some kind of warning that this part is used in FMVSS could help save lot of time.

Prabhu: Some type of indication for you to prevent inadvertent changes, right?

Interviewee #1: yes

Prabhu: Will you prefer the indication to be in documents or CAD based? How do you prefer that? Well, I mean, by CAD based, you pick up some dimension and click on that dimension, it should pop up with a message showing that the specific dimension affects other system and certain design requirements.

Interviewee #1: A warning message popping up while inadvertently changing certain dimensions of a model would be kind of nice.

Prabhu: Will you prefer documents over to CAD?

Interviewee #1: Yes. That too would be good.

Prabhu: Thank you for your time.

Appendix B : **INTERVIEW #2**

Name	: Interviewee #2
Title	: Product Engineering Manager
Years of Experience	: 8 years
Industry	: Automotive
Location	: Tulsa, OK, USA

Prabhu: What are the sources of EC that you have experienced for a product after it is released for production?

Interviewee #2: It could be design improvement of an existing design that is in production. Could be for manufacturing assemblies that could be for potential risk mitigation and we do the risk analysis for a joint. Some of our joints that we have to meet federal motor vehicle safety standards. We assemble in such a way that we normally have high margins but there are some that are more advantageous to manufacturing as far as able to make errors such as back drilling holes, edge distances, overlapping large pieces of sheet metal, very difficult to handle, so many times, we will look at those types of things. One that comes to mind is our front topping sheet from the front face of the cap back to our zero bow, some people call it as cab sheet, and the geometry of it was 44 7/16 of an inch edge to edge. Well we realized that we are taking a coil of steel from 45" and shearing off 9/16th of an inch to get the perfect dimension. So we wrote a deviation and hey, you know, why throw that quantity of sheet metal in a vehicle. It is not a lot. It gave manufacturing full 9/16th tolerance. We had instances of fasteners, materials department will run out of the fasteners or screw, and will ask for a deviation/substitution. You go look in the library and find something close with different thread pitch where you could mate with the following fastener; maybe it is a different grip range that you can find. I actually wrote a deviation one time on a huckbolt, we have two different grip ranges for huckbolts. One of them will satisfy the requirement of other one, in certain applications; but not across the board that is why we have two lengths. We ran out of it once, I said ok, for these applications you could use the shorter one. But there is also a tooling issue on that one that is why we don't go across the board.

We've written substitutions for pretty large parts, that have warranty implications, could be a durability issue, that happens in a few vehicles, you know, some of the vehicles in all 50 states now, as we have, including Alaska and Hawaii, Canada and Mexico, see all kinds of different climate impacts on your vehicle, and many times say work in Arizona doesn't work in Michigan, You may not see a corrosion issue in Arizona but you will do in Michigan. So sometimes we may have necessary change, and want to deviate on something like that.

One thing comes to my mind. We were running out of certain piece of body insulation, rectangular fiberglass insulation. We have 14 different part numbers with that installation. Well you may ask yourself, why do we have 14 different pieces of installation? Ok you just cram on in here and just cut one down; Believe it or not, we have fourteen different geometric shapes that we put in panels in the front end, rear end above the windows, below the windows, in the corner. So, you can't cut down, again, for manufacturing it is difficult 60 vehicles a day sit and try to cut one piece, so we have all those pieces so they know what they are. We will run out of it sometime. We will write just deviation and say it is ok to use 'y' material for 'x'. That kind of thing.

Prabhu: You can use this chart (Showed the DSM deviation chart) and think of some examples

Interviewee #2: Use this chart? Ok

Prabhu: What are the types of EC in product redesign and cost reduction programs? (Showed the Deviation matrix)

Interviewee #2: Thickness reduction – I have not written a deviation on thickness reduction as far as …but in cost reduction, we have done one. I have written a deviation for increasing the thickness on our bows. North Carolina requires a twelve gauge bows. The state specification changed, well, we had excess inventory, we said you can use 12 gauge bows on other vehicles but you can't go the other way. So we had excess inventory and we wrote a deviation. I am thinking about thickness reduction not isolated to metal. Actually we had a material change in undercoat.

Material change – Sure, wheel pocket covers, going from ABS plastic to TPL plastic as cost reduction, we have done one of those before. We've done deviations for certain people's floor mat. Usually in those we used to call the customer and ask whether it is ok but then you write the deviation and change the order.

Part elimination – Yaah, we try to get rid of parts before. Actually, fastener reduction is quite big, overhead lining comes to mind, driver's side sheet, driver's electrical panel access, after entrance door trim, lift door trims, side door trims, we reduce the number of fasteners. We reduced the number of fasteners in the lower lining, wheel pockets. Every time you take out fasteners, you have to introduce structural adhesive, combination systems, so, you eliminate some parts but you add some epoxy but we consider that as a reduction because you don't have to drill all of those holes.

Part consolidation – That's one of more difficult things, school vehicle industry is unique and varies with lot of complexity. Lights come to mind. Lot of that is we have six vendors on very similar part. Purchasing will go to vendor and say "hey, you are too expensive, help us out on price, because you got your competitor is selling out at 'x' cost". We used baader brown fans and lights. Then they got into some financial trouble but again they were just too expensive. We consolidated to fewer vendors basically so that it is kind of a consolidation also. That is difficult. Actually, consolidation, I don't know, Americo writes number of deviations on chassis side, for numerous things. We have done that in the past before.

Material reduction through topology change – Oh, I don't know if I have ever one of those. I don't believe we actually have one. Shape affects so many other things. We have deviated standoff clips. We have taken a clip out and clip in. That is a tough one for me there (pointing to the chart)

Part redesign: Oh yaah, my Gosh, 25-30% of substitutions are part redesigns. Harnesses, certainly. We have so many feature codes that interact with one another with Boolean constraints among each other. Well, if we miss one and we get a vehicle without a feature, we have to release a new harness. To sell it, you have to overlay to satisfy that feature. Then you have to go and redesign all the harnesses. That is in hundreds probably over the time I have been here. Those have been literally hundreds.

Entire launch of drive plus in April of 2003 was a complete part redesign. The light bar track has been redesigned five times since I have been here. We used metal with plastic, so we get away with sheet metal joint. All the five times, it was driven by cost and available tooling, Conway has tooling, well, one time we reduced the number of fasteners, added some epoxy and took some screws out. Well on another time, we said, we wanted to go to plastics. Well, government doesn't consider plastic to be federal regulated structural joint. We had a metal one and it has to be a joint as it is inside the vehicle compartment. We went to a plastic joint then," oh no, it is not a joint". Ok. We have to glue it, we don't have to screw it in, and we just have to put it in. To hold it in there, you got to trap it behind the window and then you screw it to the vehicle. Then came a quality issue, customers didn't like that over time. They would crack when the sheet metal box of the vehicle wrack around the chassis and in the vibration. Wasn't lot of durability testing done on some of those things. A cost reduction program would save $150,000 but the testing would cause a million. We build a case something around like that right? Another time was, well, we need to reduce the splices around the light bar system. Finally we came back to what we are doing now, light bar metal track is screwed up to the wall and just pop in the plastic. Parts were just snapped into the place. That was great. You didn't need as many people. That is how you save so much money there. We had a little bit of materials, but the manpower and labor we saved far and ahead exceeded that. Finally, we reduced the amount of metal we used by using a J clip. It catches half of it in the window and half of it snaps up. Less manpower and cheaper material cost. Lot of them was driven from, might sound funny, the steel prices. It fluctuated on us over the last ten years greatly. When I started, we were paying about 40-41cents a pound and it got about 62 cents a pound. Now, it went down due to special pricing because of volume, I think we are down at 39 cents a pound now. So it is a catch 22. You spend some engineering resources and try to take the cost out but then you can do with materials.

Prabhu: What is the age (range) of the product for which product redesign and cost reduction is carried out?

Interviewee #2: That is going to vary greatly. Around 20 years.

Prabhu: What fundamental difficulty, as a designer, do you face while you start a redesign or cost reduction exercise? To be more specific, with design requirements.

Interviewee #2: (answered in the next question)

Prabhu: You have team center, CDMS, requirements document database, International requirement standards. Do you have a software/design tool that links the requirements to the specific part, which you are working on?

Interviewee #2: I will answer it in a different way. The percentage of the time that you can find the design requirements is 90%. That time length would change. The 90% I say yes on I will spend 20% of the time a week. That 10% left that I can't find I spend a lot of time on it. That is also the point where you kind of go, like your bumper. What load is required? You take what you do now, apply some logic and then come up with the worst-case scenario and best-case scenario. The 90% of the time, it is easier for parts like fasteners.

Prabhu: Do you face similar difficulty of identifying the design requirements for EC's risen from manufacturing, service, marketing, etc.? Can you give some examples?

Interviewee #2: (Answered in the previous question as a whole)

Prabhu: if you have an internal manufacturing division, what types of deviations does manufacturing raise?

Interviewee #2: For me both manufacturing and assembly are same.

Prabhu: What types of issues are raised by the assembly line and how that converts as a substitution/ deviation?

Material shortages – Oh boy, we probably deviate two or three times a week. We have over 300,000 assembly variations in the school vehicle. God bless the material department manage all the material. It is not a truck. You build a chassis, which is very similar to a truck, but then you drop a 35 foot long piece of sheet metal box on back of that thing. And then you run all the wires, over 500 and 680 connectors, you run out of parts. You give an estimate of annual usage to the vendor, they just lose a truck, a shipment is gone, a million square foot facility for full warehouse, and they can lose parts. Believe it or not, we damage parts. Guy on line actually runs the screw where he is not supposed to run a screw but ruin a part. If he is in a hurry and doesn't fill a scrap ticket out, turn it into the material review board, you run short. Materials think that they got one, but they don't. So we have to come back and write all kinds of shortages there.

Interferences: The recent one that is coming to my mind is the two sheet metal panels. One on the inside and one on the outside of the zero bow near the driver side, exterior post cap was interfering with outside electrical access panel. It was an overlap issue; it was a stack up issue. The interference wasn't a hard interference. But what you ended up doing is taking the sheet metal panel and as you put your screw in you actually overdrive it. So you bend your panel. It was not a clearance interference non build situation, but terrible quality issue. Well, it was almost can't fix kind of issues. We did a deviation and removed some of the holes; so basically we shifted our entry points.

Other one we had, that was a hard interference. We got on our I-6 recharge ports, on the pressure side coolant lines. One of the service ports was oriented almost 90 degrees normal to the hood and has a hard interference with the hood. Service port is a metal and the hood is fiberglass. You don't see it until you cycle it a few times. We get call from the field service engineers "hey, I have hard interferences in the hood and we are cracking hoods". Ok, we wrote a deviation, real quick, it was more of a process deviation and clock that port over to 45 degree; it will be more of an assembly substitution. That's appropriate there.

Tool Maintenance – We do manufacture bows. Well, if the tool maintenance isn't checked the bow gets affected. The oil nozzle sprays oil while the bow is bent. If not maintained well, you don't get the appropriate amount of tool oil dispensed on your flat stock while you bend it. What was happening in it was we over bend our sheet metal bows, so that their legs kick in and they spring back. The metal was galvanized and in the process we take the galvanized flakes out from there. You take 228" long part and you bend it with quite a bit of tool force. So, if you don't maintain it, there is a tool failure. What ends up happening is you write a deviation. You will deviate to a non-conforming part because I can constraint it to the vehicle body. I had some extra rivets and hucks to make sure that it is constrained. If you take the vehicle apart, the bow will try to go but the risk there is zero because I can constrain it.

Machine breakdown – Floor welders will break and we will spot weld.

Process change – Again that is a big one.

Material shortage – Again, numerous, numerous and numerous

Assembly issues – Interferences. Again goes back to a non-conforming part that we can use. We modify the part without part holes or drill holes. Plywood comes in periodically that wouldn't fit in your vehicle. We trim it down and modify it from the assembly side.

Operator error – The operator might cut a hatch on the window section through the roof. I will go out and judge it. Hole is not driven by the feature code. There is nothing really out there to write down on a paper. Ok, I am not putting this feature code on; I am putting this feature code. Well, we have actually put three hatches on ten vehicles. Again we will call the customer, "hey, manufacturing cut the holes on the window section". So is it ok if we give you a free hatch? You have to guard yourself against that too.

Wrong assembly – Operator error, wrong assembly, those are kind of almost synonymous. They are pretty close. As a matter of fact we did have wrong assembly just few months ago. We used wrong U bolts on the front axle and didn't meet the necessary torque requirements. They just had two threads shown up past the nut. So they were able to catch that. So they came back and due to a wrong assembly operator picked up the wrong part, we had to intervene there and correct that.

Missing parts to assemble – Yaah, It is similar to material shortage. I am just trying to think of anything different. We have had missing parts out of kits that we don't have part numbers on. We have vendors who supplied kit with not all hardware in it. We have had that happened before where we had to go locally buy component parts.

Supplier – Alternate supplier, definitely with alternate supplier. The 26 Meritor axle vehicles that was short and replaced with Dana.

Interviewee #2: That's one right there. We had a different starter from a different supplier. We wrote a deviation there. David Rooming just found a lift switch that the supplier didn't provide. They didn’t ship it, didn’t show up and went locally and got an alternate switch. Basically, the same switch but different shape of body, different thread, nut, but again it all comes assembled. We have to do deviation here too.

Change of supplier: Steel is one of the biggest ones. We had deviations because the raw material was different. Supplier A sent cold rolled steel but the supplier B supplied hot rolled pickle steel. That completely offsets our computer program that is used by the floor welder. With cold rolled steel, your tip geometry degrades with so many cycles. And you take the tips away and put new ones in. We were really getting only 2 to 3 cycles in comparison with 12 to 13 cycles of supplier A. So, our cost went to the roof on our tips. We deviated and asked them to use the other steel because that was the one we had. We do pull tests in our factory and ensured that it meets the compliance requirements.

Marketing: Corporate purchasing changes things a lot. I think you might add one in the cost reduction. One of the think that comes to my mind is the badge, the engine badge right behind the entrance door. There is another one, real nice one with embossed face and raised. We have been paying $15 on each one of those. Well, marketing, came in as a cost reduction, they were able to come up with just a decal. It was real nice chrome with adhesive back. The engineering release came through and propagated all the part number on all these jobs. Well, we were sitting on the 200 of the old ones. We wrote a deviation. That was an inventory build up because of a cost reduction proposal from the marketing.

Interviewee #2: We have several obsolete parts to be salvaged. We have got, here, $4000 on stop arms. We are going to figure out how to use these. I have got another one on U bolt on the front axle. We will probably modify these and trim them down. One of the designers made a mistake and pulled a FAV in with a pack of part number and he expired it. Complete mistake, so we had different inventory. As a matter of fact, I gave **Interviewee #4**, this morning about $14000 in radiators. Manufacturing considered expired. Well, again an engineering release came through. Long story short, we rolled inventory. Brought it back in, available to use. Americo is working on a controller. We have an inventory of $32000. We locally have the IT technology that we can go and reflash the controllers to pick up a new set of ABR features into work. It cost us time and labor to do that. So we got the supplier do it. By doing that one we write a deviation on that and say it is ok to turn C2 material into C3 material. I think inventory is important. This is a big substitution/ deviation for an obsolete slow moving material. If it is slow moving__ is high. So ___we will still look at it and see if we can modify the part and just substitute it.

High field failures: Mud flaps turned out to be a supplier issue. But mud flaps were curved and it was hitting the tires and got shredded. Well apparently the raw material and they didn’t have the right elastomers made in the rubber. Well as soon as they got some UV exposure it started curving. Well basically we have to deviate to a new material.

