Electrical Build Issues in Automotive Product Development

—An Analysis

by

John Chacko

Submitted to the System Design and Management Program in Partial Fulfillment of the Requirements for the Degree of Master of Science in Engineering and Management at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

October 2007

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**ABBREVIATIONS USED IN THE THESIS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>2D</td>
<td>2 Dimensional</td>
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<td>3D</td>
<td>3 Dimensional</td>
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<tr>
<td>AIMS</td>
<td>Automated Issues Management Systems</td>
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<td>BOM</td>
<td>Bill of Material</td>
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<td>BOP</td>
<td>Bill of Process</td>
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<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<td>CAE</td>
<td>Computer Aided Engineering</td>
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<tr>
<td>CAM</td>
<td>Computer Aided Manufacturing</td>
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<tr>
<td>CATIA</td>
<td>Computer Aided Three dimensional Interactive Application.</td>
</tr>
<tr>
<td>CC</td>
<td>Clearance Calculator</td>
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<tr>
<td>CPS</td>
<td>Campaign Prevent Specialist</td>
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<td>DIAS</td>
<td>Digital Innovate and Activate Support System</td>
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<td>DPA</td>
<td>Digital Prototype Assembly</td>
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<tr>
<td>DRC</td>
<td>Design Rule Checking</td>
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<td>DRC</td>
<td>Design Rule Checker</td>
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<tr>
<td>ECAD</td>
<td>Electrical Computer Aided Design</td>
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<td>ECAR</td>
<td>Electrical Connector Arrangement Review</td>
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<td>EDS</td>
<td>Electrical Distribution Systems</td>
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<td>FDJ</td>
<td>Final Data Judgment</td>
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<td>FMEA</td>
<td>Failure Mode Effect Analysis</td>
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<td>GPDS</td>
<td>Global Product Development Systems</td>
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<td>ICD</td>
<td>Inter Company Design</td>
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<td>LH</td>
<td>Left Hand</td>
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<td>MCAD</td>
<td>Mechanical Computer Aided Design</td>
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<td>MCR</td>
<td>Material Cost Reductions</td>
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<td>NA</td>
<td>North America</td>
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<td>NPDS</td>
<td>New Product Development Systems</td>
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<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>CPDS</td>
<td>Current Product Development Systems</td>
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<td>PCI</td>
<td>Part Change Incorporation</td>
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<td>PD</td>
<td>Product Development</td>
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<td>PDL</td>
<td>Product Direction Letter</td>
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<td>PDP</td>
<td>Product Development Process</td>
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<td>PMT</td>
<td>Program Module Team</td>
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<td>RQA</td>
<td>Routing Quality Assessment</td>
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<td>SDS</td>
<td>System Design Specifications</td>
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<tr>
<td>SME</td>
<td>Subject Matter Expert</td>
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<tr>
<td>T/O</td>
<td>Take Out</td>
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<tr>
<td>TDR</td>
<td>Technical Design Reviews</td>
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<tr>
<td>VMV</td>
<td>Vapor Management Valve</td>
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<td>VO</td>
<td>Vehicle Operations</td>
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<td>VSM</td>
<td>Value System Mapping</td>
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<tr>
<td>VVT</td>
<td>Virtual Verification Tool</td>
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<tr>
<td>WERS</td>
<td>Worldwide Engineering Release System</td>
</tr>
<tr>
<td>WSS</td>
<td>Wiring Shield System</td>
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Electrical build issues in automotive product development – an analysis

By

John Chacko

Submitted to the System Design and Management Program on October 30 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Engineering and Management

ABSTRACT

To be competitive and successful within the automotive industry the Original Equipment Manufacturers (OEMs) have to bring new products with features fast to market. The OEMs need to reduce the Product Development cycle time. Prototype builds are common in automotive product development. Reducing the number of prototype builds and the related builds issues is very important. This research examines one automotive company’s product development process. Issues pertaining to electrical system typically top the list of build issues. The electrical issues for different vehicle programs were studied. Interviews were conducted with key stake holders of the electrical distribution systems to understand the issues. Finally, based on the study’s analysis and results, effective corrective actions are identified and recommendations for their incorporation are made.

Thesis Supervisor: Professor Thomas Roemer
ACKNOWLEDGEMENTS

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1 INTRODUCTION

The Automotive Product Development landscape has been changing considerably in the past few years. In the Americas instead of the Big Three in Detroit being the symbol of the automobile industry, we are now looking at a Big Six namely GM, Toyota, Ford, Chrysler, Honda and Nissan. Figure 1 below (Wardsauto.com, 2007) shows the North American market share for the Big Six for the year 2006. Plant closings, job cuts and losing market share have been the woes of the major US domestic car makers. For an OEM (Original Equipment Manufacturer) to survive in this highly competitive industry, it should bring a product faster to market faster, surprising the customers with new features and styling. It should also offer this product at a price the customer feels is a bargain. The typical average product development time for a new model is about 36 months and for a minor re-freshening model about 20 months. Bringing products faster to market requires a lot of nimbleness and efficiency in the product development process.

In addition to help grow the bottom line, cost reductions provide the company cash for investment in products that are in the pipeline. Of the various costs that make up the cost of a car, the product development cost is significant. Depending on the scalability of the new product (vehicle) program introduction, the product development costs can vary from couple of hundred million dollars to a billion dollars. Program costs are further escalated due to design failures or the design not meeting the specification. Redesign (rework) has to be performed to meet the design intent. The rework that is required in the product creation process consumes time as well as drives up cost of product development.
1.1 **Background**

The product development process essentially consists of six phases:

Phase 0 – Planning

Phase 1 – Concept Development

Phase 2 – System-Level Design

Phase 3 – Detail Design

Phase 4 – Testing and Refinement

Phase 5 – Production and Ramp-up

These different phases are explained in Chapter 3
In the testing and refinement phase of the product development process, a considerable amount of prototypes are built at certain milestones or gateways of the product development cycle. These prototypes are pre-production versions of the final product. The prototype may be built at the prototype shop, the pilot assembly plant or at the actual vehicle assembly plant depending upon the milestone or gateway of the product development process. At these builds the various prototype parts are assembled together to make the prototype vehicle that require electrical wiring harnesses. Wire harness assemblies consist of raw, coiled wire, which is automatically cut to length and terminated. Individual circuits are assembled together on a jig or table, inserted into connectors and wrapped or taped to form wire harness assemblies (just-auto.com, 2007).

These prototype harnesses along with other electrical components contribute a significant percentage of the top prototype issues. Issues that happen during the build of the prototype vehicle are called build issues. An example of an electrical issue is the wiring harness being short and hence the connector lacking the reach to plug in. Each time a build issue comes up, time and money is spent to resolve the issue for the next build. As shown later, a significant portion of the product development cost is used on such rework cost. This project is to understand the build issues and make recommendation to minimize it. Of the various electrical build issues, this thesis focuses on the Electrical Distribution System (EDS) build issues looks, at the upstream product development process and analyzes the capabilities of the tool sets. In addition the thesis studies the build issues at the OEM as well as its affiliates outside North America.

1.2 Objectives

The objective of this study is to gain an understanding of the EDS build issues in automotive product development. Value Stream Mapping (VSM) is used as an analytical tool to determine the efficiencies that can be made in the product development process. This will help us understand how prototype builds affect the entire product development processes. The primary research objectives are to:

1. Understand the EDS product development process and related prototype builds issues globally.
2. Understand the rework involved during prototype builds through Value Stream Mapping.
3. Formulate recommended changes to the organization's EDS product development process.
1.3 Scope

The extent of this study is limited to the analysis of the EDS sub-system that has the highest number of build issues. The EDS build issues at one particular OEM in North America are studied and analyzed. The analysis focuses on the main causes, recommendations to minimize the issues and roadblocks to implement the recommendations.

1.4 Approach

The prototype build issues of different vehicle programs are studied to understand what the different electrical sub-system issues were. The issues are then broadly classified based into design, manufacturing or quality issues. Team leaders for the related vehicle programs are interviewed to understand the reasons for these build issues. A survey is used to determine what the leading EDS wiring community including the suppliers thought of the different build issues. The wiring suppliers are interviewed to understand the CAD (Computer Aided Design) process. Details about the interviews and survey are presented in Chapters 5 and 6. A Value Stream mapping study is also performed to understand the cost aspect of the rework due to the build issue and is shown in Chapter 4. The EDS processes and tools that are used in the industry were reviewed and summarized in Chapter 3. Finally a Japanese OEM and an aerospace company are interviewed to learn wiring design process and best practices from these companies.

1.5 Structure of Thesis

Figure 2 shows the overall approach taken in this thesis. After an in-depth study of the underlying needs of the New Product Development System (NPDS), Value Stream mapping is applied on a rework model and is used to understand the inefficiencies in the EDS product development process. This model helps to understand the hidden Product Development (PD) factory cost for rework. The hypothesis is developed from the experience the author had working with the EDS product development process. Many PD and supplier subject matter experts (SME) are interviewed through well defined question and answer sessions to understand the working of the CAD tools in the EDS PD arena. The build issues are reviewed and key stake holders interviewed to understand the build issues and the top reasons for the build issues. The wiring community are surveyed to understand the reasons that cause these build issues and also to get recommendations to minimize them.
A Japanese OEM and an aerospace company are interviewed to understand their EDS product development process and to capture best practices. Also literature search is conducted on electrical CAD process and tools.

1.6 Thesis Organization

Chapter 1 gives an introduction of the US automotive industry, a brief background of the problem under review, the objective and scope of this study. In the next chapter a brief overview is provided of the PDP (Product Development Process) and the importance of the Testing and Refinement phase. This chapter also covers the details on the Vehicle System Partitioning and the details of the Electrical interfaces with other sub-systems. Chapter 3 details the EDS design processes and tools used in the automotive industry. It gets into some of the work that is going on in the industry for improvement of CAD tools. It also briefly touches on aerospace EDS. The next chapter provides explanation of the wiring product development process, the model developed for rework in the area of PD and product
verification and Value Steam mapping. Chapter 5 details the interview and data collection process. This chapter also provides the AIMS (Automated Issue Management Systems) data (build issues data), interview with key stakeholders and details of the survey and the interviews. This chapter covers some interviews with another automotive company and aerospace company. The next chapter provides the recommendations and the conclusions. It describes the steps to minimize rework in PD/product verification, involving manufacturing upfront, improvements for CAD tool set. The roadblocks to implement these recommendations are highlighted and future work is suggested.
At the OEM where this case study is being conducted, the product development process, for most of the part is sequential in nature. It involves sequential phases of definition, design, development, and manufacture. Product development is an interdisciplinary activity requiring contributions from nearly all the functions of the firm; Marketing, Design, Manufacturing and Purchasing.

The product development process essentially consists of six phases as shown in Figure 3 (Eppinger, 2000).

Product development opportunities are identified by many sources, including marketing, research, customers, current product development teams, and benchmarking of competitors. In the planning phase the OEM looks at these opportunities from marketing, design and manufacturing standpoints. Concepts that are developed with the consideration of the customer needs are tested during the concept development phase. The production feasibility is also assessed at this time. During the system level design phase, the product architecture is generated and the product is decomposed into subsystems and components. The key suppliers are also identified during this time. In the detail design phase the complete specification of all the parts in the product as well as all the parts are identified. The testing and refinement phase entails the construction of multiple preproduction versions of the product. These preproduction versions undergo reliability testing, life testing, and performance testing during this phase. In the production ramp-up phase the operation of the entire production system begins.

Gateways or milestones are defined under the project management process used to execute the vehicle programs. For the vehicle program to move from one phase to the next, all aspects of the system must achieve a common level of readiness at the same time. Although in a number of activities within a phase, there may be iterations to address shortfalls along the way, and all systems and subsystems move to the next phase at the same time. In some of the new product development process some of the
systems and subsystems individually have separate timing requirements for certain gateways; however collectively they will meet the ultimate timing for the program.

The testing and refinement phase of the generic product development process is time consuming. An automobile is required to meet a host of complex emergent properties, including safety, performance, weight, cost, fuel economy, manufacturability, reliability, etc. Given the complex nature of these emergent property requirements, and the number of interactions between them, automakers must perform extensive verification and validation to ensure that the system requirements are met. For example, to meet the fuel economy numbers, the weight of the vehicle needs to be reduced. To reduce the weight of the vehicle the weight of the engine and the weight of the frames need to be reduced. If the engine is made smaller and if the frames are reduced in size, it affects the vehicle performance which is an emergent property like fuel economy. In the integral product development process, every system and subsystem remains in this phase until the last one meets its requirements to proceed through the gate or milestone. In actuality, it does not take much time to design and build a vehicle; it is this extensive verification and validation process that comprises most of the development time. (Everett, 2003)

The V Model, which this particular automotive company uses, is a model of the Systems Engineering process. This is shown in Figure 4. The left hand side of the V translates iteratively from macro to micro levels. The right hand side is a mainly serial confirmation process moving from the part level up through the complete vehicle life cycle. In the left side of the V, the total systems requirements are cascaded downwards from the vehicle level through subsystems and component requirements. Feasibility is assessed at all levels of all systems and verification plans are developed to be used on the right side of the V. (Ford Motor Company, 2002) The verification of requirements occurs at each level. In the V model, the iterative and parallel processes on the left hand side will streamline with the verification and validation functions on the right hand side. The verification and validation can be completed in a mostly serial fashion, resulting in minimal redundancy or rework. Focusing on component and sub-system/system verification minimizes the need for expensive vehicle level testing, which necessarily has to occur relatively late in a vehicle program.
2.1 Vehicle Partitioning

Systems are made up of a collection of subsystems or in other words the system can be partitioned or broken into chunks into a group of system elements referred to as subsystem. For example, the total vehicle can be partitioned into five vehicle subsystems: Body, Chassis, Electrical, Climate Control, and Powertrain. The overall system behavior depends upon complex interactions/interdependencies/interfaces between the various subsystems. Ultimately they all come together to provide a system function that is greater than the sum of the functions of the individual subsystems.

Managing the interactions and interfaces between the various subsystems is a key aspect of Systems engineering and is essential to achieving customer satisfaction. The reasons for partitioning vehicles into chunks or sub-systems are:

1. To organize a complex system in a way that can be understood and managed.
2. To focus the team on the overall program objective.

The electrical sub-system, that is the focus of this study, interfaces with the other sub-systems as shown in Figure 5. With added customer wanted features like drive-by-wire, traction control, tire pressure monitoring system, reverse park aid, navigation system, infotainment system, entertainment system, and active anti-theft system etc, the electrical sub-system interfaces with all the other sub-systems of the vehicle. Within the electrical sub-system, EDS plays a major role as it is quite expensive and weighs significantly. The EDS consists of the wiring harness and the associated connections to the various functions in the vehicle. Like the electrical wiring in a home, the EDS provides the electrical connectivity between sub-systems of the vehicle. Power, control and communication circuits are all part of the EDS.
Hence it extends into all areas of the vehicle. It is present in the interior of the vehicle, in the engine compartment, the exterior of the vehicle, underbody of the vehicle and even the trunk of the vehicle. The EDS design process is described in the next chapter.
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3 EDS DESIGN PROCESS

To understand the EDS build issues at this OEM better, an insight of the EDS design process is required. Research publications, trade magazines and technical papers from the OEM are reviewed to gain a better understanding of the EDS design process at the OEM and in the industry. The material that is reviewed can be divided into three categories.

- EDS design and design process,
- Tools to minimize issues downstream, and
- EDS issues, causes and efforts to minimize them.