Customer dissatisfaction: Certainly the floor mats is the biggest one that comes to my mind. It is just tremendous. Another high field failure was when we took, we used to put floor track for handicapped wheel chair vehicles. They took the wheel chair and shackle it down to the floor, so you don’t have the occupant transfer inside the vehicle. Well, we were laying non-coated aluminum track in to routed plywood and then we use a tie down bolts that was black phosphate. We have used for years that type of system. Somebody came in and made a special request for new plywood. They wanted treated marine grade plywood and introduced a new chemical into this plywood. You routed it, put aluminum down, then you ran a bolt through the aluminum track and punched galvanized floor. Within six months you had holes in the floor. Bolt was rusted through because you had this galvanic corrosion issue. Basically what you are doing was you turned your bolt into sacrificial anode at that point. As soon as it hit salt water, it accelerated the corrosion. We have some vehicles where the nuts were actually backing off because the corrosion was so bad in Florida. Those vehicles were running on the coast side of the state of Florida. It had high mist of salt that was a very large recall for. So what we did was deviated to an anodized track and brought in, still aluminum track, but was anodized. That solved the problem along with special oil. So those are some of the things that I see.

Missing geometry to assemble: We have things for missing holes. Yaah. Frequently we drill and re drill holes. Now, I don't know if it falls in here.

Accessibility on service side: Lift doors – Back in 2005, we went to 42"from standard lift door to 43" We changed it. In this door, we have a latch side and a hinge side. The door is assembled from inside the vehicle frame. Subsequently, it is riveted and screwed. The other side of the door, hinge side, is covered with a sheet metal with glue. This made it unserviceable as this sheet cannot be removed in the field. It is necessary to remove this sheet because the door gets sagging after a period of time and the customers want it to be adjusted by tightening the hinges. Since, the sheet metal is glued and covers the hinge portion; customers were not able to access it during service. We quickly wrote a deviation and started fastening the sheet in place of gluing.

Prabhu: You buy parts from various suppliers and assemble along with the parts manufactured internally. What different issues have you experienced from the supplier parts and therefore lead to deviations/substitutions?

Interviewee #2: We do deviations for SREA's (Supplier request engineering approval). They will have their own cost reduction projects, redesigns, and those types of things. In 2006, we had a very large deviation for windshield wiper motor. The vendor went down to some cheaper components inside the motor. But the windshield wiper motor was outsourced with some of their suppliers from where they were buying their components. They outsourced. Really would have been a transparent change for us. We might have never known. But, legally they have to tell us that they have a different product because they have to change their model number. So they have to request us through SREA. For us to put it on our vehicle, our engineering department has to approve that, many times what we will do is… (Didn't continue and deviated the topic), by doing that we also got to change our part number. But they wanted to launch. So we will help them to do that. Also, partnerships, we will let them do by writing a deviation for parts or assemblies or whichever it is. That happens quite a bit.

Our step well heaters are supposed to kick on as it reaches a certain temperature. They have a thermostat in them. This heater supplier also makes floor heaters that are not under the seats but behind the wheel though. It is to maintain the heat capacity behind the vehicles.

They also have thermistors in them. The fan is supposed to kick on and cool them. Well, the thermistors are supposed to be in there and after certain temperature the fans kick on. Well, they had outsourced those thermistors overseas and they didn't check the current values. They had underrated thermistors. Fans wouldn't come on. So you are just running in heat and you are distributing it so that the entire box is seeing all of the heat from the engine coolant. The heaters were failing, fans were burning up. Current to the fan motor that wasn't actually spinning. They were seizing up and burning. So they came back through for a deviation. They quickly scrambled to rework their fans in states. They put a big orange sticker on the side of each fan so we deviated to the same part number but the reworked material allowed us to use them in the vehicles. I don't think that will fit in this column.

Interviewee #2: Supplier quality that would be a good one to use that verbage. Probably I will talk ever on this. I have seen so many. Manufacturing and assembly are literally synonymous there.

Prabhu: for this type of organization it appears to be synonymous. But if you consider a Tier I organization they will have separate manufacturing and assembly division.

Interviewee #2: Ok. I got you. 10/4. That makes sense.

Prabhu: How logistics have affected your assembly line and caused substitutions and deviations?

Interviewee #2:

JIT failure – It is again logistics. Yaah. Engines, transmissions, brakes, calipers, remember we shut down line because of brakes couple of weeks back? That is a JIT. That didn't show up. They were on the boat. You know that kind of thing.

Shipping damage: Very seldom do we use parts that have been damaged to deviate. We have used lower lining that was damaged in shipping. Because we had a 290 degree brakes in the lower lining. Well the part was completely hidden by the window and the rub rail you can't see it. Technically, if it is bent and has a wave in it, all the rivets you put in straighten it out. So, it was damaged but we were able to use it. That was noted as damaged material but ok and compliant.

Prabhu: Was there any deviations/ substitutions caused because of design office errors such as BOM, wrong installation, etc.

Interviewee #2: (answered earlier in a different question)

Prabhu: How much time do you have to react to a deviation/substitution/engineering change?

Interviewee #2: That varies Prabhu. Most of it should be answered within 10 minutes to a day. If we cannot answer and have to contact Fort Wayne, we will wait till a week's time, which is very costly to us. You know, the plant will be shut down or the inventory builds up till you get a direction from the Fort Wayne.

Prabhu: What documents/ tools do you use to assess if the change affects other system requirements, requirement for validation, etc.

Interviewee #2: We don't have a tool to identify the system level design requirements. We have vehicle engineering, at times, we may call them and ask. We will have design review with senior managers and experts will let their thoughts on it.

Prabhu: What type of tools do you think, if present, could improve the visibility of affected system requirements while doing an engineering change which we talked earlier (documents, CAD based, team center, etc.,)?

Interviewee #2: CAD based will be a good one.

Prabhu: Thank you for your time. It was a good interview with good examples.

Appendix C **: INTERVIEW #3**

Name	: Interviewee #3
Title	: Line support Engineer
Years of Experience	: 21 months
Industry	: Automotive
Date of Interview	: 07/15/09
Location	: Tulsa, OK, USA

Prabhu: What are the sources of EC that you have experienced for a product after it is released for production?

Interviewee #3: Generally it is from the production when we first run the new parts, their installation difficulty drive the next round of engineering change. We do get quality driven changes, and the warranty driven changes. Warranty groups give us call and say that we have seen lot of this happening in the field. For example, leaks on vertical kick out windows. We had variety of things and I would say 80% of them are driven by production and the rest of it is quality driven.

Prabhu: Can you divide the proportion of change request within production such as manufacturing and assembly?

Interviewee #3: I would have to put everything as assembly because technically we don't manufacture any of our parts, correct?

Prabhu: You manufacture some parts, right, like floor pans, sills etc

Interviewee #3: We do bend bows and it is pretty simple. We don't have to change the bows at all since I have been here. Most of the change that comes in is in ease in installation, assembly, making it stronger or fit better

Prabhu: What are the types of EC in product redesign and cost reduction programs?

Interviewee #3: I have never been directly involved that changed the material thickness. I know they are out there. Most of the cost reductions that I have been involved are fastener changes. Sometimes fastener reduction, placing the epoxy in joint and reducing fasteners, changing the spec of the fastener to allow a cheaper one is some I could think of. I haven't been involved in lot of cost reduction ideas. Sometimes warranty reduction can be deemed as a cost reduction. But it is after the fact.

Prabhu: What is the age (range) of the product for which product redesign and cost reduction is carried out?

Interviewee #3: Most of them have been in production since the introduction of drive plus, which I believe it was six years ago. The oldest parts in Amtran. I haven't changed any of those.

Prabhu: How old are they?

Interviewee #3: The oldest one. I mean, there are parts fifteen years old and still running.

Prabhu: What fundamental difficulty, as a designer, do you face while you start a redesign or cost reduction exercise? To be more specific, with design requirements.

Interviewee #3: The biggest problem facing any redesign within vehicle is maintaining all of the variations and to make sure that you cover all of your bases with all feature interactions. I mean, we have so many different features; you have to consider every possibility or whatever you structure and redesign and possibly not work. That is the biggest thing that is trying to keep track of every feature that could possibly interfere with what you are doing.

Prabhu: Is it like having a feature and it is going to interfere with some other part?

Interviewee #3: Yes. A/C is always a good example. Just because we have fourteen different A/C codes and within those you have different evaporator and condenser placements. But with the rear evaporator, say if you have a Colorado reinforcement package that dictates where you put your evaporator. You also have to pay attention to where kick outs and emergency exits are. You have to make sure that everything passes. You can't just get a list of parts and structure them to the vehicle and make the model because you can come up with a non-compliance vehicle.

Prabhu: So do you mean to say that it might affect the design requirements?

Interviewee #3: Yes

Prabhu: So that is one of the major issues, which you face, right?

Interviewee #3: Yes

Prabhu: To put in other words, while you do design changes, the design requirements are not visible to you, right?

Interviewee #3: Yes

Prabhu: You have team center, CDMS, requirements document database, International requirement standards. Do you have a software/design tool, which links the requirements to the specific part, which you are working on?

Interviewee #3: To get through a vehicle built, you have to use CDMS. CDMS will let you see the actual parts released and will also allow you to see part joints. BAAN, which is an actual traveler, which rides with the vehicle, has parts pulled from CDMS, and also any adjustments made at the facility to adjust for something that was done wrong in the first release. You can add parts, switch out parts, which don't change CDMS, but it will show up in BAAN. Ok, We also have EOFF, which will allow you to pull individual orders or job numbers, look all the features on it within the vehicle and look at FAV's, which will steer you to work. There is team center but I had only the training and we didn't even have it here. I am not good at team center yet. I wouldn't be able to tell exactly what it does. Pharos is quite a bit quicker for accessing drawings, installation drawings. Not all installation drawings are listed within CDMS.

Prabhu: Do you have any software or design tool where you can access design requirements for the parts, which you are looking on? While looking into CDMS do you have any connection between design requirements?

Interviewee #3: No. I mean, if you want to know the design requirements, basically all of our requirements are driven by FMVSS. So basically you have to know what you are working on and know what regulations are going to be affected by that. So you need to go through the section of FMVSS that apply to the project. If I get a random piece there is nothing that tells me where to look, you kind of open the FMVSS documents and look for it.

Prabhu: Do you have to know by experience?

Interviewee #3: Right. Then you have link to Conway engineering page where you have link to all of FMVSS and it is broken into sections. So, you should know for the most parts by experience. Have a general idea of what you are going to affect. You can scroll through and find your exact page and make sure that you are compliant.

Prabhu: But there could be cases where one of the dimensions could affect some other FMVSS. Are those things learned by experience? Do you have direct link/tool, which tells you all these information?

Interviewee #3: No, you don't have anything that tells you correctly, I mean, we also have a compliance group in Conway, and if we have questions we will enquire that group.

Prabhu: If you have a system supplied with multiple suppliers, how would you handle cost reduction and redesign activities? For instance, a front axle assembly will have parts supplied from different suppliers and put together

Interviewee #3: I have not come across as I deal with body side. I don't know anything of the scale, which you are talking about.

Prabhu: ***Do you face similar difficulty of identifying the design requirements for EC's raised from manufacturing, service, marketing, etc.? Can you give some examples?***

Interviewee #3: Yes. Production is cut into sections and they manage. Whatever is causing them problem, they have to change and they wouldn't take into account what they will do somewhere else in the plant. Basically we have to take their request and look what the problem is and then run that all the way through the plant and think what are they going to do here? So same problem, you just have to be careful and the biggest part knows by experience. What happens where and what affects what? And that's the steepest learning curve. It takes quite a while, because, I mean, there are things that you will never think of. You will change it and it will go through the finish line where a Decal has to go on but there is an emergency exit. You moved a light, you didn't think of it. You have to come up with another solution, which you remember that next time. I mean, there are things that you have to learn and work through.

Prabhu: Is this gain of knowledge through experience captured in any of the system?

Interviewee #3: No, there is not one system; there is nothing that covers every possibility. We have so many features and so much variation that there is a lot of it that you just learned. There are just features out there which are completely incompatible and we will write edits but to find those combinations all time. If those combinations weren't found when they were created, somebody has to see that it is not a viable combination so we can block on that feature but we work through that all the time. A little bit of foresight on the front side would help eliminate those and help up production quite a bit.

Prabhu: ***What types of issues are raised by the assembly line and how that converts as a substitution/ deviation?***

Interviewee #3: Part shortages come up fairly often with all of our variations. We generally have a part that is close to what they are meeting. So we can go and we can pull parts. Depending on the feature combinations we can, sometimes, substitute parts. Most things for the part shortages are not exterior parts. You don't deal with frames and joints when you do with the substitution. As far as what drives the quality engineering change, we have our ITBR, which will call us down, and if they have seen a trend of misaligned parts or something that doesn't look quite right, function quite right, we will document the problem, and we will find a solution, write a pyxis concern and then release that. Production is basically the same thing. They have something that slows down and they need better ways to fit parts and assemble easier. It is the biggest driving force that the production wants.

Prabhu: Have you faced anything on operator error like wrong assembly?

Interviewee #3: We have plenty of that. The vehicle is put together completely by hand. When you have operator error it is just a matter of going in there and evaluating it. If it is a joint for FMVSS that required quite a bit tension for the repair, I mean, adding fasteners or completely updating the vehicle parts. You cannot put a blanket cure on any of the operator errors because they are never the same. If we do happen to see one area where an operator is continually missing something and, that's lot of time, that's result of the bad design. So we can look at that if fixtures are not working correctly that is one thing. If it is a bad design and it is hard to put together that falls on us and then we will go and try and release something that we can physically go and put together in a timely manner without messing it up.

Prabhu: ***if you have an internal manufacturing division, what types of deviations does manufacturing raise?***

Interviewee #3: We do have manufacturing errors. I mean there are temporary manufacturing changes till whatever is remaining

Prabhu: Is it a deviation or substitution?

Interviewee #3: It is a deviation if we allow the supplier to bring in something that is not to print. If it comes in under a part number and if we know so, we can write a deviation to allow that part in. Then we will write within the deviation how to install the part correctly and make it work. I kind of think of a good example for deviation. Deviations don't happen near as much as substitutions do and we can submit deviations sometimes when the design is not correct. The GPS units that we ran through, we deviated and we added plates and cut holes on the overhead lining. We also have to deviate the promoter, which you applied to the topping sheets and promoted adhesion of the GPS units itself. As it turns out, the in house safety engineer did not approve the promoter. So we have to go out and find a suitable substitution/ deviation because there is not a part number for the new piece. That is the biggest part. There are deviations due to our own manufacturing at times. Not every instance is documented. For operator error, if we do those, if we go down and make a repair. We are not making the repair but we tell them how to make the repair. But that's not always in a deviation. It is case by case and is on the spot.

Prabhu: ***You buy parts from various suppliers and assemble along with the parts manufactured internally. What different issues have you experienced from the supplier parts and therefore lead to deviations/substitutions?***

Interviewee #3: I think I answered this question just now.

Prabhu: ***How logistics have affected your assembly line and caused substitutions and deviations?***

Interviewee #3: For the most part, our logistics are extremely well. The only time we will run into trouble is when we release new parts and within two to three weeks run vehicles containing those parts. If the process goes and create parts, then the parts have to be put in to contract by the purchasing groups. It takes fair amount of time to get that all in that system and the parts arriving at the plant. If we truncate that into a week or two a lot of times we will run into parts issues. There are times when due to customer request orders pull up and the purchasing group cannot always keep up with the orders. We will also run into if the order board runs short and if we only have 8 to 10 days of line set. Then we are not giving our suppliers very much notice. Therefore shorter the line set that drives most of our part shortages. The next biggest cause of part shortages is the incorrect BOM. For example, we have small rubber caps that we place inside of the bulkheads to cover up the screw heads. The BOM called up 17numbers whereas in reality each vehicle took up 60. At some point that goes bad. As those issues come up we can adjust immediately in BAAN and write a pyxis and do a release. We damage some parts. Short line set and incorrect BOM is what kills us.

Prabhu: ***Was there any deviations/ substitutions caused because of design office errors such as BOM, wrong installation, etc.,***

Interviewee #3: Wrong dimensions are a rarity. I am thinking of a case but I am sure it has. I don't remember.

Prabhu: ***How much time do you have to react to a deviation/substitution/engineering change?***

Interviewee #3: Production doesn't know until they go to replace a part on the vehicle. Our station time right now is 8.5 minutes and we need a decision within 8.5 minutes of that vehicle coming in and station in. They probably don't call you within first two or three minutes. Therefore you are left with 5 minutes. Something that you can install later offline will be leftoff. That is one thing. If you are in pre paint and floor pan assembly you can't generally stop the vehicle because the layers are building on the vehicle, they need a decision and you cannot stop the vehicle. You have to make decision almost on the spot and you don't have lot of time to dig around to see if we could do this or do that. There is sometime when the vehicle can be taken offline where you can pull the floor out and have it send it in queue. If it started on the chain answers have to be given quickly.

Prabhu: ***What documents/ tools do you use to assess if the change affects other system requirements, requirement for validation, etc.,***

Interviewee #3: Generally, depending on the issue, if it is a part issue, we can substitute. If it is a large deviation we can do that in workflow

Prabhu: I am asking about the design tools.

Interviewee #3: With that short of time, you sometimes, you know, you can pull up CDMS. Sometimes you can pull Pharos, UG, you don't have time to dig through a model. That is part of where the experience comes in and you have to remember what you did last time basically. Most of the problems that we come through are similar to the problems in the past. If you remember what you did before, you probably are on the road of the right solution. So you can try to apply to whatever the specific problem is. As far as the design tools and assistance, no, we don't have. Depending on the time table, it is in the finish line and you can let run up the line a little bit, then your UG, CDMS, Pharos or BAAN will be used to figure out the problem. I mean, it depends on the problem and your timetable. Some of the decision you just need to make with your experience and apply.

Prabhu: ***What type of tools do you think, if present, could improve the visibility of affected system requirements while doing an engineering change which we talked earlier (documents, CAD based, team center, etc.,)?***

Interviewee #3: I cannot actually fathom a system that would automatically tell you everything that you need to look at within the release. I think the best thing, the biggest help would be just more knowledge of general sections of FMVSS, you know, may be feature codes, a general break down of FMVSS affected within that feature code and keep a running log of that. Most of the feature codes are not completely new. It is modified for a slightly different purpose. And if you know that originating feature and everything that was affected by it, your new feature code will have the same implications. But I cannot think of a tool that would help you.

Prabhu: No, I am just asking in a hypothetical situation. If you were given what would happen. Say, you open a CAD model and click on certain dimensions to change. Immediately there would be a pop up indicating you that change of dimension is going to affect certain FMVSS or certain system requirements. Something of that sort?

Interviewee #3: That would be great and I know there are some workings towards actual vehicle models. Within team center they say they can have a complete vehicle model with complete representation of all features. If you have that information and as you said letting us know that change in dimension could cause lack of edge distance or interference, that would be amazing, astounding and that would be cool. That would be huge, I mean, That is a quantum leap above where we are now.

Prabhu: don't worry about the leap

Interviewee #3: I know, something like that would definitely would be a huge leap

Prabhu: Instead of a CAD solution if we give a document or software where you can go find the requirements by typing in the part no and the affected requirements. How does that sound?

Interviewee #3: If it gives a complete list of the parts where to start and where to investigate that would save time

Prabhu: Thanks for your time.

Appendix D **: INTERVIEW #4**

Name	: Interviewee #4
Title	: Line support Engineer
Years of Experience	: 17 years
Industry	: Automotive
Date of Interview	: 07/22/09Time of Interview: 04:00PM
Location	: Tulsa, OK, USA

Prabhu: What are the sources of EC that you have experienced for a product after it is released for production?

Interviewee #4: Engineering change request can come from, for International, from the product center for new product development. It can come from CRC for special equipment orders and then from engineering manager for whatever changes.

Prabhu: What are the types of EC in product redesign and cost reduction programs?

Interviewee #4: More part consolidation. That will be the most of it. The other one would be the supplier changes. Historically, that would mean to me, going from one brake lining to other brake lining that they would have found something cheaper that would do.

Prabhu: Can you give additional examples?

Interviewee #4: One of the bigger initiatives that the company took years ago was fasteners; the elimination of most of the fasteners. Spent a lot of time going through installation drawings and looking for similar fasteners. You have one over here 1 inch long and somebody else there would say there is one with one and a quarter inch long. Why do you want one and a quarter inch long? Those types of things.

Prabhu: What is the age (range) of the product for which product redesign and cost reduction is carried out?

Interviewee #4: Most of the parts that I have worked on at least been for ten or more years.

Prabhu: What fundamental difficulty, as a designer, do you face while you start a redesign or cost reduction exercise? To be more specific, with design requirements.

Interviewee #4: Most of it will come in with making sure, from brake stand point; I had all the coverage that were needed for a product going forward if we are doing a cost reduction, so making sure that if all of the options were going to be covered and then eliminating some options that were very low volume that create a part that may not be used.

Prabhu: What about the design requirements? Earlier you quoted an example of brake lining. When the lining changes how do you identify the design requirements?

Interviewee #4: We would have to go do a brake testing. The brakes have to meet either FMVSS 121 standards or FMVSS 105 standard. So there would have been at least anywhere between 6 months to all the way up to 18 months of actual field testing of the lining material to ensure that the product is going to meet FMVSS and international safety standards which were actually higher than FMVSS by 20%. So what that meant was FMVSS 300 ft. braking distance at 60 mph, we would have to meet at par the organization requirements of another 20% better than FMVSS. So we would have a requirement of 240 feet of stopping distance. We have a torque test that the lining material has to meet on a mechanical device. Quite a bit of testing would have to go along. Unfortunately, most of the time, the testing and the product implementation go concurrently because of the amount of time that is needed for testing. Basically, when a supplier or somebody in the product development says the cost reduction has to be made for a particular part the program cycle and the project cycle are kind of begin together. And what I mean by that is me working on the product development side of it, will have to identify the vehicles also that would be evolved with the testing. Because, in one particular case, we were implementing a standard change for vehicle, we have to look for what wheelbase vehicle, and what power of the vehicle would you want to use for the brake testing. I have to identify that first. And then look for how many brakes are going to be affected. Because, the brake themselves are setup by axle, vehicle weight and the suspension of the vehicle. That is where you get into all of the options. So maybe, for the argument sake, if we have CAT533 engine, with 23,000-pound axle with an air suspension and it turns out that we hardly build that vehicle. The decision is we will not cover that combination through this change. If it comes back in future we will cover it through SE (Special equipment).

Prabhu: Do you find any difficulty in accessing the design requirements?

Interviewee #4: No. We were in the brake department. All of those records we have to keep them for legal issues. So, all the previous specification and related documents were held by a specific manager who held on to all of the data. It was just a matter of simply going back to him and saying, hey, where are all these specifications and the test requirements that were done on this particular lining. So you had him and you also had a project engineer who delving into that information. So you always had access to that because legally as a company we have to have that in case there is a lawsuit.

Prabhu: You have team center, CDMS, requirements document database, International requirement standards. Do you have a software/design tool, which links the requirements to the specific part, which you are working on?

Interviewee #4: hmmm (thinks a while) I am going to say No. To find the design requirement and the system I would go to, if I had that part no or FAV to look up a part number and find the design requirements, not the design specifications (thinks a while), No.

Prabhu: Do you have any software or design tool where you can access design requirements for the parts, which you are looking on? While looking into CDMS do you have any connection between design requirements?

Interviewee #4: No

Prabhu: If you have multiple suppliers for a system where you think you can get some cost out of it. Brake is a classical example. Let's consider a situation where you have an idea to reduce the cost on the spring brake actuator supplied by 'X'. At present, you contact them, propose your change, get feedback and contact other suppliers to verify if the proposed change is acceptable. How do you verify what system level requirements are getting affected by the proposed change?

Interviewee #4: No. We don't have one. That is the problem we have here. The only thing that you have out there but here is no process. But it kinds of alludes to what you are talking about and that is the infusion and validation rules. So what I mean by that is, if you know that you are going to change an axle and you know that a particular part number is tied to a feature number. You could use that to find affected systems. But there is nothing like a process, if you are going through a workflow and you are saying that you are going to do a cost reduction, there is nothing that is going to say hey, you are affecting this and is going to link you over here and start giving you that information, no.

Prabhu: You told about the affected systems, I am curious about system requirements?

Interviewee #4: No, we don't have one.

Prabhu: Do you face similar difficulty of identifying the design requirements for EC's raised from manufacturing, service, marketing, etc.? Can you give some examples?

Interviewee #4: like...

Prabhu: Manufacturing may come up and ask you to replace a part 'x' with part 'y'. How do you ensure that the part 'y' will meet the same design requirement as part 'x'?

Interviewee #4: There is nothing in the system that would automatically tell you that. No, No… There is no set process also either prevents because I would be thinking about like a bolt. There is nothing in our system that would tell you what you need to do with the design process or design specification except for the joint itself, in that case with the bolt. I would expect my bolt joint to have some design requirements on it.

But there is nothing again as a process to do that or a piece of software that would say put this number in that would match up with that. There is nothing like that.

Prabhu: What types of issues are raised by the assembly line and how that converts as a substitution/ deviation?

Interviewee #4: The easiest one would be like, for whatever reason, set number of orders was supposed to get part number 1 as brakes. For whatever reason, there was a material shortfall and they didn't get them and have to substitute with another brake. That would be one that I would say more consistent.

Manufacturability, they try to use part number 2, they couldn't assemble it and I have to give them part number 3. That would be another one. Most of them are manufacturing, assembly issues. Process change would be another one we do. We changed out to disc brakes. That was a process change for material handling because the components were heavier.

We have to, at one point; we have to come up with a mounting pattern drawing for production to use a star pattern. Because the production will use a radial pattern and they were not as good in putting torque on the brakes to mount them to the axle because in the radial pattern they were shaving material off the pilot hole. So that was a big one of coming up with a star pattern and getting the line people to do a star pattern. That was a big one.

Other is the clipping and routing. Making sure that the clipping is done in six-inch increments. Also, making sure that the clipping, tubing is not rubbing against sharp corners of any kind. That always was a big one. These are fairly consistent issues.

Interviewee #4: The electronic control modules for ABS.

Prabhu: What type of deviation was that?

Interviewee #4: Usually, that was another material shortfall or it would be problem with order coding itself for whatever reason. The requirement for the ECM or the ECM was incorrectly ordered for the application. That has happened before and has to substitute with another ECM.

Prabhu: How did you do that substitution?

Interviewee #4: You have to just know by experience or you know to look in certain areas for similar components and start using the validation rules to sort out to use those and point you back to the part.

Prabhu: Is the ECM a bought out part?

Interviewee #4: yes

Prabhu: In that case how did you handle the deviation and how long did it take?

Interviewee #4: We talked to the supplier and it took a day's time for decision.

Prabhu: Till you get a decision from the supplier, did you stop the line?

Interviewee #4: They were getting close until. To your point, there is nothing in the system to stop you from placing an ECM in the area of the heat source. That was a design issue that had happened years ago. By the way your ECM has to be opposite of the exhaust and there is nothing in the system that would tell an engineer or a designer to not do that. We are about to build a pilot vehicle and put a brand new ECM and it was going to be on the same side of the exhaust. Obviously computers don't like heat.

Prabhu: Do you have any other example other than ECM?

Interviewee #4: Any of the axles. That would be another one. Good example would be the Meritor developed an axle that would not package with Hendrickson's new suspension. It literally wouldn't package. You couldn't package foundation brakes with the new supplier axle and Hendrickson's suspension.

Prabhu: Did this problem come up after the development or before?

Interviewee #4: After it was fully developed

Prabhu: Did you try to substitute axle 'A' with Meritor axle?

Interviewee #4: They wanted to implement. They developed the whole thing. But I went and told them, they developed it and then they showed it to me and that's when I told them it wouldn't work with our new air suspension at all. Physically the components couldn't, you wouldn't be able to put them together.

Prabhu: so, it is a development issue and not an issue after it is released for production.

Interviewee #4: In that case, the axle was fully developed and the suspension was in development. Probably, 70% of the way through the suspension. At that point, obviously, suspension supplier was not going to agree for a change. We have already developed pilot vehicles and all that. That was the case where Meritor lost out. Because they were late to the party. Suspension was already in development; they came back in and wanted to do a vendor forced change, which was going to be impossible.

Process issue there is nothing between product centers. As a program manger is beginning his program to link him into another program manager like a vehicle program manager and a heavy-duty program manager. If they were working on things that could go across because their development would work with Meritor or somebody likes that. That happens quite a bit. That goes right back to your design specification or design requirements. There is nothing in the system that would interface two different program managers.

Prabhu: if you have an internal manufacturing division, what types of deviations does manufacturing raise?

Interviewee #4: (covered in the previous question and therefore not asked)

Prabhu: You buy parts from various suppliers and assemble along with the parts manufactured internally. What different issues have you experienced from the supplier parts and therefore lead to deviations/substitutions?

Interviewee #4: (Covered in the thread of discussion in the earlier question and therefore not asked)

Prabhu: How logistics has affected your assembly line and caused substitutions and deviations?

Interviewee #4: Years ago, there was a snowstorm that closed down the highways to prevent; I want to say, it was axles and brakes to get to Springfield. That was the one I could remember right off my head. Another one was a strike at Meritor for their brakes. That was the biggest one. The strike only lasted, I am going to exaggerate, say the strike lasted for 48 hours. But the effect it had on logistics was it lasted for may be six months. Because, we ended up, I don't remember how many we did; we ended up recalling thousands of orders to substitute parts.

Prabhu: How did you do the substitution?

Interviewee #4: By experience. There is nothing in the system that would tell this Dana brake is equivalent to Meritor brake. You wouldn't be able to find that out easily without experience.

Prabhu: Was there any deviations/ substitutions caused because of design office errors such as BOM, wrong installation, etc.,

Interviewee #4: I can put a scenario when we thought that basically that something was going old. That was the ones I can give you. Components that end up failing tests or components that may have been involved with a crash of the vehicle, those are the ones, what happens is that a designer, like myself, might get a phone call from someone in the management and they would ask about a particular component. And what happens is that they would ask how many vehicles are affected by that component and management might decide to have a substitution on all of those vehicles. That happens. That would be the biggest one.

Fuels tanks, it happened on fuel tanks. Many years ago, fuel tanks failed and had to find substitution fuel tanks and get them out of production immediately. And again, there is nothing that would tell a person that they can put in a part number and it would let them just see and would cross reference to these other fuel tanks. You can't do that. There is nothing like that.

Prabhu: How much time do you have to react to a deviation/substitution/engineering change?

Interviewee #4: As quickly as possible. If we wait too long, they (manufacturing) will issue a line stop, which is very expensive.

Prabhu: What documents/ tools do you use to assess if the change affects other system requirements, requirement for validation, etc.,

Interviewee #4: I have told you earlier. We have nothing in the system like that.