3.1 EDS Design Process

The EDS design is complex for a number of reasons. Firstly the EDS wiring design requirements determine the number of wires to be included in each sub-system and this determines the shape of the curvature and the weight distribution. The environment through which the harness is routed, the capability to service or maintain parts in the vehicle and the accessibility to these parts are some of the important factors that need to be considered in the design. Figure 6 below shows the functional dependencies among design entities for wiring harness design. Thus in the EDS design process, a small modification to the design results in the revision of the entire design. The flexibility of wire harness enables different routes that meet the packaging space conditions. Generally EDS design is determined after considering other sub-systems that impact the vehicle interior package space, so it requires constant design revisions and changes. EDS design is a repetitive operation and is always the first item to be considered in design revision over any other parts from the initial stage of vehicle development. This is because of the short lead time to make changes and the low tooling cost compared to other parts in the vehicle. These design changes are more frequent for a brand new vehicle program especially when there are new added features and contents.

At every automotive OEM, the product development system gives emphasis on reusability and commonality. This strategy helps in reducing the product development cost significantly. Figure 7 below provides an overview of the EDS design process. The existing systems design will be used as a starting block to create the new system designs. With the design transmittals received from other systems and subsystem of the vehicle, the logical schematics are developed. The design transmittals provide all necessary electrical information required for connectivity to other systems or sub-systems. The logical schematics incorporate the vehicle power distribution and grounding.
A 3D harness model root configuration is developed and is used to determine the 2D layout configuration. The most common 3D design tool that is used in the automotive and aerospace industry is CATIA (Computer Aided Three dimensional Interactive Application). CATIA is a 3D Product Lifecycle Management software suite that supports multiple stages of product development. The stages range from conceptualization, through design (CAD), analysis (CAE) and manufacturing (CAM). The 2D layout is developed and the maximum complexity harness topology (the physical routes the wires will take through the vehicle) and the nets (signals) converted into actual wires inside harness bundles are created. Fuses and wires are sized based on the current they are expected to carry. The physical schematics are created. Design Rule Checking (DRC) is performed on the design. DRC is a tool that is used by the designer to ensure that the design meets the specification requirements. Generally the CAD tools have built in menus to perform the rule check. A generic design rule check model is shown in Figure 8.
The wiring harness design is further refined with updates from packaging, adding mechanical components such as grommets and clips. The connectors, terminals, splices, multi-terminations, harness dressings and coverings are also specified. At the topology level the Electrical Computer Aided Design (ECAD) and the Mechanical Computer Aided Design (MCAD) gets integrated. The various devices from the initial schematics are now placed into the harness topology at their correct locations. The bundle and take outs are mapped into the topology. The maximum complexity harness and the Bill of Materials (BOM) are updated. The different derivatives of the harness are generated. The whole design process is repeated a number of times based on the EDS design changes. Four types of input data are merged within a wiring harness software application: (Colonnese, 2007)

- Wiring data that originates from the vehicle electrical design.
- Physical harness information (branch geometry, coverings, clips, etc), which originates from the mechanical design domain.
- Configuration data that describes option relationships and hence, describes variable content within the harness.
- Component data, which originates from a library of approved components.

Once the design is complete, a set of outputs such as harness prints, data feeds to manufacturing are produced.
3.2 Tools To Minimize Issues Down Stream

To minimize downstream issues automated interpretative analysis is performed as early as possible in the design. Analysis like Failure Mode Effect Analysis (FMEA), sneak-circuit and component sizing can be conducted early. Digital Buck is a simulation methodology to analyze component and system interfaces within a full vehicle environment relative to fit, package, and assembly. Digital Prototype Assembly (DPA) is the process by which virtual manufacturing takes place. Built-in tools like Clearance Calculator (CC) are used to check part to part interfaces. One of the ancillary tools that are used during the 3D mechanical design is DIAS (Digital Innovate and Activate Support System). DIAS is used to model physically representative wire harness bundle routings and clearance envelopes in 3D
CAD domain. This tool takes into consideration the wire harness' physical properties and gravitational forces. The key features of this tool are that

- it provides more realistic and accurate 3D harness path representations and
- it develops clearance envelopes to account for dynamic characteristics of harness bundles between retention points (Ford, 2004).

DIAS application tool is run on one of the branches of the engine harness that runs to the sensor that measures the coolant temperature. As shown in Figure 9, the route originally in 3D CAD (shown on the left) does not interfere with any of the surrounding background. When the DIAS deviated surface (the clearance envelope around the harness) is applied (shown on the right) a potential interference is displayed. As a result, various design changes are implemented including tighter bundle length tolerances and a different retainer.

### 3.3 EDS Issues, Causes and Efforts to Minimize Them

Analysis of the electrical design process in many car companies reveals a common list of problems, including (Wilson, 2002):

- Poor integration of the different groups involved in design,
- Poor integration of the design tools used,
- Reliance on a small number of key experts and 'tribal knowledge', with an absence of a well-defined formal design process,
- Absence of tools or procedures for top-down applications of system, subsystem, and component design rules,
- Absence of a formal process for capture and application of knowledge and lessons learned,
- Incomplete procedures and processes for verifying the design,
- Lack of procedures and processes to enforce design and component commonality between successive designs and across vehicle platforms.

More digital verification is done to reduce development cost and time in the automotive industry. Digital mock ups and assembly simulations are used at an early stage of the simulation process. Assembly simulation is performed on the virtual prototype for feasibility and use of assembly. Currently flexible parts like the wiring harness are treated as rigid bodies by the simulation.
Thus the assembly simulation does not truly represent the actual shape of the wire harnesses. This creates build issues at the vehicle assembly plant during the builds. An example is a wire harness showing sufficient clearance to the adjacent components in the assembly simulation because of the rigidity whereas in actuality the harness is flexible and may have a hard interference condition with the adjacent component at the time of the actual assembly build.

There is developmental work happening at the OEMs as well as at the suppliers to simulate flexible bodies. One approach is to consider a wire harness as a spring-mass system with torsion springs for the bending forces that are proportional to the bending angle. The harness is modeled using the Cosserat theory, taking into account the conservation of length, the weight, the bending and the torsion. The Cosserat model for rod like solids models such a three dimensional body like the wire harness as one dimensional while taking into account the properties of the cross section. For the wire harness, one of its dimensions (the length) is much bigger than the other two and its centerline contains most of the information needed to represent them. The rod is modeled as a sequence of mass points (lying on the centerline of the cable) which are connected with different kinds of springs: linear springs for length conservation and torsion springs for bending. The knowledge of the centerline leaves one degree of freedom unspecified, namely for the material rotation around the center line. In order to easily formulate the bending and torsion interaction, a mixed coordinate system is used where each mass point had three space coordinates and the orientation of each segment was represented by a normalized
Each type of interaction was then calculated on the base of the coordinate type that is best suited. (Gregoire, 2006)

Another approach is to use a mechanical simulation function of a 3-D real time simulator. The harness simulation method has two types of modeling of a curve shape, a simplified modeling and a modeling with mechanical properties. The simplified harness simulation function approximately calculates the curve shape of a harness and generates a simple 3-D model based on it using Bezier curve. A third order Bezier curve is determined by four control points. They are the start point, an end point, third point on the extension in a tangential direction from the start point, and a fourth one on the extension in a tangential direction from the end point. The 3-D model from a curve shape model only requires sweeping the cross sectional shape of the harness. A model with mechanical properties is obtained by minimizing the potential energy and is used to simulate an accurate shape. A fifth-order Bezier curve has six control points. The Bezier curve parameters for simple curve modeling are used as the initial parameters for the optimization calculation when the harness is still, and additional parameters like the location of two intermediate control points and the directional component of control points adjacent to both ends are used when the harness is deformed. The system was capable of interactively designing a harness route while verifying the interference and curvature (Hashima, 2006).