Prabhu: What type of tools do you think, if present, could improve the visibility of affected system requirements while doing an engineering change which we talked earlier (documents, CAD based, team center, etc.,)?

Interviewee #4: To be honest, probably a combination of CAD and document based solution would be good. Because the person that would be thinking about would really need or would find the most benefit out of it would be someone who is less senior with less experience and definitely like a product manager could use both sets of information from the CAD data and technical specifications. Combination of both would be really what is required. Because going back to the fuel tanks, you want to know what the physical size of the fuel tank substitution is. It might be two inches wider or two inches shorter or whatever. That would be some very valuable information.

Appendix E **: INTERVIEW #5**

Name	: Interviewee #5
Title	: Line support Engineer
Years of Experience	: 8 years
Industry	: Automotive
Location	: Tulsa, OK, USA

Prabhu: *What are the sources of EC that you have experienced for a product after it is released for production?*

Interviewee #5: The type of change you can have is a substitution where you basically replace an existing part with another part for some reason. You have a deviation; those are done on engineering basis where a change is done to an existing part for an existing application. You have pyxis concern which is written to redesign or restructure material due to a problem that you have online. And, in official standpoint, that covers all changes that you have.

Prabhu: What are the sources for those substitution/ deviation/pyxis concerns?

Interviewee #5: Typically, engineering errors or mistakes that comes from, probably #1 for the bus is lack of understanding of the product variation. That pretty much covers the whole realm of things. Now, our product variation is so vast that not one person could be expected to know it all. I don't know it all even after 8 years. Also, the structure of our product or the product feature are not set up so that they can be easily understood as far as location wise or where they are going to go on the bus. So lot of times what you end up having is a feature conflict when you have two features trying to occupy the same space. That is the root cause of the most of the issues: lack of understanding of the variation and inability to have access to that information in an easy format to understand or read.

One of the other causes is that, you have the SE group, that is the special equipment group, and lots of errors come from that group because of the timeline and lack of understanding in product variation, no product validation is done on most of those designs. It is basically a shortly designed part and released into the plant, and most of the validation and assembly work is basically done here in the plant. Most of the designs are validated at that time.

Prabhu: Where do you get the engineering change request?

Interviewee #5: Oh, we get a good deal of request from supplier warranty manager, which is directly driven from the field and the field service engineers. The other large majority of them come from the production line. The line will have an assembly issue or something; we will validate it and make sure that it is an issue. Then they request, actually it comes from us but driven from the line. An issue on line would be some feature or some part is not working correctly. Supplier can also drive the change. Those changes are typically due to them changing their product lines, making improvements; updates to the product and those are also fairly common.

Customer driven changes- Customer can also request changes. Customer can order a feature as a result of them not liking some feature. The requests are driven from the customer to the engineering through the plant manager to fix something, which they don't like. The change can also come from major or minor program team in Fort Wayne. It can also come from cost reduction and it can also come from ... (thinks)... I think that is it. And, program oriented change.

Prabhu: ***What are the types of EC in product redesign and cost reduction programs? (Showed the Deviation matrix)***

Interviewee #5: Part redesign and part consolidation is most of ours, you know, part consolidation and part elimination are kind of hand in hand. There are lots of things for which we have designed several assemblies for which we have designed a single part to replace the piece parts. (Looks through the chart under cost reduction column and thinks…) Some of these are tied together.

Prabhu: If you see some things are tied together please mark it.

Interviewee #5: You got these tied together pretty well. You have tied together that I would tie together. We are on the same page here.

Prabhu: ***What is the age (range) of the product for which product redesign and cost reduction is carried out?***

Interviewee #5: The average age of the product that we are redesigning, is that what you are asking for?

Prabhu: Yes

Interviewee #5: Ok. Let's go for windows. That window itself has been around since 2003 but is really been around since 1996. They are evolutionary designs. That one window and the technology have been the same for thirty plus years. Technology made some improvements over time, evolutionary, but not drastic changes to the window assembly. I don't consider what we are doing is a revolutionary change but it is evolutionary. Most products on bus are there since last twenty or thirty years and we do changes on those parts. Let's take the floor mat. The school bus is same that I rode to school and I am 35 now. They had the same floor matting in. Nothing changed much. Let's take something else. Floor track, again, we are planning to rivet it to the floor as per the cost reduction program right? The floor track has been fastened using bolts and nuts to the floor for as long as I know, infact, twenty or thirty years as well.

Most bus designs are the base design. They are very old. There has been improvements made on but the base design is very old. There have been no major changes, you know, over the years. Wheel pockets, there has been a drive to change the wheel pockets' material. That was the new one but has been there for six years. Most designs are very old.

Prabhu: ***What fundamental difficulty, as a designer, do you face while you start a redesign or cost reduction exercise? To be more specific, with design requirements.***

Prabhu: Can you go ahead and find out the design requirement for a given part?

Interviewee #5: No. In the bus world, most of the design is driven from the feedback of the field failure scenario. Bus is a highly tested unit for reliability and durability. Field is from where most of the change is driven. So there is no bank of documents out there other than the personal knowledge that some of the older engineers holds like test engineers and also from your own experience. A consolidated database or any of the references does not exist at this point.

Prabhu: ***You have team center, CDMS, requirements document database, International requirement standards. Do you have a software/design tool, which links the requirements to the specific part that you are working on?***

Interviewee #5: Absolutely not. Absolutely not.

Prabhu: None of the available software does that job?

Interviewee #5: No. There is no single software, which comprises all data, and it makes easier to look for design requirements from the part number. The first time I saw a set of requirements was with Craig Welch when he showed the system level requirements document but he is in a different location and there is no link to the requirement database which he had to a particular part number. Also, we don't have access to that level of information from here.

Prabhu: ***Do you face similar difficulty of identifying the design requirements for EC's raised from manufacturing, service, marketing, etc.? Can you give some examples?***

Interviewee #5: Yes. I do. Depending on what the subject is. In particular, if it is a bus body issue, 8 years of experience has given me a database in my mind where I can pull my answers from and also provide me with a list of people to contact with. From my experience, I know the contact to answer the questions. If you move over the issue to the chassis side, say, that network of people or knowledge doesn't exist in my head. So that is not available to me for whom I can contact and where I can get the answers from immediately to do that. You know, it would be the same for Americo. He could probably tell you based on experience where to go if an air tank had an issue. There is a guy in the Fort Wayne that does that. There is a group. I can do the same for the body. But that is just based on whatever I learned over 8 years of being here and there is not an established system that you can easily go through and look for it.

Prabhu: ***What types of issues are raised by the assembly line and how that converts as a substitution/ deviation?***

Interviewee #5: This one happens quite often to me. Manufacturing will built something incorrectly. Partially due to the variation in the parts and most of them due to their inability or the fact that they do not carefully read their traveler or bill of materials that goes down. So they will assemble something wrong. You have a variation come through and they don't catch it. In one case, the axle case that you and I looked at, they put the wrong steering arm on the axle. Question was asked from the manufacturing, could we not just leave it like this? Through a battle of week's process, I think it was, we were able to get that answer through Fort Wayne. So, the answer was a variable. I know it was a technical decision, right. It was probably that is very simple that you can look at it but that is something; some information was not made available to me to make the decision. I had to rely, you had to rely on somebody else to make that decision for you and tell you what was right or wrong. It is not that you don't have the ability to make that decision; it is you don't have that information to make that decision.

Prabhu: ***if you have an internal manufacturing division, what types of deviations does manufacturing raise?***

Interviewee #5: For me manufacturing and assembly are same. I will continue with examples that relates to assembly in our plant. Tool failures are good examples. We had a failure on the rear bumper torque gun several years ago. The gun was not torquing correctly but they wanted to use it. It was an impact gun with no rating on it. It is a large bolt, I know, it will take up pretty high torque. They wanted a deviation to allow them to use it. To cut the long story short, we contacted Fort Wayne fasteners group and asked them if manufacturing could use a lower torque on that size of the bolt. That information I don't have to get to him. I am pretty sure I could have got that information such as clamp loads, etc. but the reason I contacted Fort Wayne is because this bolt had an issue earlier. Also, it was my early days; I have to work my way to find out whom to contact to get the right answer. In our industry, you build your friendships, alliances and working relationships with the people. That's what allows you to get things done in our industry. If you don't have these relationships then you got to struggle to get things done. It is the fact of the business but at least to our business.

Material shortage, yaah (laughs), we got a lot of material shortages for which we have to do deviation / substitution. Typically it involves a part that is similar and altering it to make into the part that was shortage. Typically, in that case you use your own piece of knowledge. If it is a piece of sheet metal, if it is a joint, most of the decisions we can make with the information that we learned over the years. I can't think back on a particular deviation on that one.

Operator error, this is a huge one. Typically what happens in operator error, on a side emergency door all of the sheet metal around the door around the trim is all FMVSS 221 joint. To meet joint there is a specific edge distance that they must maintain from the centerline of the fastener to the edge of the material. In this case, they missed the basic material they are supposed to be screwing to and they are off on that and they were also off on the epoxy in the joint as well. The fastener spacing was not correct and the edge distance was not correct and the epoxy was not there in the joint to meet 221. It is not that they built just one. They built several like that. So, decision has to be made how we repair that. Right? The operator error that caused it but manufacturing would ask us a question, Gosh, we don't want to take them all the way apart which is a pretty cumbersome and time consuming process. What can we do to make it compliant? So in that case, we know, we can add fasteners. So we ended up adding fasteners to that joint. The knowledge of how many to add came from test data and speaking with our test engineer. We had to make a phone call, have him look his test reports and get an answer. Then we make a decision on how to repair. That is one of the common and is a very crucial decision when you make that. That happens more than you like to say.

Interference: In our business interference happens all the time. Typically due to design interference and not due to manufacturing interference because they did not put something together. Two features on their own would work just fine. But when they are combined together may not work correctly or interfere with each other or not one of them could be installed. In the case of an interference, typically there is not a whole lot we can do from the design stand point, we can do a deviation to change a part, both of them co exist together. Most often we would have avoided blocking one feature from interacting with the other. That happens in our ERIG department by not writing the edit. ERIG is the engineering release integrity group. They should use Boolean operations and define how different features should be combined with other feature.

Prabhu: Can you give an example?

Interviewee #5: I will give you an example. Stanchions and lum covers. We have a feature that pulls a stanchion. Stanchion is basically a steel pole. It basically separates different compartments of the bus It will be just a padded pole going from ceiling to the floor and a cross bar going to the bus wall. When the body plan controls the location of a stanchion, it tells you where it goes in the bus and when you have a first position stanchion and driver's lum cover, the installation of the stanchion arm interferes with the cover. So that we actually have to cut a semi circle hole in it, so that these two parts do not occupy the same place together. The lum cover was not released like that. It didn't have a hole in it. Because the designer didn't think that the first position stanchion will not be located here one day. So, we do a deviation first of all, modify the part, mark up a model and send it to the vendor, have the vendor change the part, so that it will fit. In this case, it is difficult because no part exists, right? You have a standard lum cover but it doesn't work. Can't modify the standard one all the time, so you have to create a new part number. Usually what we do is, based on how many times the combination is going to happen before we do the engineering work and some quantity of it from the vendor and one time park by; give it to manufacturing so that they can use those, and place under the deviation, and that will allow them to manufacture it correctly. Then we will write a pyxis concern, goes into the system, and wait until it is corrected.

Prabhu: As an interim solution, you just give a deviation?

Interviewee #5: Yes, later it is permanently changed through an engineering change release.

Missing geometry: We talked about the SE group (special equipment group). There is a fire suppression system called as Jo mar part suppression system, System goes in the engine compartment, and then in the case of fire, it is supposed to put out the fire. It is primarily used on the handicapped units to provide extra evacuation time for the handicapped folks. An original feature existed and it was existing for several years.

Somebody wanted extra options to it and new feature was created such as low-pressure light, charge light, communicate the system readiness. The designer redesigned the bracket in the hood that holds the nozzle, and also redesigned the routing and clipping location. All was done in CAD, UG. We had the parts in the plant. The bracket was in an assembly and it would actually bolt together. The area he showed to mount didn't work because it was already occupied by other equipment. The hose length was not long enough, the nozzle wouldn't fit to the bracket; in that case it was a lot of poor engineering work, probably due to the time table, and probably due to inaccurately analyzed CAD data that should have been out there, right? Now, to the designer's concern, a good model doesn't exist to go out and get a standard bus. Cowl, for example, this is all standard equipment in cowl and therefore I have this much of space to place my component. That model doesn't exist. That exist right here (points to the mind). You go talk to people, and ask them "what kind of features you know that exists here?" He might say, "You know nothing ever really goes out there". That's how you figure out how to not make that kind of mistake.

Prabhu: Do you mean variations by features?

Interviewee #5: Product variations... Jomar is a feature that a customer orders. Missing parts to assemble…That happens quite a bit. It is usually because of our product structure, and the complexity of our bill of material. It is common for an engineer to release something and not catch all the parts in the assembly. The recent one was one of the engineers copied a bill of material and pasted on to the new one. But, the bill of material already had a mistake and the engineer copied the erroneous bill of material. The plant had higher inventory with thousands of reinforcements that we really didn't need. In this case, it was a heavy-duty package, and put all those reinforcement into the bus body specifically for Colorado requirements. The engineer structured those parts in a feature that really didn't require that. That mistake was probably due to the engineering error.

Prabhu: ***You buy parts from various suppliers and assemble along with the parts manufactured internally. What different issues have you experienced from the supplier parts and therefore lead to deviations/substitutions?***

Interviewee #5: I think we discussed this under cost reduction.

Prabhu: ***How logistics have affected your assembly line and caused substitutions and deviations?***

Interviewee #5: Part shortage: Oh lord. Part shortage is another major drive for engineering to come up with the solution to keep the line running. Supplier ran out of a lift door switch. It is a double pull- double throw switch. Material and plant manager will come to the engineering for a solution. That will be done on a deviation basis. For those, we will use our judgment of the part we are deviating. There is a base requirement for the switch, right? We make a decision whether or not to substitute. But there is no system that could tell us what the old switch's design requirements are. In that case, it is a fairly critical decision. That switch performs couple of functions. It performs just a buzzer function and also performs a part brake interlock feature. It will not allow the bus to move forward when the door is open. So, if we have a failure in that area that is considered safety and it is critical. You know there is a part leaning on that decision whether or not to replace the switch. The plant will mark red tags. Those are very common. It comes on a daily basis and we have to research something on switch or they will anticipate a shortage of some parts and request if they can replace with some other part. That is a very large portion of our job here to understand the shortages and work around to find a part to substitute and keep the line running.

Prabhu: Can this shortage be applied to any complex part such as power steering pump?

Interviewee #5: Power steering pump. A good example. We were short with power steering pump. We have the three power steering pumps and they order #2 powering steering pump. If I categorize, then it is standard, better, and best. Most of the times we have the option of, customer ordered the standard pump and we run short of that pump. In such case we go ahead and give the better one at no additional cost. Most of the decision for this would be based on is it available for that wheelbase, axle and chassis. It will be a tough decision if the power steering pump has not been designed for this combination. At that point we have to make a call to the Fort Wayne. There is no decision path for us to walk on our own.

We also had axle shortages and we were asked if manufacturing can use some other axle. Another example is the 42-ounce Vinyl fabric for the seats. We also have 52-ounce vinyl fabric. We will give customers the upgrade for free if we run into shortage. There is no visual difference in that case. That happens a lot.

We have lots of different kinds of adhesives in the plant. We had a part shortage on a contact adhesive for shoulder rails. A vinyl fabric is bonded to pre prime steel. Contact adhesive is sprayed into and wrapped around. Manufacturing ran out of that material. We had another contact adhesive that we used to put up scrammer over head. It is the fabric that keeps over the installation and prevents fibers from falling out on the kids. They wanted to use that contact adhesive for the shoulder rails. We compared the datasheets of both the adhesives and we did a trial in the production line and made a decision to switch. In this case we did switch. We wrote a substitution and changed the bill of material. A risk evaluation was carried out on the change. If the shoulder rail fails, we can fix it though customer would be unhappy. We have a floor mat adhesive and we ran out of it. They asked if we could use another adhesive. I was not ready to change, as a failure of the adhesive would cause a heavy repair cost. The cost to replace the floor mats would be substantial. It is $2500 a unit. Lot of times I will not have all the information I want to have to make one. I weigh against customer impact, safety, FMVSS. I will weigh all those things in my mind before I make that decision. If it is a low impact decision like contact adhesive then if it falls of it falls off. We will go fix it, if it comes out after two months, and we can replace in warranty. But, if the floor mat comes out, it will be costly to replace and the customer would be very unhappy. These are not taught or explained to me. It is time and experience tells you how to make decisions on such requests. It is ok to have uncertainty in low risk parts but on high-risk parts you better be damn sure that what you are doing is right.

Prabhu: Do you have a mind map of risk level for each part?

Interviewee #5: Marketing. I don't have to deal with marketing that much. Most of the time they change the badging / decal.

Interviewee #5: Service, Accessibility. I assume the ability to access the parts.

Prabhu: Yes

Interviewee #5: That happens to some degree. Not everything is highly accessible. The service folks have grown to understand the product and I don't hear lot of complaints about accessibility at my level. Now, who knows, maybe if you go interview the service guys they may have a list of a page long on what they want better. They are probably minor enough they wouldn't drive back to me.

Warranty, is another large issue that we work on. Originally, we started with the cost reduction on the windows and we came up with a co-extruded rail and we did some changes to it. As we are doing that our field warranty manager got involved and said, "hey, while you are changing this portion in the window, why don't you consider these failures in the field which happens a lot. Why don't we look at why these latches are failing? Why don't we look at why the plastic slides are failing? Why don't we look at the closing portion of the window? Sometimes we don't get that right." The requirements just add on to the product that is running. They also come directly from the field. I will give a recent example. The defrost duct. The main defrost duct that runs across the twin A pillars of the bus. They provide the airflow to the windows, windshield. That product has been the same since 2003, had some field warranty. It actually started about a year and a half ago. Some customer was complaining that the duct was rattling. They were appearing on their own and charging warranty. It was about a year until it got enough warranty claims before it popped up and caught in the radar of the service manager. Hey, we got to fix this. These guys are charging us $250 – 300 a part. They asked to us to improve the defrost duct to keep from rattling. So we brought 3M into the plant, and we used a special tape, that would stick to the duct. I think it is polypropylene. It will also stick to the powder coat on the cross bus beam, which is a steel member. We fixed it through a deviation by allowing this special tape to be used before we went ahead and made a permanent change. We fixed a problem that probably had been out there for several years.

Customer dissatisfaction, Espar heater is a good example. High field failures will dissatisfy customer but in this case there was no functional issue, no failure, we built it to print as per the document and as per the design. The customer just didn't like it. They wanted something different. There is a little bit of designer in everybody. The customer chose that they wanted them redesigned. And we did redesign it and actually it is released now. That was redesigned under deviation. The customer came back and said "I don't think your exhaust routing is acceptable, I want you to attach it to the side sheet, in addition to what other points you have to attach. There is nothing indicating that we had warranty issues on it. There is nothing indicating that we had field failures. It is just this is what they wanted. They ordered around 117 in the first round. So, from a customer satisfaction standpoint, we made a change, documented and let them have what they asked for. That happens a lot with the state specification. Customers order features and they don't match with their interpretation of what the state specification is and so they will ask for some changes and lot of times we will do those changes under deviation, come back and document it through a new feature code. Ideally, most of those would happen during pilot inspection. When we built the bus, to print, and per all the specification and let them see it and review it. They will let us know this, this and this have to change and we go back and say, that is fine, we have to release new features for you to order so you can have what you want. But lot of that comes straight from the customer to us at the plant level. It also drives up to the warranty and field service channel too. There are two ways to get to us, through the service manager or through the plant manager to us.

Prabhu: ***Was there any deviations/ substitutions caused because of design office errors such as BOM, wrong installation, etc.,***

(Answered in an earlier question.)

Prabhu: ***How much time do you have to react to a deviation/substitution/engineering change?***

Interviewee #5: Almost, always the same day. Most of the time, by the time it gets to us, it is already broken or trying to cut it off or coming that day we have to come up with a solution. Very seldom do we get an indication of forthcoming change like we are going to have an issue with this. We have a very little time to react. Now, if it is a joint issue and I couldn't get the right people, if the risk is high, I would tell manufacturing to wait until I get the information from the right people. That happens sometimes.

Prabhu: What will you do with the bus till that time?

Interviewee #5: We will hold the bus or apply red tag, stop the line, which is very expensive.

Prabhu: ***What documents/ tools do you use to assess if the change affects other system requirements, requirement for validation, etc.,***

Prabhu: I will give you an example. Can you identify what design parameters in braking system gets affected when you do a change in the suspension system?

Interviewee #5: No. For a change of that magnitude, upper management and the release engineer, we decide to do a design review which at that time we gather a group of experts and they use the personal knowledge to point out any missed steps, weakness or flaws in the proposed design. That is the only thing we do to prevent a disaster.

Prabhu: ***What type of tools do you think, if present, could improve the visibility of affected system requirements while doing an engineering change which we talked earlier (documents, CAD based, team center, etc.,)?***

Prabhu: To quote an example, you open up a CAD model and click on the dimension, which you are going to change. A feature in the CAD system would let you know what requirements are going to be affected by that change.

Interviewee #5: That would be wonderful. That would be very nice. I would think that would take a massive effort to get in place, right? Some effort to maintain and I think that would be a valuable tool. Nothing is easy, in our system, to find out the right information. What we should be using our mind for is what you speak out. But lot of our thought process and effort is driven into finding the parts and getting the requirements from the parts. That is another gigantic effort. There is nothing there. Expect for the personal knowledge that we talked about.

Prabhu: for high-risk items, you also don't have access to calculation models right?

Interviewee #5: Yes.

Prabhu: If a tool lets you know what would happen if you change the tire size by just typing in the tire, will it not be useful to you?

Interviewee #5: Yaah, it would tell us the tire size would affect braking, vehicle top speed, etc. that would be very handy. Software doesn't exist to do that, is it?

Prabhu: Yaah, it doesn't exist. I am just putting you in a hypothetical situation.

Interviewee #5: That would be a gigantic improvement in the process efficiency. That will reduce the time to complete every pyxis concern. Time talking to people, identifying requirements, making decision, waiting for Fort Wayne's decision takes a lot of time away from us. A tool of that nature would definitely improve the efficiency of our work.

Appendix F : **INTERVIEW #6**

Name	: Interviewee #6
Title	: Line support Engineer
Years of Experience	: 11 years
Industry	: Automotive
Date of Interview	: 07/16/09
Location	: Tulsa, OK, USA

Prabhu: What are the sources of EC that you have experienced for a product after it is released for production?

Interviewee #6: As line sustaining engineers we are just taking care of the integrity of the product when something doesn't fit well or doesn't go well in form or bill of material error. We fix up the errors that show up in the line. This is where we generate a new release or an engineering change to fix the existing issue.

Prabhu: Do you get engineering change request from manufacturing. Anything from quality?

Interviewee #6: Yes. We get quality issues on existing product that can compromise the integrity of the product, which has to be resolved from engineering standpoint.

Prabhu: What are the types of EC in product redesign and cost reduction programs?

Interviewee #6: We do everything starting from getting the requirements. First of all, if it is feasible to change or not, we build prototypes and mock up some parts.

Prabhu: I think we are deviating from the topic. I would like to know about types of EC such as material change, thickness reduction, etc.

Interviewee #6: Well. I am just trying to remember. Last year I did a cost reduction but not from engineering stand point out. We moved from a process where we normally weld 9" frame rail to specific wheelbases. But the engineering has set up a different manner that the largest wheelbase will not be long enough for the longest body. So by changing the design we saved one technician that needs to be half time working as a welder at the beginning of the chassis line. That's a cost reduction idea but not from the engineering stand point. I have some assignments right now. One of them is changing the part with different finish. By having a different finish we will reduce the price of the bolt from 60 cents to 30cents.

Prabhu: In the earlier example, you mentioned about changing the finish. While you changed the finish from one to another, did you have access to the design requirement of the existing finish to know why it was specified?

Interviewee #6: No. The previous design has a stainless steel cap, as it was a part of a bumper. Everything that is exposed to customer view has to be protected against the rust right? So that's why speaking with the fastener group they showed some other sample of cheaper material that can do the same work as the stainless steel. So that's why we are moving in that direction. With respect to your question, I didn't have that information.

Prabhu: What is the age (range) of the product for which product redesign and cost reduction is carried out?

Interviewee #6: Things have been there for 5 years or more. I haven't checked that but it is there since the very beginning of this plant. I don't know if it is older than that.

Prabhu: Have you come across of any part, which was there for fifteen years or older?

Interviewee #6: No, not that I am aware of.

Interviewee #6: The other cost reduction work was the tow hooks. It wasn't actually intended to be a cost reduction idea. It was specifically redesigned to improve the tow hook system from a field complaint. The improvement we came up was with a solution that saved $35 a piece per vehicle and reduces weight in the complete configuration.

Prabhu: What fundamental difficulty, as a designer, do you face while you start a redesign or cost reduction exercise? To be more specific, with design requirements.

Interviewee #6: To find requirements is one. It is kind of a complicated to find out why we are doing things in that way. I don't know whether it is because I have lack of knowledge on where to find out parts or if there is a special website or special book or manual. It was hard to find. In the example quoted in the previous example, actually I couldn't find all requirements for tow hooks. Sometimes each information is not here basically. It is available in different locations such as Conway, Tulsa, and then we look for information from Fort Wayne. It will delay little bit more. When I was in Escobedo, in the initial days, it was taking longer but now it takes two or three days rather than a week. But I think it could be better.

Prabhu: Is experience helping you to access data quickly?

Interviewee #6: Yes, you know, we will come to know the contacts of the specific person who is working with a given product. So we will go directly to the right person. But if you are brand new here, and you don't have anyone behind you it will be tough and will take you longer.

Prabhu: This will create work pressure also on you, right?

Interviewee #6: Yes.

Prabhu: You have team center, CDMS, requirements document database, International requirement standards. Do you have a software/design tool, which links the requirements to the specific part, which you are working on?

Interviewee #6: No. CDMS is the software that we use in order to introduce, repair and update parts. It is linked to spectrum because that is the part management software at the part level but does not include the rules or the assembly. That is the interface that we are using. CDMS is the link that links to assembly.

Prabhu: So, you have limitations in software where you can identify links between product and requirement list.

Interviewee #6: Can you give me an example?

Prabhu: If you open a bumper drawing in CDMS, can you look into the design requirements?

Interviewee #6: No. That falls into the same category of previous question on how to find design requirements; we cannot identify the requirements because it is not linked.

Prabhu: Do you have any software / design tool relating to the system requirement?

Interviewee #6: You can find out who was the designer changing the dimensioning. But you may not be able to find out why the change took place unless they type in the release or unless you call him and ask, "Hey, why do you change it? Let's say that they change brake part for a new requirement but there is no link that tells you that there is a new requirement for that specific vehicle. You can find out that the part was changed from A to B with engineering release number and you can find out the engineer who provided that one. You can see how they work with release level like installation, part, FAV but you will not find the reason unless they specify in the release description.

Prabhu: That's good point. But if you are asked to change the suspension tomorrow can you find out how many system requirements are getting affected because of the change.

Interviewee #6: You can do it based on the experience but not like software, which tells you, hey careful, if you touch this it is going to affect that. We don't have one.

Prabhu: Most of the parts are vendor parts, how do you handle that?

Interviewee #6: If you do a part change that involves multiple vendors it will matter because the way they structure the system. Let's think about changing the suffix from C1 to C2. Once you set that release into effect, what we call it set to E; it is going to flag in purchase. Purchase is responsible to pick those drawings and send it to the vendor. There is another group who is in charge of assigning the introduction dates for the new releases. Pretty much, if they know the engineer, they will ask if there is any hot job or something that you need to introduce earlier. Otherwise they will set it to break for 12 weeks from the release date. This is the system we normally use for material purchase etc. So to answer your question, it doesn't matter if it is one vendor or multiple vendors, once your structure is released and if it is set to E, the other department will communicate the information to the vendor.

Prabhu: Do you face similar difficulty of identifying the design requirements for EC's raised from manufacturing, service, marketing, etc.? Can you give some examples?

Interviewee #6: Yes, we have the same problem and we don't have the design requirements. Let's say, finish in the bolt. The experience is also included. For example, before paint booth, in the chassis line, I got this bolt and used in brakes, which was a M6 bolt with phosphate oil coating. They were running short so the manufacturing asked for an equivalent part they can use. Let's think about finding out the same length, but with different finish. You will not be able to say go ahead because a different finish for the bolt with a phosphate oil nut will require a different torque. It would be great if we have any booklet, which can tell this? Fuel tanks are another example where they use zinc finish with M20 bolts. If they are asking can I do a change on this bolt? Yes they can do this but torque would be way higher. It again depends where you use the bolt or the nut? You must find out the correct torque and the correct finish. In order to do a substitution, there is nothing, you have to contact the special group or the expert group or any particular group like for hardware group in Fort Wayne.

Prabhu: Anything from service?

Interviewee #6: Rear suspension on the BE model. There was a clip that was hitting with the exhaust hanger bracket, which was basically a wrong design. We send a deviation to allow the vendor to relocate that clip. First of all they couldn't relocate it but they just flipped the part and then somebody in Fort Wayne did the release.

Prabhu: What types of issues are raised by the assembly line and how that converts as a substitution/ deviation?

Interviewee #6: It is missing parts from the materials and from production it is, not very often, operator errors. The operators will interchange a shorter hose for a longer hose and raise an issue. The other way round will not affect and based on my experience I know this will not affect. We had different block of heaters. There is a harness that goes from the engine to the front bumper. There are two different parts in which one is longer than the other. The difference is just an inch. The longer goes in I-6 and the shorter one in V-8. Once they made a mistake and assembled the longer hose in V-8. They did it for 50 vehicles and they asked if they could leave that part as such. It was just a matter of fixing the extra length properly and do the correct routing. Yes, you can do that and agree for such deviations. That will be a sample of production request for substitution. For quality, they don't request, normally it is vendor who make the request. Requests will be of the having parts with certain finish which is not as per the print. Based on experience, if we decide that it is not going to affect the product integrity, we will go ahead and issue it. An example for tires. Customer is asking for Michelin and you have Goodyear, you can approve the change. Well, in that case, customer should agree with that, but you can go ahead and change tires. Pretty much, these are the most common department from which we get deviations and substitutions. We also get substitution/ deviation from Product center on new products. They want to introduce or they want to use the existing parts, we will also approve that one. Therefore, to summarize, four groups like materials, production, Fort Wayne and quality request for substitution/ deviation.

Prabhu: if you have an internal manufacturing division, what types of deviations does manufacturing raise?

Interviewee #6: I have answered just now.

Prabhu: You buy parts from various suppliers and assemble along with the parts manufactured internally. What different issues have you experienced from the supplier parts and therefore lead to deviations/substitutions?