Wiring issues during builds are prevalent not only in the automotive industry, but in the aerospace industry too. In both industries, the EDS design process involves the OEM as well as the wiring suppliers and hence there are several locations that are concurrently working on the design. CAD data is very often transferred between multiple locations. It is very important that the CAD design tools are compatible for the transfer of data and that all the sites or locations have one common CAD master package. If they are not compatible, the quality of the data is not good and hence the merging of the wiring and the mechanical data becomes problematic. Faulty wiring harness designs are the root cause of the repeated A380 jet liner delays that have set back the program about two years and delivered a large financial hit to Airbus. A problem in the original build approach was that not all Airbus sites were using the CATIA design tools and some locations were not employing the tools properly. One of the end results is that at the time of the assembly of the harness in the aircraft some of the wire harness is short and could not reach to connect to other harnesses or devices in the aircraft (Wall, 2006).
4 WIRE HARNESS DEVELOPMENT AND REWORK

The objective of the enhanced wire harness development process is to minimize the number of issues identified during physical builds by utilizing virtual tools earlier in the process to flush out incompatibilities with surrounding parts. Correcting issues virtually is much more efficient as well. It saves time and money. It is a matter of correcting harness designs in CAD rather than physical tooling, parts, or providing expedited shipping after harnesses have been built. The time savings are also an enabler for the implementation of the NPDS at my company. NPDS calls for shorter product development cycles to provide new vehicles faster to market. It also calls for simultaneous freeze dates for all components—allowing for collaborative development.

4.1 Value Stream Mapping

Value Stream Mapping (VSM) is a lean technique used to analyze the flow of materials and information currently required to bring a product or service to a consumer. Although VSM is often associated with manufacturing, it is also used in logistics, supply chain, service related industries, software development and product development. It is a visual representation of every process in the product's path from order to delivery (Nightingale, 2004). It is a systems approach to

- Visualize the Entire Product Flow,
- Identifies the Sources of Waste,
- Basis of a Lean Implementation Plan, and
- Determine Future Operating State.

The VSM tool is used to understand the wire harness development process. The following are the basic steps in the VSM process.
1. Define the boundaries
2. Define the value
3. “Walk” the process
   - Identify tasks and flows of material and information between them
4. Gather data
   - Identify resources for each task and flow
5. Create the “Current State” map
6. Analyze current conditions
• Identify value added and waste
• Reconfigure process to eliminate waste and maximize value

7. Visualize “Ideal State”
8. Create the “Future State” map
9. Develop action plans and tracking

4.2 Setting Value Stream Boundary

The boundaries of the VSM are identified to start when a program is first initiated and end at the release of designs to support physical builds - see the boundary diagram in Figure 10. It is crucial to choose these boundaries to maximize the focus on items that can be controlled quickly such as wiring connector arrangement and more efficiently through virtual development. The purpose is to avoid physical build issues by being proactive in the virtual development instead of reactive during physical builds.

4.3 Value/Goal Statement

The overall process and the individual steps within the process are measured against the goal statement to understand the contribution of each step. Those steps that have no contribution are then identified as non-value added. All work performed leads to the ultimate goal of releasing parts for production. With this in mind, the goal statement becomes:

*Release wire harness designs that have been validated virtually to meet all inputs and which improve the quality of initial physical builds.*

The main purpose of the physical builds and the virtual validation is to confirm the design. Historically, more issues occur on physical builds for wiring than during virtual development. This is because of the limited use of activities or tools in the virtual development. An issue that happens during virtual development is easy and relatively inexpensive to fix compare to an issue found during the actual physical build. As mentioned in the goal statement, if we are able to validate the wiring design virtually as much as possible to meet all the input requirements, then we should see few numbers of issues downstream during the physical builds. Therefore, the metric that will be used is the number of design issues identified during physical builds.
Evaluating tasks for their contribution to the goal must occur in order to ensure that the improvements being made are positive. The single most important aspect of value in this project is the elimination or minimization of uncertainty and risk due to issues caused at the time of the physical builds thus improving the quality of the builds.

4.4 Current State VSM

Now that the boundary, goal statement, and aspect of value to consider are completed, the value stream map could be constructed. While assessing each task for contribution, it is clear that the map can be
consolidated to a higher level without losing opportunities for improvement. See Figure 11 for the final "Initial State" Wire Harness Development VSM.

The process mapped encompasses initial CAD development through and including physical builds. There are fourteen (14) major tasks, and thirteen (13) tools or activities identified—see Table 1 below for breakdown.

<table>
<thead>
<tr>
<th>Major Tasks</th>
<th>Tools/Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sections/Initial CAD Created</td>
<td>1. Design Reviews</td>
</tr>
<tr>
<td>2. CAD Refinement</td>
<td>2. Limited DIAS</td>
</tr>
<tr>
<td>3. Finalize Design Freeze</td>
<td>3. Virtual Builds</td>
</tr>
<tr>
<td>4. Bridge 3D / Complete 2D</td>
<td>4. ECAR</td>
</tr>
<tr>
<td>5. Release Package to OEM</td>
<td>5. RQA/Fit Reviews</td>
</tr>
<tr>
<td>7. Prototype Build</td>
<td>7. Identify Cross-functional Team</td>
</tr>
<tr>
<td>10. Mark-up Prints</td>
<td>10. Contain Issue during Build</td>
</tr>
<tr>
<td>11. Mock-up(Initial Verification)</td>
<td>11. Parts from Manufacturing/Final Verification</td>
</tr>
<tr>
<td>12. Update 3D &amp; 2D</td>
<td>12. Focused DIAS</td>
</tr>
<tr>
<td>14. WERS Release/Order</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Description of Major Tasks, Tools, and Activities

Within the VSM shown in Figure 11, tasks are identified as rectangles with a number in front of the task. Tools and activities are identified as rectangles with no numbers. The solid arrows are major information flows, or considered part of the critical path—while the solid unfilled arrows are critical path flows only as required. The thin arrows are considered minor or feedback flows. Finally, the triangles, with numbers, are used exclusively for clarity and indicate continuation of the VSM. They perform no other function.

The major tasks contributing to improving wire harness design are colored red. The activities performed during virtual development are:

i. Design Reviews
ii. Limited DIAS
iii. Virtual Builds

These items could have the most impact on minimizing uncertainty or risk; however, due to the CPDS (Current Product Development Systems) timing, they are not used to their fullest capabilities. In the
CPDS process each component has its own freeze date which causes issues with part compatibility. Components with shorter freeze dates are the parts that have longer lead time. Theses parts need to provide input too early in the process before the design is finalized. An example of this would be an engine. The freeze date for engine is very early because of the longer lead time. Parts with the shorter lead times often become the parts that change more often to fix interface issues even though, from a system's standpoint, it may not always be the most efficient or cost effective. The process becomes inflexible to change. With the staggered freeze dates, design reviews become reactionary. DIAS is run on a limited basis because of the amount of resources required to counteract the flaws in the CPDS timing. This is a powerful tool which models wire harness range of motion between retention points. In future updates to DIAS, it will also be able to check tolerances as well. "High Risk" areas, such as high current cables, or transition areas, are targeted instead of the entire vehicle. It is used with some success in all the vehicle programs that follow the CPDS. Virtual Builds become a "non-event" because they are usually run after long lead and before short lead part freeze dates—creating a mixture of representative parts for the virtual builds.

The majority of the activities are performed on Physical Builds—increasing the reactionary effects. These activities are ECAR and RQA/Fit Reviews. ECAR is the assessment of connectors by manufacturing. The assessment includes insertion efforts, grip type, connector orientation and operation. If an insertion effort issue is identified, there is little time to react efficiently. It is often too late to make a change to a connector, so the only alternative is to add a lubricant to decrease insertion efforts. Unless the connector is an inline—mate between two harnesses—it is nearly impossible to change a connector orientation or type to improve grip. As for operation, if tooling or job allocation is affected, manufacturing processes are often difficult to change the longer you wait. The second activity is RQA/Fit Reviews. This activity checks the overall wire harness packaging and compatibility to surrounding components. Again, system issues are usually resolved by the parts with the shortest lead times. Many times the physical builds occur after the freeze dates for the next build. This causes a domino effect on getting parts reworked and supporting the next build. Changes to tooling or quick builds cause for inconsistent and poor quality parts. Expediting shipping is often used which also increases cost.
Figure 11: VSM - Present State
In the current process, many issues during the physical builds are due to the non existence of virtual verification. (See steps 8 to 11) This causes multiple part changes and the quality of the physical builds to suffer. Reworks are often used to support existing builds so parts are not production representative, which in turn "masks" other issues. The ultimate goal is to improve the virtual verification tools and activities. Since NPDS was being implemented, it was a perfect opportunity to verify the application of the current NPDS tools that are being proposed and to incorporate some enhancements uncovered by this exercise. As mentioned earlier, NPDS forces simultaneous freeze dates which will enable the use of existing and new virtual tools and allow for quality of event activities to occur. True systems trade-off analysis can be performed to determine optimal solutions instead of "band-aid" fixes.