Interviewee #6: That's what I say, it is pretty much quality. We don't produce at least in Chassis but in body side they do. If something is not to print, quality will not request the deviation; it will be the vendor, if possible.

Prabhu: What kind of issue quality comes up with? For instance, low tightening torque, wrong finish, wrong dimensions, etc.

Interviewee #6: Yes, like scratches may be. Yes not that it is happening, but just to say something you got a bumper, you got a frame rail and you have a scratch, or extra hole which shouldn't have been there. You can say go ahead by writing a deviation.

Prabhu: How logistics have affected your assembly line and caused substitutions and deviations?

Interviewee #6: That will be considered as materials shortage. Sometimes, they have the material shortage that they don't even know. It happens, not every day, but there is someday that they called and said, you know what, and we cannot find this part. We should have six pieces and we couldn't find it. Then they ask for a substitution /deviation/ something that you can replace with. Very good example in that are starters. We have like, may be, around ten different starters, and some of them are upgrades from the basic parts. There are cases when they lost the material supply truck and couldn't find the correct part in the warehouse or they thought they should have it but they don't have it. Then they basically ask us" can we use the next part" which is probably an upgrade. In that case we can normally go ahead and use it. That is also a good example of production request for substitution when they put the incorrect starter or incorrect material. They will ask whether they can live with the incorrect part instead of reworking / retrofitting with the correct part in all the vehicles.

Prabhu: Was there any deviations/ substitutions caused because of design office errors such as BOM, wrong installation, etc.,

Interviewee #6: Installation, that is a huge topic, I think. Like I said, I think, this is a huge topic because every new design, installations are not accurate. When I say not accurate sometimes you don't have the installation to show how to route a harness, brake line or to some point also the air conditioning. The installation on heater hoses coming out from the engine has inaccuracy. Other example that is coming to my mind is the wheelchair lift with a circuit breaker but engineering said that it should be placed in the firewall. However, there was no place to fit it. There is a state requirement, in some states, to have the circuit breaker in the firewall. Normally what we do is put those on the battery box. The installation drawing called for mounting the circuit breaker on the firewall. We found out during pilot lot that we have no place to install the circuit breaker on the firewall and issued a deviation note for this change and corrected the drawing.

Prabhu: How much time do you have to react to a deviation/substitution/engineering change?

Interviewee #6: Depending on who put that one in place? If it is material, it is probably less than zero minutes (laughs). In general it is less than 30minutes for material deviation.

If it is vendor deviation it will be a week's time and you will have more time to take a decision. Production will request a deviation after they put the incorrect parts on the vehicle. The vehicle will be already outside the production line and will request for a production with details of overtime cost and implications on monthly delivery targets. We have very less time to make a decision and high pressure to release the vehicle with incorrect parts. Fort Wayne, usually e-mail you with enough time to take the decision and you are pretty much informed that some change is on the way.

Prabhu: What documents/ tools do you use to assess if the change affects other system requirements, requirement for validation, etc.,

Interviewee #6: S something that warns that this change is going to affect the other system requirements? No. But we have a process that tells us how to do the release. You can start with containment and you can raise a concern. The concern will generate a resolution. The resolution will allow you to generate a release or engineering change. You can work in team center or Unigraphics to fix the drawings, installations depending on the issue.

Prabhu: What type of tools do you think, if present, could improve the visibility of affected system requirements while doing an engineering change which we talked earlier (documents, CAD based, team center, etc.,)?

Interviewee #6: Right now, the new guy is trying to vary the battery box location. If we have something that can identify the number of affected installations, what parts are going to affect, relocation suggestion for air drier, that is definitely going to help. Even to me, it will be tough to know how many installations it is going to affect. If the 3D model/ UG have the capability to let us know that the proposed modification is going to interfere with some of variations available in the chassis, then such a system would be extremely useful. Not to mention the area surrounding the part under change. That too will definitely help. I remember now that we have a frame piercing software, which will tell us the parts in the surrounding area. That's pretty much we have and that is what, in my view, we want.

Appendix G **: CHANGE CAUSE AND EFFECT DATA**

Table G. 1 Examples for Changes

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
In the chassis line, the front axle and the rear axle are placed in pairs for each vehicle based on a document called "traveler". Traveler contains all the part numbers to assemble for a bus. The operator pulls the appropriate axle and position on the production line. The brakes, tie rod, steering arm are assembled in subsequent station.	The steering arm meant for subsequent vehicle in the assembly line was assembled. The steering arm offset was the only difference between the two axles. The mistake was identified and reported to engineering.	Operator error	Wrong assembly	Intervie wee #5
The rear bumper of the bus is bolted to the chassis using a torque gun. The torque gun is capable of producing higher torque.	The torque gun failed. Manufacturing wanted to use a torque gun, which produces lower torque in the rear bumper bolt.	Tool failure	Modify design specification	Intervi ewee #5
The bus body has a side emergency door. Fasteners and epoxy join all the sheet metal and the trim around the door. The joint strength is	The operator didn't apply epoxy and missed a sheet metal on which the fasteners are to be screwed to.	Operator error	Modify design specifications	Intervie wee #5

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
governed by design requirements. The joint strength is considered to be very important in the organization.				
Stanchions are placed in the bus behind the driver, side of the entry, either side of the alternate entry door (if present). They are placed in regular intervals, which kind of divides the bus into compartments. It runs from the floor to the ceiling of the bus. The lighting track passes adjacent to the stanchions.	In one of the bus, the stanchions and the light cover (also called lum cover) interfered. The body planner was not aware that a lum cover would ever exist in the proposed location of the stanchion.	Design error (Lack of understanding of the system)	Part interference	Interviewee #5
A Jo Mar fire suppression system is placed under the hood, near the engine compartment, to suppress the fire in case of a fire .It is primarily used on the handicapped units to provide evacuation time for the handicapped folks. In one of the bus	To accommodate the new options of the feature the designer redesigned the hood in the bracket that holds the nozzle, redesigned the routing and clipping location. Everything was done in CAD (Unigraphics). Parts were received in the plant. However, during the assembly of the parts it was identified that there was a pre-occupied part.	Design error (Out of date CAD models, lack of understanding of the system)	Part interference	-do-

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
orders, additional options for this feature (fire suppression system is a feature) such as low pressure light, charge light, system readiness communication light were requested.				
The parts are ordered based on the bill of materials. An engineer while releasing a part copied a bill of material from previous bill of material, which had an error and was not corrected. In this case it was reinforcements	Parts that is not required for a particular vehicle was received and had huge inventory. Parts that are required for that vehicle were of shortage.	BOM error	Material shortage	Interviewee #5
Three different power steering pumps are used in a vehicle. The axle, chassis and the wheelbase, primarily drives the selection of the power steering pump. The three power steering pumps are categorized as base model, better (#2)	Logistics failure led to part shortage.	JIT failure	Material shortage	Interviewee #5

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
and the best (#3). The category #2 was ordered for the vehicle and the plant was running short of that pump. Any of the power steering pumps can be replaced if they are validated for the combination of axle, chassis and wheelbase.				
Floor mats are placed on top of plywood floor in the bus using suitable adhesive	Shop ran out of floor mat adhesive. Hence, requested for alternate adhesive	Material shortage	Modify design specifications	Interviewee #5
The air duct that supplied air to the windows and windshield runs across the twin 'A' pillar of the bus.	The duct made rattling noise led to customer complaint. Warranty cost increased and hence noticed to product engineering by service manager for redesign.	Customer dissatisfaction Warranty cost	Warranty cost Product redesign	Interviewee #5
Bus body skins are purchased from the supplier. This particular skin was of low volume	The holes in the skin were not meeting the drawing specification and hence leading to a deviation	Vendor drawing error	Modify design specification	Interviewee #3
When new parts are released, the purchasing group has to put that part in contract with a supplier. The entire process takes fair amount of time before	1. The new released parts are used in the vehicle within two to three weeks of the release date. The purchasing group can't sign the contract with the supplier and have the parts in the production line. Therefore, they will run of	Short introduction time High customer	Material shortage Material	

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
everything is put into the system. Once everything is in the system, purchasing group can order parts from the supplier and have them in the plant in a given fixed time, as per the contract.	part shortage. 2. High customer orders 3. Moving the order queue up by order review board	order Moving the order queue	shortage Material shortage	All Interviewee
The BOM is the basis on which the parts are ordered by the purchasing group	BOM called up 17 nos for a part but in reality each bus took 60 nos. This led to a part shortage after some point of time	BOM error	Material shortage	All interviewee
North Carolina school bus requires higher thickness bow in the bus body. Bows are structures that run laterally in the bus body	The state specification change leading to excess inventory of the higher thickness bows. Higher thickness bows can be used in other buses but not the other way round. Hence, to salvage the excess inventory, a deviation was issued	Change in state specification	Excess inventory	Interviewee #2
Wheel pocket covers were made with ABS plastic. As a cost reduction exercise, the material was changed. In such cases, the customer was informed before implementing the change. On acceptance of the customer, the	The material of the wheel pocket cover was changed from ABS to TPL plastic to reduce cost and has been deviated internally. Similar exercises has been conducted for floor mats also	Cost reduction Cost reduction	Material change Material change	Interviewee #2

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
material changed with a deviation note until a formal engineering change				
The vehicle uses several fasteners at different locations such as driver's electrical panel access, overhead lining, side door trims	As a cost reduction exercise, these fasteners are reduced and replaced with structural adhesive. Deviations are issued to eliminate fasteners until the engineering change	Cost reduction	Part elimination	Interviewee #2
A light bar track has been redesigned five times. Redesigning was either driven by cost or available tooling in other manufacturing plant	Available tooling at other manufacturing plant leads to redesign of the part. To reduce cost, the material was changed to plastic which later lead to failure in the field and hence deviated to other material	Available tooling Cost reduction Material change Field failure	Part redesign Material change Field failure Material change	Interviewee #2
Multiple vendors are available on a similar part. Pricing difference between these vendors motivates the purchase department to consolidate price among them.	Lights were purchased with multiple vendors and to consolidate the price purchasing department consolidate the vendors which leads to number of deviations	Vendor consolidation	Part consolidation	Interviewee #2
Parts are redesigned very	The vehicles are with several variants and each	Incorrect BOM	Part redesign	Interviewee #2

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
frequently and it amounts to 25-30% of substitution	of them is related by Boolean constraints in the part list. If the designer misses one of the feature codes then a vehicle may require a new design if no suitable design exists. In such cases new harness has to be redesigned and deviations are issued.			
Annual estimate is provided to the vendor for supplying parts.	Vendor can lose a truck or lost shipment leading to material shortages and hence a substitution	Logistics issues	Material shortage	Intervie wee #2
The parts are stored in a million square foot warehouse	Parts can be lost causing material shortages	Poor inventory tracking	Material shortage	Intervie wee #2
Any damaged part by the operator in the manufacturing has to be reported to the material review board for them to replace it.	Operator damages the part by drilling at a place where he is not supposed to and then not reporting to material review board for material replacement. This leads to material shortage and write substitutions	Operator error	Material shortage	Intervie wee #2
In a I-6 engine, one of the service ports is located near the coolant lines and it is supposed to be oriented away from the hood	The operator oriented it almost 90 degrees to the hood and the hood started to crack in the field which lead to deviation	Operator error	Field failure	Intervie wee #2
The body of the vehicle is made up of circular tubes bent in C- shape	The tool to build the bow needs constant oil spray from the nozzle. Improper maintenance of this oil	Improper tool maintenance	Tool failure	Intervie wee #2

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
called bows.	nozzle led to tool failure because it required higher tool force which lead to a deviation			
(no context)	Vendors supplied kits with not parts in it leading to material shortage	Missing parts from vendor	Material shortage	Interviewee #2
Two vendors supplied axles.	One of the suppliers did not supply parts due to unknown reasons and hence another supplier replaced it.	Logistics issue at the supplier end	Material shortage	Interviewee #2
Two different steels from two different suppliers were used: cold rolled and hot rolled in the same machine for different vehicles	The tool wear rate increased when the hot rolled steel was used in comparison with cold rolled steel. The manufacturing raised a request to use cold rolled steel in future and also for the existing vehicles. This lead to deviate the hot rolled steel to cold rolled steel. Engineering conducted a test and approved the deviation.	Tool failure	Change in material and change in supplier	Interviewee #2
An engine badge is placed near the entrance door of the vehicle, which costs $15.	Marketing proposed a cost reduction suggestion with a decal. The engineering change propagated for all models while there were 200 numbers of old badge in the inventory. This lead to a deviation	Release of engineering change without considering the inventory (or Introduction date error in ECN)	Excess inventory	Interviewee #2
	One of the designers made a mistake by indicating that a set of parts is	Incorrect BOM	Excess inventory	Interviewee #2

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
	expired. This lead to huge inventory, which has to be salvaged. "I have $4000 on stop arms, $14000 in radiators"			
Mud flaps are provided right behind the wheel to prevent mud splashing on to the sides and the underneath of the vehicle.	Mud flaps supplied by the vendor got shredded after hitting the tire. There was increased number of failures in the field. To address this complaint, the material was changed to through a deviation.	Vendor design error (Limited validation)	Field failures	Intervie wee #2
To fix the wheel chair to the bus floor, non-coated aluminum track was fastened to plywood. This set up was used for several years.	A request for marine grade plywood with new chemical came in. The bolts were rusted through and there were holes in the floor due to galvanic corrosion. The situation was of higher degree near Florida. This lead to a major recall.	Material change	Field failures	Intervie wee #2
The lift doors have two sides: hinge and latch. The hinge side of the door is covered with a sheet metal by fastening. This fastening is required for the customers to remove the sheet metal and have access to the hinge for tightening in case the door starts sagging.	A redesign activity led to change the fastened sheet metal to glued sheet metal. This act made it unserviceable, which was later, identified in the field.	Part redesign	Poor accessibility	Intervie wee #2

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
The cooling fan starts after the thermistors reach a set temperature. The entire heating and cooling system is provided by the supplier	The thermistors didn't turn the fans on after the required temperature. This was because the supplier's outsourced the thermistors to a different country and didn't check the current value. This was identified in the vehicle and a deviation was issued for a different system.	Supplier initiated design changes	Non-conformance internal	Interviewee #2
During the month of either The December or The January, either the suppliers or the distributors are switched.	The OEM tends to find it difficult to manage the quantity of the parts and leads to deviation	Change of supplier Change of fleet distributor	Material shortage Material shortage	Interviewee #1
An improvement to the B-pillar panel to make easy assembly was conducted two months after it is introduced into the production	The material quantity in the BOM was wrong and lead to deviation	Product improvement	BOM error	Interviewee #1
(No detailed context provided)	Part shortages, parts not to print, wrong assembly are the most common issues from the manufacturing line	(Unknown)	Material shortages Wrong assembly Parts not to print	Interviewee #1
(No detailed context provided)	Interference of parts could lead to deviations. This could be because of wrong assembly, wrong installation, and operator error. In addition, it can	Wrong assembly Wrong installation drawing	Interference Interference	Interviewee #1

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
	also be from design error	Operator error Design error (poor design assumptions, limited validation, lack of understanding of the system, tolerance issues)	Interference	
(No detailed context provided)	Material shortage and logistics are the two that have close relationship with each other (after looking into the chart)	Logistics	Material shortage	Interviewee #1
(No detailed context provided)	Operators cause wrong assembly. If the operator is continually missing something that is the result of the bad design	Design error (Design not suitable to manufacturing)	Operator error	Interviewee #3
(No detailed context provided)	New customer orders pulled up at an earlier date can affect the production schedule and cause difficulties for the purchase department to keep with the orders.	Order change	Material shortage	Interviewee #3
(No detailed context provided)	We have small rubber caps that we place inside of the bulkheads to cover up the screw heads. The BOM called up 17numbers whereas in reality each bus took up 60.	Incorrect BOM	Material shortage	Interviewee #3
(No detailed context provided)	Part consolidation due to product redesign and cost reduction program. For	Product redesign	Part consolidation	Interviewee #4