4.5 Cost of Current State VSM

The estimated cost of making a single change based on a single issue, from identification to design completion and part order, is $6379. This cost includes the labor wages for workers in the assembly plant, the engineers, the designers and other administrative costs. It also includes the cost for the revised prototype wire harness that is required for the next build. The labor cost is based on a conservative average hourly rate of $50. Time is estimated in hours and converted to days within the VSM. For every four (4) hours time, one (1) day was assumed to elapse. This estimate is used because the workers have multiple assignments and cannot be exclusively dedicated to the build. However, being a build event, half of their day is still consumed by resolving build issues. It did not affect the cost structure. It is only used to quantify elapsed time.

For a typical wire harness that has ten (10) issues identified during a given build, the cost breakdown is as follows. It is known that a single change through the entire process costs $6379. For each additional issue, the process only goes through Tasks 8-11 (see Current State VSM in Figure 11). This is because the steps 12-14 are common steps and require the same time and efforts whether it is one issue or more than one issue. The costs involved for steps 12 – 14 are $1275. Therefore, if there are nine (9) additional issues, then the added cost would be 9 x $1275 = $11475. The total cost to change a single harness with ten issues is then the cost for steps 8 – 14 for the 1st issue plus the cost for the other nine issues for steps 12-14 which is $6379 + $11475 and is $17854. Similarly for the future state VSM, the total cost to change a single harness with 8 issues is $6379 + 7*1275 and is $15304. Putting the cost numbers into perspective, if we assume that a
A typical build event has (a) 40 AIMS issues on the major harness families, (b) every major harness family changed due to the build issues, and (c) the issues are distributed equally, the total impact would be $71416 as seen in Table 2 below.

<table>
<thead>
<tr>
<th>Base P/N</th>
<th>Description</th>
<th>Current State VSM</th>
<th>Future State VSM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td># of Issues</td>
<td>Total Cost</td>
</tr>
<tr>
<td>14A005</td>
<td>Body Harness</td>
<td>10</td>
<td>$17854</td>
</tr>
<tr>
<td>14401</td>
<td>Instrument Panel Harness</td>
<td>10</td>
<td>$17854</td>
</tr>
<tr>
<td>12A581</td>
<td>Engine Compartment Harness</td>
<td>10</td>
<td>$17854</td>
</tr>
<tr>
<td>14405</td>
<td>Frame Harness</td>
<td>10</td>
<td>$17854</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td></td>
<td></td>
<td><strong>$71416</strong></td>
</tr>
</tbody>
</table>

Table 2: Cost Model for Rework

With the new Future State VSM, if it is assumed that there is a twenty percent reduction in physical build issues due to the improvements, the cost avoidance would be $10200 per build phase. If a program has four build phases, and there are ten vehicle programs, then the total cost avoidance becomes $408,000 over the life of the ten (10) vehicle programs identified.

As seen, the costs quickly add up as issues are identified on physical builds rather than during virtual development.

4.6 Desired Future State VSM

Knowing the NPDS process and having the current state VSM, with the deficiencies noted, the desired future state VSM, as seen in Figure 12, was completed. The major activities/tools are color coded to indicate one of the following:

i. Yellow—New/Modified task per NPDS confirmed by this project to improve upfront wire harness design

ii. Green—New/Modified task in NPDS that can benefit from proposed enhancements from this project

i. New/Modified Task per NPDS Confirmed By This Project to Improve Upfront Wire Harness Design
DIAS
It can be easily seen that the use of DIAS on the complete vehicle would reduce uncertainty and risk. Coupled with production representative parts in the virtual environment, and simultaneous freeze dates, this is a vast improvement over the limited use from today.

Clearance Calc / Virtual Verification Tool (VVT)
As its name indicates, this tool is a clearance calculator. It is automated and performed in the virtual environment. Static parts are checked based on Design Specifications loaded into the system. For harness development, the use of this tool needs further development; however, conceptually, it is a much needed. The biggest risk is that this tool is not "smart" enough to indicate whether parts are attached to each other. It flags any non-compliance based on the inputs provided. Since wire harnesses touch every area in the vehicle, 90% of the issues identified will be as designed. For example, if a wire harness is routed along a frame, and it retains on the frame using clips, the touch-points are flagged as non-compliances every time. Engineers will end up discounting the VVT if this cannot be addressed. Currently, there is an investigation to perform a limited clearance calculation event. However, this would have to be completed manually and the risk is that it may miss some of the true issues.

\textit{ii. New/Modified Task in NPDS That Can Benefit From Proposed Enhancements from This Project}

Virtual RQA / RQA Fit Reviews (Physical Build)
One of the main proposed enhancements of this project is the pull-ahead of the RQA (Routing Quality Assessment). The RQA is a quantitative assessment of the compliance to the design specifications. The key enhancement that this project brings is the continuous review and incorporation of lessons learned. The issues analysis performed during this project is assessed and fed directly into the RQA matrix. Therefore, the matrix will include design specifications and lessons learned. The lessons learned address things to look for during the review of a specific design specification such as areas difficult to see on built vehicles and cross vehicle package environments (i.e. alternators, batteries, etc) which have caused issues in the past.
Virtual ECAR / ECAR (Physical Build)
On a limited basis, parts of ECAR have been performed virtually on recent programs with great success. In NPDS, the process will formally change to a virtual event with only select physical validation required. Utilizing the "Jack" study, which contains a virtual operator with user defined characteristics, it can confirm grip, orientation, and, operation activities. Along with having a better understanding of existing insertion efforts, all phases of ECAR can be completed in the virtual environment. Physical Builds will only be used for selective reviews where insertion forces may be in question or are unknown due to being a new connector. This should eliminate or minimize the number of connector issues identified by the assembly plant. Performing the virtual RQA will minimize the amount of reviews required on the Physical vehicles. The Vehicles can then be used for focused discussions around design environments not easily solved virtually—such as flexible hoses and wiring.

Design Reviews / Digital Pre Assembly (DPA)
An offshoot of improving the RQA documentation is its utilization during Virtual Design Reviews and DPA. Currently, design reviews are performed on an ad-hoc basis. There is no formal approach or focus. Institutionalizing the use of RQA will improve the quality of the virtual design reviews. As for DPA, which are an enhanced version of virtual builds where the design is checked against process, and sequence, in a virtual assembly environment, the RQA will also improve the reviews. In fact, the DPA checklists developed by VO utilize many of the requirements identified in the RQA and suggestions from this project are being assessed.

4.7 Conclusion of VSM Study
As indicated at the beginning of this section, the main goal of this VSM study was to:

*Release wire harness designs that have been validated virtually to meet all inputs and which improve the quality of initial physical builds.*

The goal requirements are met with an increase in the use of virtual validation in the future state VSM as compared to the current state VSM. This cannot be accomplished, to this extent, if the CPDS process is not changing to NPDS. Not only has this been accomplished, but also the quality of the build event has greatly improved due to the nature of NPDS as well. It is intended that the number of overall process steps will not change—only the number of iterations will.
Figure 12: VSM - Future State
Although virtual validation will be more, the number of virtual changes, which are quicker, and cheaper, will increase, while the number of physical changes, which take longer and are more expensive, will decrease. It is believed that the increase of virtual changes will be offset by the number of non-value-added changes in the virtual environment as well as due to the improved tools and processes.