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
	example, fastener reduction	Cost reduction	Part consolidation	
(No detailed context provided)	Part consolidation is also done by supplier changes. For example, changing from one brake lining to other	Vendor consolidation	Part consolidation	Interviewee #4
(No detailed context provided)	Part shortages are more consistent. For whatever reasons, they didn't get the brake part number 1. Then, I have to replace them with another.		Material shortages	Interviewee #4
As a product improvement exercise, the hydraulic brakes were replaced with disc brakes in select vehicles	The forklift truck in the manufacturing plant is limited to carry certain number of hydraulic brakes. This issue led to deviate to hydraulic brakes for certain period of time before a forklift truck with appropriate capacity is purchased.	Product improvement	Process change	Interviewee #4
(No detailed context provided)	Incorrect ordering of the purchase department led to material shortage in electronic control module for ABS. This led to a substitution	Part ordering system issues	Material shortages	Interviewee #4
(No detailed context provided)	Snow storm led to logistics delay and caused material shortages	Logistics issues	Material shortages	Interviewee #4
(No detailed context provided)	Fuel tanks failed in the field and there was an immediate instruction to replace them. This led to a substitution	Design error	Field failure	Interviewee #4

Situation Description	What went wrong & led to deviation?	Cause	Effect	Data source
The circuit breaker for wheel chair lift is placed near the battery unit.	Engineering as an improvement placed the circuit breaker in the firewall. The installation layout indicated the firewall; however, it was identified in the pilot run that there was no place in the firewall for locating the component.	Incorrect installation layout	Wrong assembly	Interviewee #6

Appendix H : SEVEN-STEP PROCESS FOLLOWED IN INDUSTRY: CASE-A

H.1 Step 1: Identify System Level Requirements

Table H. 1 Identified Requirements

Requirement type	Requirement Index	Requirement
Functional performance and legal	DV-R1.1	The product should not fatigue at the rated pressure
	DV-R1.2	Product should operate at a pressure above 20 psi of supply pressure
	DV-R1.3	The product must not show excessive wear
	DV-R1.4	The valve assembly must allow reverse flow without damage and remaining latched
	DV-R1.5	The valve assembly should not be damaged during rapid opening events
	DV-R1.6	The valve assembly must not be damaged at high flow rates through the valve
	DV-R1.7	The flat head Screw should not interfere with the seal facing
	DV-R1.8	The valve assembly should be operational in salt water environment
	DV-R1.9	The seat must have clearance to fit through mounting ring
	DV-R1.10	The seat must fit into valve body
	DV-R1.11	The valve must not be damaged at the rated pressure
Manufacturing	DV-R2.1	The cast geometry of all machined components should have sufficient machining stock
	DV-R2.2	The machining process must be capable of meeting print specifications
	DV-R.2.3	The operator must be able to safely assembly components per relevant prints and specifications
	DV-R2.4	The valve assembly should be assembled with tools readily available
	DV-R2.5	Critical assembly specifications of the valve assembly must be maintained
Service	DV-R3.1	The product should be easily removable/ replaceable
Shipping	DV-R4.1	The product should be able to be transported through roadways/ seaways/airways without any failure /loosening of components

H.2 Step 2: System Analysis

Table H. 2 System Analysis Matrix

	Component name		Internal																				External				
			A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**X**	**Y**
Internal to the system boundary	Mounting Ring	**A**					1		1				1	1	1		1		1			1	1			1	1
	Clapper	**B**			1	1		1				1		1			1	1	1							1	1
	Striker	**C**		1			1					1														1	1
	Seal facing	**D**		1				1														1				1	1
	Lever	**E**	1		1					1			1		1	1		1	1					1		1	1
	Bump stop	**F**		1		1																	2			1	1
	Retaining ring	**G**	1										1	1												1	1
	Screw	**H**					1						1			1		1								1	1
	Stud	**I**											1				1	1								1	1
	Flat head screw	**J**		1	1													1								1	1
	Lever pin	**K**	1				1		1	1	1				1			1	1						1	1	1
	Hinge pin	**L**	1	1					1								1		1							1	1
	Lever spring	**M**	1				1						1													1	1
	Lock washer	**N**					1			1																1	1
	Teflon washer	**O**	1	1							1			1												1	1
	Loctite	**P**		1			1			1	1	1	1													1	1
	Grease	**Q**	1	1			1						1	1												1	1
	O-ring1	**R**																				1	1			1	1
	O-ring2	**S**																				1	1			1	1
	Seat	**T**	1			1														1	1		1			1	1

	Component name		Internal																				External				
			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
External to the system boundary	Valve body	U	1					2												1	1	1			1	1	1
	Push rod	V					1																			1	1
	Reset handle	W											1										1			1	1
	Water	X	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		2
	Air	Y	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	

Table H. 3 List of Affected Elements and Change Modes (Partial list)

Change element (Highlighted in the yellow color)	Change mode	Affected elements
Lever	Material change	Mounting ring, striker, screw, lever pin, lever spring, lock washer, Loctite, grease
Seal facing	Feature modification	Clapper, bump stop, seat, water, air
Mounting ring	Part addition	Lever, retaining ring, lever pin, hinge pin, lever spring, Teflon washer, grease, seat, valve body, water, air
Seat	Part division	Mounting ring, seal facing, O-ring 1, O-ring 2, valve body, water, air
Push rod	Material change	Lever, water, air
Lever pin	Material change	Mounting ring, lever, retaining ring, screw, stud, lever spring, Loctite, grease, reset handle, water, air

In Table H. 3, in the affected elements column, only those that have variants are selected and used for the next step. However, water and air is included in the next step after extensively discussing on the different possible variants, and the one that is considered appropriate by the team is used in the list.

H.3 Step 3: Identifying Assembly Combinations

Table H. 4 Element-Supplier-Variant Combination Identification Matrix

Affected elements	Supplier	Variants	E-S-V identifier	Element- supplier-variant combination selection	Reason for selection/ rejection	No of E-S-V's identified per element
Lever (P2)	S1	V1 (Material-1)	P2.S1.V1	Y	To verify galling is not an issue	2
		V2 (Material-2)	P2.S1.V2	Y		
	S2	V1	P2.S2.V1	N	No significant variability between suppliers, and the quantity is around 20 per year	
		V2	P2.S2.V2	N		
	S3	V1	P2.S3.V1	N		
		V2	P2.S3.V2	N		
Valve body (P3)	S1	V1 (Material-3)	P3.S1.V1	Y	Different material; one with ductile iron and the other stainless steel	2
	S2	V2 (Material-4)	P3.S2.V2	Y		
Push rod (P4)	S1	V1 (Material-5)	P4.S1.V1	Y	Two different materials; 300 series stainless steel and Aluminum Bronze	2
		V2 (Material-6)	P4.S1.V2	Y		
	S2	V1	P4.S2.V1	N	No significant variability between suppliers, and the quantity is around 20 per year	
		V2	P4.S2.V2	N		
	S3	V1	P4.S3.V1	N		
		V2	P4.S3.V2	N		
Reset handle (P5)	S1	V1 (Material-7)	P5.S1.V1	Y	Different material; one with Brass, the other one is Stainless Steel	2
	S2	V2 (Material-8)	P5.S2.V2	Y		
Water (P6)	S1	V1	P6.S1.V1	Y		1
Air (P7)	S1	V1	P7.S1.V1	Y		1
Lever spring (P8)	S1	V1	P8.S1.V1	Y	Different sizes and different input force	2
		V2	P8.S1.V2	Y		

Questions to be asked in this step:

Does any element variant dependent on other element variant (yes/no)? Yes

Which is the element on which other element variants are dependent? Valve Body

Table H. 5 Parent-Child Relationship Data

Valve body – P3.S1.V1		Valve body – P3.S2.V2	
Lever:	P2.S1.V1	Lever:	P2.S1.V2
Push rod:	P4.S1.V1	Push rod:	P4.S1.V2
Reset handle:	P5.S1.V1	Reset handle:	P5.S2.V2
Lever spring:	P8.S1.V1	Lever spring:	P8.S1.V2

Total number of combinations = Sum of number of E-S-V identified per independent element = 2

Table H. 6 Combination Vector Table

Element	E-S-V combination	Combination Vectors (Read column wise)	
		C1	C2
Seal facing (P1)	P1.S1.V1	1	1
Lever (P2)	P2.S1.V1	1	0
	P2.S1.V2	0	1
Valve body (P3)	P3.S1.V1	1	0
	P3.S2.V2	0	1
Push rod (P4)	P4.S1.V1	1	0
	P4.S1.V2	0	1
Reset handle (P5)	P5.S1.V1	1	0
	P5.S2.V2	0	1
Water (P6)	P6.S1.V1	1	1
Air (P7)	P7.S1.V1	1	1
Lever spring (P8)	P8.S1.V1	1	0
	P8.S1.V2	0	1

H.4 Step 4: Filter Assembly Combinations

Table H. 7 Requirement to Design Parameter Mapping

Requirement index	Requirements	Variants of the affected elements									
		Valve body		Lever		Push rod		Reset handle		Lever spring	
		Material	Geometric	Material	Geometric	Material	Geometric	Material	Geometric	Material	Geometric
DV-R1.1	The product should not fatigue at the rated pressure			1		1		1			1
DV-R1.2	Product should operate at a pressure above 20 psi of supply pressure			1		1		1			1
DV-R1.3	The product must not show excessive wear			1		1		1			
DV-R1.4	The valve assembly must allow reverse flow without damage and remaining latched										
DV-R1.5	The valve assembly should not be damaged during rapid opening events	1									1
DV-R1.6	The valve assembly must not be damaged at high flow rates through the valve	1									1
DV-R1.7	The flat head Screw should not interfere with the seal facing										
DV-R1.8	The valve assembly should be operational in salt water environment	1		1							
DV-R1.9	The seat must have clearance to fit through mounting ring										

Requirement index	Requirements	Variants of the affected elements									
		Valve body		Lever		Push rod		Reset handle		Lever spring	
		Material	Geometric	Material	Geometric	Material	Geometric	Material	Geometric	Material	Geometric
DV-R1.10	The seat must fit into valve body										
DV-R1.11	The valve must not be damaged at the rated pressure										1
DV-R2.1	The cast geometry of all machined components should have sufficient machining stock	1									
DV-R2.2	The machining process must be capable of meeting print specifications										
DV-R.2.3	The operator must be able to safely assembly components per relevant prints and specifications										
DV-R2.4	The valve assembly should be assembled with tools readily available										
DV-R2.5	Critical assembly specifications of the valve assembly must be maintained										
DV-R3.1	The product should be easily removable/ replaceable										
DV-R4.1	The product should be able to be transported through roadways/ seaways/airways without any failure /loosening of components										

H.5 Step 5: Creating Design Validation Plan Matrix

Table H. 8 Design Validation Plan Matrix

DVP #	2		Date	08.10.2011
DVP Ver #	0		System	DDX valve
Program #	09-25		**Team**	
Requirements doc #	#1		Physical test engineer	Engineer #5
			Virtual test engineer	Engineer #1
			Development engineer	Engineer #1
			Supplier	Engineer #8
			Manufacturing	Engineer #3
			Service	Engineer #6
			Marketing	Engineer #7
			Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R1.1	The product should not fatigue at the rated pressure	Clapper strength must withstand 2 times the rated pressure of 250 psi (**Test #1)**	C1, C2	Physical test	Pressure and time	No damage to seat assembly (no cracks, no deformation) when visually inspected and pass a low pressure operation test	Y				Pass

DVP #	2	Date	08.10.2011
DVP Ver #	0	System	DDX valve
Program #	09-25	**Team**	
Requirements doc #	#1	Physical test engineer	Engineer #5
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		Development engineer	Engineer #1
		Supplier	Engineer #8
		Manufacturing	Engineer #3
		Service	Engineer #6
		Marketing	Engineer #7
		Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R1.2	Product should operate at a pressure above 20 psi of supply pressure	Must operate above 5 psi at a supply of 20 psi (**Test #2**)	C1	Physical test	Pressure	Valve operates above 5 psi	Y				Pass
DV-R1.3	The product must not show excessive wear	500 trips at the rated pressure of 250 psi (**Test #3**)	C1, C2	Physical test	Depth	Wear should not exceed 1/16th of an inch and conduct a low pressure operation test	Y				In-process

DVP #	2
DVP Ver #	0
Program #	09-25
Requirements doc #	#1

Date	08.10.2011
System	DDX valve
Team	
Physical test engineer	Engineer #5
Virtual test engineer	Engineer #1
Development engineer	Engineer #1
Supplier	Engineer #8
Manufacturing	Engineer #3
Service	Engineer #6
Marketing	Engineer #7
Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R1.4	The valve assembly must allow reverse flow without damage and remaining latched	Must meet the reverse flow requirement per FM Std 1020 (**Test #4**)	C1	Physical test	Flow rate, pressure	When visually inspected, the valve assembly should not be damaged and it is latched open	Y				If DV-R1.1 meets then DV-R1.4 need not be tested. In addition, agency did not want this test to be done after their review for the change

DVP #	2
DVP Ver #	0
Program #	09-25
Requirements doc #	#1

Date	08.10.2011
System	DDX valve
Team	
Physical test engineer	Engineer #5
Virtual test engineer	Engineer #1
Development engineer	Engineer #1
Supplier	Engineer #8
Manufacturing	Engineer #3
Service	Engineer #6
Marketing	Engineer #7
Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R1.5[6]	The valve assembly should not be damaged during rapid opening events	Must meet shotgun test per FM Std 1020 (**Test #5**)	C1, C2[7]	Physical test	Pressure	Should not be damaged visually (no deformation on the clapper, no cracks) and conduct a low pressure operation test	Y				Stainless steel combination is not tested because of higher ultimate

[6] Requirement for which new test are scheduled is highlighted in magenta color
[7] New assembly combination identified is indicated in green color

DVP #	2
DVP Ver #	0
Program #	09-25
Requirements doc #	#1

Date	08.10.2011
System	DDX valve
Team	
Physical test engineer	Engineer #5
Virtual test engineer	Engineer #1
Development engineer	Engineer #1
Supplier	Engineer #8
Manufacturing	Engineer #3
Service	Engineer #6
Marketing	Engineer #7
Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
											strength
DV-R1.6	The valve assembly must not be damaged at high flow rates through the valve	Must meet Endurance test per FM Std. 1020 (**Test #6**)	C1, C2	Physical test	Pressure	Should not be damaged visually (no deformation on the clapper, no cracks) and conduct a low pressure operation test	Y				To be conducted

DVP #	2
DVP Ver #	0
Program #	09-25
Requirements doc #	#1

Date	08.10.2011
System	DDX valve
Team	
Physical test engineer	Engineer #5
Virtual test engineer	Engineer #1
Development engineer	Engineer #1
Supplier	Engineer #8
Manufacturing	Engineer #3
Service	Engineer #6
Marketing	Engineer #7
Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R1.7	The flat head Screw should not interfere with the seal facing	Tolerance analysis, CAD packaging (**Test #7**)	C1	Analysis	Interference	Should have 1/32" clearance in the worst case	N				Pass
DV-R1.8	The valve assembly should be operational in salt water environment	Corrosion resistance between striker and clapper shall meet RASCO Salt spray test (**Test #8**)	C1, C2	Physical test	Pressure	Should be operational after corrosion test	N				C1 being ductile is susceptible to corrosion which is why C2 is developed; hence, only C2 is tested