In Chapter 4 where the EDS development process is reviewed, we see that the design process was very iterative and complicated. There was a significant cost associated with the rework due to design issues at the build. Upstream actions are recommended to minimize issues downstream. In the next chapter we try to understand what the design issues are.
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5 DATA COLLECTION, INTERVIEWS AND SURVEY

5.1 Data Collection

To understand electrical wiring build issues better, the wiring build issues from three different programs are collected. The three programs are chosen to understand the following:

1) Are the build issues seen in the North America product development organization different from those that we see outside North America? Are there any common global systemic issues?
2) Is one product development organization better than the others? Can we learn best practices from this organization?
3) Are there any trends of a build issues that are prevalent at only one of the location? Are the build issues a consistent theme for all the organizations?

The build issues data is stored in a database. A query could provide description of the issue, the type of the issues and how that issue is addressed for the next build.

Here is the summary of the three different programs –

Vehicle program A is a major brand new vehicle launched as a 2006MY in North America.
Vehicle program B is a 2008MY vehicle that gets minor freshening in North America.
Vehicle program C is a major brand new vehicle for 2009MY developed outside North America.

Table 3 below gives the summary of the total electrical issues during one of the build events.

<table>
<thead>
<tr>
<th>Program</th>
<th>Type of issue</th>
<th>Total # of issues</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design</td>
<td>Manufacturing</td>
</tr>
<tr>
<td>Vehicle Program A</td>
<td>135</td>
<td>51</td>
</tr>
<tr>
<td>Vehicle Program B</td>
<td>39</td>
<td>13</td>
</tr>
<tr>
<td>Vehicle Program C</td>
<td>160</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 3: Summary of issue for 3 different vehicle programs
5.1.1 Summary of the findings from the data of the three programs

Design issues are significantly higher than manufacturing and quality issues. Program A and Program C had more issues compared to Program B. There is lesser number of issues in Program B because there are only few design changes in a minor freshening program as compared to major brand new program. Compared to Program A, Program C has lesser number of issues. Program A is a 2006MY program and there have been improvements in the CAD toolset as well as the design and development process. Since Program C is developed outside North America and the design & development process may be more efficient when compared to the Program A that was developed in North America. Since design issues are more than 50% of all the electrical build issues, it is clear that if we want to reduce the electrical build issues, then we need to minimize or eliminate the design related build issues.
The design related build issues are a common theme irrespective of whether the vehicle program was developed in North America or outside.

### 5.2 Interviews

To better understand the design issues, interviews are conducted with three key wiring team leaders from the three different programs. They are asked to share their experience of the build issues. The following are the summary of the findings from the interviews with the wiring experts.

- The electrical design issues included wiring related issues, in operation of electrical accessories, unwanted operation of electrical accessories etc
• Majority of the electrical design issues are wiring related. The leaders provided key examples of build issues.

• They all agreed that improvements have been made in all aspects of the wiring harness design and development process in the past couple of years.

• New CAD tools are added and incremental virtual tools were added. But they all felt that there is room for improvement.

• Compared to the North American organizations, the outside of NA organizations have more cross functional digital reviews of the design.

• The outside of North America organizations have issues related to component libraries for wiring not being updated.

• They all agreed that late changes are common and made a big impact to the product development.
5.3 Survey

To understand the primary reasons for the design related electrical wiring issues a survey of the members of the wiring community is thought to be ideal. The survey will give all the key stake holders an equal opportunity to voice their opinion. A survey with four questions is developed to seek the opinion of all the community members that were involved in the design and development of the wiring harness development. The members of the community include wiring design engineers, packaging engineers, designers, manufacturing engineers, technical experts and design managers. The examples that are illustrated by the three wiring design experts are used as the basis for the survey questionnaire. The survey required the community to share their experiences in the automotive industry regarding design related wiring build issues. It also asks recommendations to minimize the build issues. The intended outcome of the survey is not only to get a better understanding of the design related wiring issues from the different product development groups globally, but also use it as an avenue to allow the community, especially the supplier members who do business with multiple OEMs to share their best practices.

The survey is sent to 70 prospective participants. The survey is provided as Appendix A. Question 2 of the survey is modified for half the participants. They are provided the recommendations for minimizing the build issues and asked to add comments where as the other half of the participants have to come up with their own recommendations to minimize the build issues. Only 12 out of the 35 responded from the group of 35 that are not provided the recommendations. For the group of 35 that are provided with the recommendations, 22 of them responded.

5.3.1 Survey results

Overview

A group of electrical wiring professionals is surveyed to uncover the main reasons that cause design related wiring issues and get recommendations to minimize the issues.

The online survey is presented as four questions, asking respondents to rank the main reasons for electrical wiring issues during prototype builds. The survey also asked for their recommendations to minimize the issues from their experience working with the OEM, and working with other OEMs.

Demographics

The survey is distributed to a broad range of individuals in the electrical wiring harness field that includes:
- Employees working at the OEM, which includes design engineers, design supervisors, manufacturing representatives and technical experts.
- Employees working at the Full Service Suppliers, which includes designers, design engineers, design managers and technical experts.

Respondents Role on Product Development Projects

For survey reporting purposes, roles have been consolidated into following categories.

<table>
<thead>
<tr>
<th>Role</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Engineers</td>
<td>10</td>
</tr>
<tr>
<td>Supervisors/Managers</td>
<td>8</td>
</tr>
<tr>
<td>Manufacturing representatives</td>
<td>8</td>
</tr>
<tr>
<td>Technical Experts</td>
<td>4</td>
</tr>
<tr>
<td>Others</td>
<td>3</td>
</tr>
<tr>
<td>Total Respondents</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 4: Details of survey respondents

![Breakout of Respondents by Role](image)

Figure 16: Breakout of the respondents by role
5.3.2 Response to the 1st question

The first question asks the respondents to rank the probable reasons for the build issues. The six probable reasons that are provided in the survey are extracted earlier from the interviews with the three team leaders.

The ranking received for the main cause is shown as in Table 5.

The main two issues that received equal votes are

1) Late program direction forced late wiring design changes.
2) The CAD design tools are not fully capable of showing the flexibility of harness.

In this section of the survey the participants were also asked to mention any other reasons that would cause the build issues. The following are the additional reasons that survey participants mentioned:

1) Design transmittals are not available in time from other sub-systems.
2) Component libraries are not updated with the latest connector, seal and or terminal information.
3) Real world positional tolerances are not accommodated in CAD.
4) Manufacturing capabilities including ability to contain complexity are not integrated into the designs that are released.

The top ranking breakout by role is shown in Figure 17 above. Some of the comments that are received for Question 1 of the survey are attached as Appendix B.

The main reason is the limitation of the CAD tools to show the flexibility of the harness. This results in a different length for the wire harness on the 3D drawings when compared to the 2D print or the manufacturing print. The actual physical wire harness at the assembly plant during the installation takes a different shape or routing when compared to same wire harness that is packaged in 3D. The other main reason is "late changes" due to program direction, and constituted 27% of the votes. Late changes are design changes that are made after the design freeze date. When such changes are forced, design completeness and compatibility gets pushed downstream causing late compatibility reviews. There is not sufficient amount of time to validate and prove out before parts have to be built. Often CAD is not even complete and parts barely make the builds. The electrical wiring design team has to compromise certain steps involved in the design process to meet the timing of delivery of the wire harness to the assembly plant. When we deviate from the normal design and development process, unintended results are obtained. This ends up in design issues during the builds.

The main reasons that come out in the survey were also the main reasons that were hypothesized. The survey also brings up some reasons for the electrical build issues due to lack of discipline in some of
the steps of the design and development phase. One such is the lack of discipline to update the component libraries with latest information regarding connectors, terminals, seals etc.

The current manufacturing simulations tools are not fully capable
Current design compatibility reviews don't follow disciplined process
Agreements made at design compatibility reviews with manufacturing are forced to change by manufacturing during the builds
Last minute changes are forced due to other sub-system issues
Late program direction forced late wiring design changes
The CAD design tools are not fully capable of showing the flexibility of harness

![Breakout of Top Reason by Role](image)

**Figure 17: Breakout of top reason by role**

**5.3.3 Response to the 2\textsuperscript{nd} question**

The second question in the survey seeks recommendations from the respondents to minimize or eliminate the build issues. They are included in Chapter 6 as part of the recommendations. Since this question was open-ended, a lot of comments are received for this question. Most of the responses have some common themes which echo with the hints or thought starters that are provided to half of the respondents.

Most of the respondents acknowledge that last minute change is inevitable. To minimize the quality issues that may arise to added content, one of the most common feedback is to design and package a
maximum option content wire harness and establish a common wire routing pattern that can be reused. Another recommendation is to expand the current cross functional team for the RQA reviews to include experienced senior engineers from other programs to share learned lessons. The respondents also want the suppliers build advance proto types of portions/sections of wire harnesses to understand flexibility issues not seen in digital builds/reviews. The verbatim are included in Appendix C.

<table>
<thead>
<tr>
<th>All Respondents</th>
<th>Number that ranked this reason as their topmost</th>
<th>Percentage that ranked this reason as their topmost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The CAD design tools are not fully capable of showing the flexibility of harness</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>Late program direction forced late wiring design changes</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Last minute changes are forced due to other subsystem issues</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>Agreements made at design compatibility reviews with manufacturing are forced to change by manufacturing during the builds</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Current design compatibility reviews don't follow disciplined process</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>The current manufacturing simulations tools are not fully capable</td>
<td>1</td>
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</tbody>
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Table 5: Breakdown of the votes for the main ranking

5.3.4 Response to the 3rd question
The third question in the survey asks the respondents to share best practices from other OEMs. Some of the respondents are the wiring suppliers. They work with multiple OEMs and follow different design process for the different OEMs. The CAD tools are also different from OEM to OEM. Other OEM's encourage design optimization and sharing of mounting brackets and similar points. At other
OEMs various options are not offered a la carte, hence they have 2 to 4 vehicle levels. This reduces the wire harness complexity significantly. Another OEM hires outside workers to perform operations deemed difficult by the Plant production staff until the next model change where improvements are effected in through the prototype and development phases. They are summarized in Chapter 6.

5.3.5 Response to the 4th question
This question in the survey asks the respondents what kind of professional they are. The details are as shown in Table 3. The information from the 4th question is used to break out the main ranking by role. As show in Figure 17 there is tie for the main rank. It is interesting to note that the working level design engineers consider the limitations of the CAD tools as their top reason for build issues because they deal with these tools on a daily basis. While among the design managers, their top concern was late changes due to program directions. At a managerial level, they have limited hands on time with tools but interface regularly with the vehicle program management. Vehicle program management provides program directions to the vehicle system and sub-system teams.

5.4 Interview with Wiring Suppliers
The EDS suppliers are Full Service Suppliers (FSS); they have the lead responsibility to design the wire harness. The top reason for build issues is identified as limitations of the CAD tool. To understand the CAD tools, the CAD process and to get recommendations for improvement the wiring suppliers is interviewed. The interview process begins by identifying the key EDS suppliers to this automotive company and subject matter experts (SMEs) that are familiar with the EDS electrical harness design. A cross functional interview panel of five members is formed. Three of the panel members work with each one of the wiring suppliers. Of the other two, one is an EDS Technical Specialist and the other is an Electrical Engineering CAD expert. The CAD manager and his team at the suppliers are contacted for these interviews; each interview session lasts somewhere between two to three hours in duration.

A detailed question and answer session follows in a structured fashion with questions related to PD processes in EDS. The electrical build issues of one specific vehicle program are discussed at all the interviews so that the team has one common reference point. Emphasis is placed on questions that relate to the PD processes that are unique for one particular OEM. The questions for the supplier interviews and the findings are included in Appendix D. Each supplier has a different process for the wiring harness design. This is because of the interfacing tool sets and the computer systems they have.
in house. An additional challenge to the suppliers is that each OEM that they work with has unique software and process. Thus the suppliers have to maintain multiple systems and interface to meet the requirements for their different customers. Most of the feedback is to improve the quality of the design work. The general consensus is to have them incorporated by modifying existing check lists and design verification processes. The suppliers request actions to improve the capabilities of the current CAD tool set. The details are shown in Appendix D

5.5 Interview with another OEM

The EDS wiring experts at an OEM which is an affiliate of the company under study are interviewed. The purpose is to:

- Understand whether there are any common PD systems
- Learn EDS design process and practices
- Learn and recommend best practices

The following is the summary of the observations:

- The wiring harness is designed in CAD with an envelope or no touch zone around it.
- There is upfront cross functional team review.
- The mechanical package is fully developed upfront in advance of the DPA milestone.
- There are three main progress reviews during the mechanical package development.
- The sub-standard clearance and interference conditions during the virtual designs reviews are dealt immediately.
- During these reviews, design engineers and managers from other programs are also invited to contribute their wealth of experience from their programs.
- At these reviews, manufacturing department also provide their input and feedback.
- Simulation tools are used extensively to simulate assembly conditions.
- Upfront manufacturing and performance requirements are received and agreed upon. These agreements cannot be violated by either party after the freeze of Mechanical Package.
- The mechanical package leader has final say on the package and always takes the best economical decision after performing trade-off studies.
- The FSS is responsible for confirming and finalizing the wiring CAD package.
• The FSS is also responsible to make actual wire harness or portions of the harness to check for flexibility and stiffness before the actual physical builds.

5.6 Aerospace EDS

EDS design is an integral part of the aircraft product development. As we see in Chapter 2, EDS wiring harness issues happen in the aerospace industry too. When compared to the automotive industry, the EDS design requirements are different and are sometimes very strict in the aerospace industry. The aircraft has to meet the MIL (military) specifications and standards in the design. Due to the landing and take offs in an aircraft, the wire harness design has to consider several G forces. The wire harness has to be routed that it has to endure severe temperature conditions like in the wheel well of the landing gear. The wire harness needs to withstand mechanical stress too, especially the wires routed through the wings and the landing gear. The EDS experts of an aerospace company were interviewed. The purpose is to understand the EDS wiring issues they have and to learn from the best practices they have. The details of the interview are attached in Appendix E.

From the interviews we understood that they don't build prototypes. They rely heavily on tools that work with CATIA for upstream analysis. Some of these tools may provide better analysis than what we have in the automotive industry. The most significant lesson we learn from them is the upfront work that gets done with the pathway creation and reserved space allocation for the wire harness.
6 RECOMMENDATIONS AND CONCLUSIONS

The recommendations that are received from the survey and the interviews are parsed and grouped based on common themes as shown in Appendix F. Below is the summary of the recommendations.

6.1 Recommendations

Many of the recommendations in this section are the culmination of the rework model developed, the survey and the interviews. As a part of this research the author had the opportunity to work with several stakeholders that were involved with the EDS design and development process. Some of the recommendations that are easy to implement are acted upon by the key stake holders immediately. The modifications to the current development processes as identified in chapter 4 are incorporated for the NPDS. The upstream process steps that are not part of OPDS which is now part of the NPDS are the virtual RQA, virtual ECAR, virtual design reviews and DPA.

1) Provide design envelopes as early as possible to protect (example: protect for a larger wiring bundle size, sheet metal trough, wiring shields package protect etc.) space. Team need to work with other commodities to get wiring routing paths designed into the components up front (i.e. wiring channels in sheet metal, space for wiring along frame rails, "river bed" in sheet metal etc). If we establish more common/consistent routing and retention of main harness bundles so that a common BOP (Bill of Process) can be developed then there is an emphasis on continuous improvement of the package rather than a constant re-design (or start from scratch) approach.

   The program teams typically aren't staffed early enough in the program to do this work. The EDS has never been real successful in getting that level of commitment helping with the wiring design. Programs start with an electrical based architecture and preferred routings to achieve, but the ability to deliver to these routings is largely impacted by the Program and Design Studio as well as the packaging efforts and designs of other groups.