DVP #	2	Date	08.10.2011
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		Development engineer	Engineer #1
		Supplier	Engineer #8
		Manufacturing	Engineer #3
		Service	Engineer #6
		Marketing	Engineer #7
		Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R1.9	The seat must have clearance to fit through mounting ring	Tolerance analysis, CAD packaging (**Test #9**)	C1	Analysis	Interference	Should have ‘x’" clearance in the worst case	N				Pass
DV-R1.10	The seat must fit into valve body	Tolerance analysis, CAD packaging (**Test #10**)	C1	Analysis	Interference	Seat assembles into valve body by hand torque	N				Pass

DVP #	2		Date	08.10.2011
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			Virtual test engineer	Engineer #1
			Development engineer	Engineer #1
			Supplier	Engineer #8
			Manufacturing	Engineer #3
			Service	Engineer #6
			Marketing	Engineer #7
			Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV R1.11	The valve must not be damaged at the rated pressure	Cycle test: The valve must be operated for 500 cycles **(Test #11)**	C1, C2	Physical test	Pressure, count	No excessive wear or damage	N				C1, C2-Fail
DV-R2.1	The cast geometry of all machined components should have sufficient machining stock	Tolerance stack up analysis and design review (**Test #12**)	C1, C2	Analysis	Result of stack up analysis	Machine stock is available in worst case tolerance	N				Pass

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DVP Ver #	0		System	DDX valve
Program #	09-25		**Team**	
Requirements doc #	#1		Physical test engineer	Engineer #5
			Virtual test engineer	Engineer #1
			Development engineer	Engineer #1
			Supplier	Engineer #8
			Manufacturing	Engineer #3
			Service	Engineer #6
			Marketing	Engineer #7
			Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R2.2	The machining process must be capable of meeting print specifications	Sample machining run (**Test #13)**	C1, C2	Demonstration	Part geometry	Part meets print specifications	N				Pass

DVP #	2		Date	08.10.2011
DVP Ver #	0		System	DDX valve
Program #	09-25		**Team**	
Requirements doc #	#1		Physical test engineer	Engineer #5
			Virtual test engineer	Engineer #1
			Development engineer	Engineer #1
			Supplier	Engineer #8
			Manufacturing	Engineer #3
			Service	Engineer #6
			Marketing	Engineer #7
			Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R.2.3	The operator must be able to safely assembly components per relevant prints and specifications	Trial run (**Test #14**)	C1	Demonstration		As per release for production (RFP) requirements	N				In progress*[8]

[8] Tests that are previously planned, before applying this VV&T method, but the testing is in progress

DVP #	2	Date	08.10.2011
DVP Ver #	0	System	DDX valve
Program #	09-25	**Team**	
Requirements doc #	#1	Physical test engineer	Engineer #5
		Virtual test engineer	Engineer #1
		Development engineer	Engineer #1
		Supplier	Engineer #8
		Manufacturing	Engineer #3
		Service	Engineer #6
		Marketing	Engineer #7
		Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R2.4	The valve assembly should be assembled with tools readily available	Trial run (**Test #15**)	C1	Demonstration	Properly assembled	No extra tools required to assemble the valve	N				In progress*
DV-R2.5	Critical assembly specifications of the valve assembly must be maintained	As per RASCO spec number 10141 (**Test #16**)	C1	Demonstration	Spring retraction distance	Is spring force sufficient to retract the piston?	Y				Pass

DVP #	2	Date	08.10.2011
DVP Ver #	0	System	DDX valve
Program #	09-25	**Team**	
Requirements doc #	#1	Physical test engineer	Engineer #5
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		Development engineer	Engineer #1
		Supplier	Engineer #8
		Manufacturing	Engineer #3
		Service	Engineer #6
		Marketing	Engineer #7
		Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R3.1	The product should be easily removable/ replaceable	Someone unfamiliar with the product should be able to disassemble it using either standard or reliable supplied tools (**Test #17**)	C1	Demonstration	Can they do it without significant difficulty?	Should be better than the existing design	N	Engineer #5	09/01/2011	09/05/2011	To be conducted

DVP #	2
DVP Ver #	0
Program #	09-25
Requirements doc #	#1

Date	08.10.2011
System	DDX valve
Team	
Physical test engineer	Engineer #5
Virtual test engineer	Engineer #1
Development engineer	Engineer #1
Supplier	Engineer #8
Manufacturing	Engineer #3
Service	Engineer #6
Marketing	Engineer #7
Packaging engineer	Engineer #4

Requirement Index	**Requirement**	**Test**	**Combination vector**	**V&V method**	**Test measurable**	**Acceptance criteria**	**Need for legal certification**	**Responsibility**	**Start date**	**End date**	**Remarks**
DV-R4.1	The product should be able to be transported through roadways/ seaways/airways without any failure /loosening of components	Increase the vibration level from ‘x’ to ‘y’ Hz in the current vibration test specifications (**Test #18**)	C1	Physical test	Hertz	Should not have any visible deformation or crack	Y	Engineer #4	09/01/2011	09/20/2011	To be conducted

H.6 Step 6: Identifying Acceptance Criteria

(This step was not used in this project, as it was not required, so it was skipped)

H.7 Step 7: Trade-Off Analysis Matrix

Table H. 9 Trade-Off Analysis Matrix

		Tests																				
Requirement	Severity	Clapper strength test (**Test #1**)	Inlet pressure test (**Test #2**)	Wear test (**Test #3**)	Reverse flow test (**Test #4**)	Shot gun test (**Test #5**)	Endurance test (**Test #6**)	Corrosion test (**Test #7**)	Screw - seal Tolerance analysis (**Test #8**)	Screw- seal/ CAD packaging (**Test #9**)	Seat - mounting ring / Tolerance analysis (**Test #10**)	Cycle test (**Test #11**)	Seat body tolerance analysis (**Test #12**)	Machining stock analysis (**Test #13**)	Machining process test (**Test #14**)	Assembly test (**Test #15**)	RASCO Spec 10141 test (**Test #16**)	Disassembly test (**Test #17**)	Vibration testing (**Test #18**)	Low pressure operation test (**Test #19**)	Verification complexity index (VCI)	Rank
The product should not fatigue at the rated pressure	9	4																		4	648	2
Product should operate at a pressure above 20 psi of supply pressure	9		2																		162	8
The product must not show excessive wear	9			4																4	3240	1
The valve assembly must allow reverse flow without damage and	9				1																243	5

Requirement	Severity	Tests																			Verification complexity index (VCI)	Rank
		Clapper strength test (**Test #1**)	Inlet pressure test (**Test #2**)	Wear test (**Test #3**)	Reverse flow test (**Test #4**)	Shot gun test (**Test #5**)	Endurance test (**Test #6**)	Corrosion test (**Test #7**)	Screw - seal Tolerance analysis (**Test #8**)	Screw- seal/ CAD packaging (**Test #9**)	Seal - mounting ring / Tolerance analysis (**Test #10**)	Cycle test (**Test #11**)	Seat body tolerance analysis (**Test #12**)	Machining stock analysis (**Test #13**)	Machining process test (**Test #14**)	Assembly test (**Test #15**)	RASCO Spec 10141 test (**Test #16**)	Disassembly test (**Test #17**)	Vibration testing (**Test #18**)	Low pressure operation test (**Test #19**)		
remaining latched																						
The valve assembly should not be damaged during rapid opening events	9					4															324	3
The valve assembly must not be damaged at high flow rates through the valve	9						1														243	5
The flat head Screw should not interfere with the seal facing	3								1												3	12
The valve assembly should be operational in salt water environment	9							1												1	324	3

		Tests																				
Requirement	Severity	Clapper strength test (**Test #1**)	Inlet pressure test (**Test #2**)	Wear test (**Test #3**)	Reverse flow test (**Test #4**)	Shot gun test (**Test #5**)	Endurance test (**Test #6**)	Corrosion test (**Test #7**)	Screw - seal Tolerance analysis (**Test #8**)	Screw- seal/ CAD packaging (**Test #9**)	Seal - mounting ring Tolerance analysis (**Test #10**)	Cycle test (**Test #11**)	Seat body tolerance analysis (**Test #12**)	Machining stock analysis (**Test #13**)	Machining process test (**Test #14**)	Assembly test (**Test #15**)	RASCO Spec 10141 test (**Test #16**)	Disassembly test (**Test #17**)	Vibration testing (**Test #18**)	Low pressure operation test (**Test #19**)	Verification complexity index (VCI)	Rank
The seat must have clearance to fit through mounting ring	3										1										3	12
The seat must fit into valve body	3												1								3	12
The valve must not be damaged at the rated pressure	9											1									81	9
The cast geometry of all machined components should have sufficient machining stock	9													1							9	11
The machining process must be capable of meeting print specifications	9														1						243	5

		Tests																				
Requirement	Severity	Clapper strength test (**Test #1**)	Inlet pressure test (**Test #2**)	Wear test (**Test #3**)	Reverse flow test (**Test #4**)	Shot gun test (**Test #5**)	Endurance test (**Test #6**)	Corrosion test (**Test #7**)	Screw - seal Tolerance analysis (**Test #8**)	Screw- seal/ CAD packaging (**Test #9**)	Seal - mounting ring / Tolerance analysis (**Test #10**)	Cycle test (**Test #11**)	Seat body tolerance analysis (**Test #12**)	Machining stock analysis (**Test #13**)	Machining process test (**Test #14**)	Assembly test (**Test #15**)	RASCO Spec 10141 test (**Test #16**)	Disassembly test (**Test #17**)	Vibration testing (**Test #18**)	Low pressure operation test (**Test #19**)	Verification complexity index (VCI)	Rank
The operator must be able to safely assembly components per relevant prints and specifications	9																1				27	10
The valve assembly should be assembled with tools readily available	3															1					3	12
The product should be easily removable/ replaceable	1																	1			1	17
The product should be able to be transported through roadways/ seaways/airways	3																		1		3	12

		Tests																				
Requirement	Severity	Clapper strength test **(Test #1)**	Inlet pressure test **(Test #2)**	Wear test **(Test #3)**	Reverse flow test **(Test #4)**	Shot gun test **(Test #5)**	Endurance test **(Test #6)**	Corrosion test **(Test #7)**	Screw - seal Tolerance analysis **(Test #8)**	Screw- seal/ CAD packaging **(Test #9)**	Seal - mounting ring / Tolerance analysis **(Test #10)**	Cycle test **(Test #11)**	Seat body tolerance analysis **(Test #12)**	Machining stock analysis **(Test #13)**	Machining process test **(Test #14)**	Assembly test **(Test #15)**	RASCO Spec 10141 test **(Test #16)**	Disassembly test **(Test #17)**	Vibration testing **(Test #18)**	Low pressure operation test **(Test #19)**	Verification complexity index (VCI)	Rank
without any failure /loosening of components																						
Cost/test		3	3	9	3	3	3	3	1	0	1	3	1	1	3	1	1	1	1	3		
Lead time/test		3	3	9	9	3	9	9	1	0	1	3	1	1	9	1	3	1	1	3		
Performance indicator		9	9	81	27	9	27	27	1	0	1	9	1	1	27	1	3	1	1	9		

Appendix I : INTERVIEW SUMMARY WITH ENGINEERS IN PASSENGER CAR MANUFACTURING COMPANY

I.1 Meeting Summary with Senior Executives of a Leading Passenger Car Manufacturing Company (OEM-#3)

This document is a summary of the meeting held between Prabhu Shankar, Clemson University, and senior executives of OEM-#3. The meeting is about obtaining expert opinion about the verification, validation, and test planning method, as a part of method validation exercise. The details about the experts are provided in Table I. 1

Table I. 1 Experts' Experience Information

Expert	Qualification	Position held	Department	Experience in this auto company
Expert #5	Ph.D.	Manager	Reliability and quality	15
Expert #6	M.S	Team lead	Reliability and quality	14

This meeting was held on 08/04/2011 using teleconferencing system. The meeting began with a presentation by the author about the VV&T method to the experts. After the presentation, experts were requested to present their opinion about the method, specifically on the inclusion of assembly combination vectors column in the design validation plan (DVP) matrix. As the experts provided the opinion jointly, their opinion is expressed as "expert" instead of specifically differentiating between them. As the experts expressed concern in creating an interview transcript, the summary of the discussion, which is written immediately after the discussion, is presented next.

Prabhu: Do you think that including assembly combination vectors can help reduce change propagation effects similar to the example (referred to brake drum overheating problem) presented earlier in the presentation?

Expert: The most important aspect of DVP&R is the identification of appropriate test method to address the failure modes. In the failure example you showed, it is essential to identify the failure mode first then you can identify the appropriate test. We do not recommend identifying tests directly from the requirements. Designers have to understand the functions first, identify their failure modes, and identify corresponding tests. Jumping directly from the requirements to tests may not be sufficient, as some of the failure modes may not be tested at all.

Prabhu: I see where you are coming from, the conventional approach of developing DVP&R from FMEA. The reason why we moved away from FMEA is its limitations in terms of supporting causal reasoning to identify interaction based failures, insufficient description of functions, identification of failure modes from designer's experience, and limitation in occurrence, severity, and detection constructs.

Expert: Failure modes are not identified only based on experience. We have the warranty data from past failures. Also, designers do not do it alone. It is identified based on the team's input. If we are developing a product with new technology, we may not know past failure modes. So, I will not consider that as a limitation. It is very important for the designers to analyze functions and the associated failure modes. In your presentation, in the second step, where you conduct system analysis, you can include steps to analyze functions and their failure modes.

Prabhu: Ok, I will include it. Do you think that if I include functions and failure mode column next to the requirements column in the DVP matrix, it will be strengthened?

Expert: We think so, yes.

Prabhu: What is your opinion about the combination vectors column?

Expert: We feel that including assembly combinations early in the validation plan will help in avoiding problems. Any early work is always helpful. You can keep this step after function analysis.

Prabhu: Do you have any other feedback about this method?

Expert: We do not find much difference between your method and the one we follow, except for the assembly combination study. Apart from the inclusion of functional analysis, we do not have any.

Prabhu: Can you apply this method in any of your current cost reduction projects and provide me a feedback on the effectiveness of this method to address problems of the nature shown in the presentation?

Expert: We deal with projects early in the design and there is no question of assembly combinations at this stage. So, we cannot try it here, but we feel this method is beneficial in the production stage.

Prabhu: Yes, I agree. This method is specifically developed for engineering changes in the production phase and this identification of assembly combinations are more useful at that stage. Thank you very much for your time and feedback.

Appendix J : **E-MAIL FROM THE CUSTOMER**

Message

RE: Questions – Important

David Deurloo (ENG – GVL)

Sent: Friday, September 23, 2011 11:20 AM

To: Prabhu Shankar

You replied to this message on 9/23/11 12:00 PM. Show Reply

You forwarded this message on 9/23/11 12:02 PM. Show Forward

A copy of this message is on the server. Delete from server

Prabhu,

I will try to answer your questions, but some of the answers will be estimates due to the unknowns of when the issue would have been caught.

1.) The time saved in finding the issue during testing is likely between one and three months. This is the typical lead time for this type of component. The only other issue is that if it was not caught when it was, it would have been possible to modify the current parts to remedy the problem. While this would have saved time it would have added to the cost. I would estimate the cost savings to be somewhere around $2000 to $4000. Again this is assuming it would have been caught in the production phase and not after the valve was released.

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If you have any other questions, let me know.

Thanks,

David Deurloo, Product Development Engineer

Figure J. 1 Customer e-mail

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