2) Minimize complexity (option variants) of the wire harness. Wiring complexity is driving a significant hidden design cost (designs, digital buck files, including design reviews, buck maintenance,
supplier design cost) via the virtual design process. Reduce the complexity by tying features or offerings. An example is anyone that orders a satellite radio option would also get the DVD player. Bundling of options increases the revenue per vehicle but limits the customer from picking and choosing features a la carte. This needs upfront discussions with marketing department and can easily be implemented if agreements are made.

3) Improve CAD tools or better usage of CAD tools.
CAD is not automated and engineers and designers need to use the tool to create the design. The designers are to follow and continuously evaluate the rules in the CAD for things like bend radius to try to prevent designers from showing unrealistic designs. As mentioned in Chapter 3, there is developmental work happening in the industry that may not provide immediate solutions.
Using the CAD tools to evaluate wiring tolerance and other items (like clips, gravity etc) is the role of the EDS Design Engineer, and goes back to many years of having FSS suppliers for EDS. Accordingly, the company has lost some of this design experience and it will take time for the new EDS engineers to develop these skill teams.

4) Work upfront with VO from manufacturing organization.
The following three actions summarize the upfront work with VO and are easy to implement
- VO should be more involved and have more ownership at design reviews and there should be a DIAS sign-off where VO Approves each harnesses DIAS envelopes.
- Conduct pre-build review with VO (Vehicle Operations) on a physical buck at the time when harness is available for electrical breadboard.
- VO needs to discuss assembly constraints. Design teams need to have a better understanding of assembly constraints, i.e. ergonomic issues & complexity. This comes with experience of the EDS design engineer.

5) Improve compatibility reviews.
The following three actions were considered.
- Assign compartment leaders to address all Digital Buck compatibility issues. Today each functional area is expected to resolve its own problems.
Implementing this change needs an organizational change where more authority is given to the compartment 'leader. The compartment leader will do the cost trade off study and give direction to the appropriate sub-system for the compatibility issue resolution.

- Perform "Fresh Eyes" review with senior engineers of other programs during Virtual Phase and early Physical Phase.
  The company can gain from the wealth of experience and lessons learned from cross member teams.
- Wire harness suppliers should come with wire harnesses for "fit" evaluation long before a functional harness is due for the actual build. The suppliers should not have to build any wire harnesses. They build advance proto types of portions/sections of wire harnesses to understand flexibility issues not seen in digital builds/reviews. This can be easily implemented.

6) Implement lessons learned from other OEMs.

The following three actions were from the best practices followed at other OEMS.

- Respects design freeze dates. The only exception they make is for any safety issues or "no-builds." If a feature is not ready for implementation by the freeze date then it is either incorporated in a future build or future vehicle freshening.
  This is slowly being practiced in the company. In due course this will catch on to all vehicle programs.
- Other OEM's encourage design optimization and sharing of mounting brackets and similar points. The current process at this OEM encourages everyone to look out only for their own parts.
  This requires a cultural change where everybody is part of the same team. This would also require more resources dedicated to the basic design group and process that take lead during the pre-program stages.
- Hire outside workers to perform operations deemed difficult by the plant production staff until the next model change where improvements can be effected in through the prototype and development phases.
  This is very hard to implement in a union environment. Need union contract negotiations.
6.2 Conclusions

During the course of this study I had the opportunity to participate in sessions with several talented people of the company. It is observed that wiring design related build issues are inevitable. There is always going to be last minute changes after design freeze due to design validation failures or late program direction. It is also noticed that compared to other parts in the vehicle, wiring is the activity preferred by the vehicle program to make changes, to the last minute because of the relatively short lead time and low tooling cost. In many cases it was also observed that improvement in certain areas reduces the number of build issues. Upfront virtual RQA, virtual ECAR, virtual design reviews and DPA in the NPDS are primary examples. Reducing the number of issues reduces the rework cost portion of the product development cost. Some of the suggestions mentioned in this work are already implemented. Some of them are in progress. Some of the suggestions that involve upper managements support are compiled as a report to senior management.

This study provides a perspective of how complex EDS design and development is. One small design change to a wire harness involves several design steps in the process. Hence the fewer number of changes we have downstream the less cost of rework and less chance for errors. There are still limitations to the CAD tools and progress is being made to improve the tools. Global standards should evolve in the EDS wiring industry to make tools and interfaces common among OEMS and wiring suppliers. Common tools and standards among OEMS and their wiring suppliers will significantly reduce the cost and time for development. In conclusion, there is room for improvement in the EDS design and development process but I think it will take more partnership between the key stakeholders in the industry.

The work done in this thesis can be further extended as follows:

- Develop common standards for wiring design tools and process. Areas of significant interest include the issue of data exchange/data format between key stakeholders.
- Extend the CAD tool applications in the aerospace wiring to automotive wiring, especially the usage of tools upstream.
• Develop analysis tool for Virtual Builds which is an area that is still at its infant stage. The more upfront digital builds we can have, the more build issues we can catch upstream without actually building the part.

• Measure the success of the steps taken.
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APPENDIX A

Here are the details of the survey that was send to the wiring community

1. Introduction

Dear Survey Participant, Whenever we have vehicle builds prior to Job1 of a vehicle program, we encounter electrical wiring issues pertaining to electrical sub-system. As a member of the wiring community, you may have dealt with wiring issues at these builds. The purpose of this survey is to seek the expert opinion of the EDS (electrical wiring) community in regards to

1) Determining the top categories of design related wiring issues
2) Minimizing or eliminating these issues
3) Sharing information about any new tools or technology being used at other OEMs or other industry like aerospace.

This survey should not take more than 30 minutes of your time.

Question 1

Please review the following most common causes of wiring design build issues (with examples that illustrate the various types). Rank them on a scale of 1 - 6, with 1 being the most frequent cause and 6 the least frequent. Please add any other type of issue(s) that you think is/are important.

1) The current CAD design tools are not fully capable of showing the flexibility of the harness. Example - The front LH WSS comes out of the bottom of the Under Hood Harness. As a result the T/O was caught between the main loom and where the hard shell retains on the VMV.

2) The current manufacturing simulations tools are not fully capable.
Example - During manufacturing simulations, the connector design was approved. The design was reassessed as infeasible for manufacturing after the vehicle package completion (including the covering plastic panels).

A new connector was required, unique to the package location for manufacturing to assemble, and the cover with the plastic shroud. If the manufacturing tools had been able to run simulation reliably with final design, the late new costly redesign would have been avoided.

3) Agreements made at design compatibility reviews with manufacturing are forced to change by manufacturing during the builds.
Example – There was no turtle shield on the body harness and during the physical build in the plant, manufacturing forced engineering to design a shield.

4) Current design compatibility reviews don't follow a disciplined process.
Example - Driver-side front door (only) window does not meet System Design Specification for stall force requirement (250N). Window system is carryover from previous model. New model wiring is all new and the line resistance is not the same as carry over. Carry over driver-side front door line resistance is 0.150 Ohms; New model driver-side front door line resistance is 0.110 Ohms. If the requirements were informed earlier and reviewed earlier, the wire gage didn't have to be reduced or length changed.

5) Last minute changes are forced due to other sub-system issues
Example - Cooling issue required an increase in cooling fan motor power. The requirement changed the wire size, and the relay size. As the relay would no longer fit in the relay box allocated space, and redesign of relay (and box strategy) was required (just before final prototype builds).

6) Late program direction forced late wiring design changes.
Example - New integrated E/C mirror and compass just weeks before 1PP for cost reduction resulted in bad appearance on the wire to the mirror.
Question 2

In this section, give your recommendations to minimize or eliminate wiring build issues. Here are a few thought starters.
Kindly expand on these thought starters or make new recommendations.

1) Upstream extensive digital buck and digital build cross functional reviews.
2) Include supervisors, engineers and designers from other programs at the key reviews (three during mechanical package development) for knowledge sharing.
3) Empower vehicle program digital build leader to direct the correction of digital buck issues
4) Make a rule that all manufacturing requirements are provided and complied during development of mechanical package.
5) Make a rule that manufacturing has to abide by the agreements and cannot change them during the builds.
6) Insist on wiring suppliers to build portion of wire harness to understand the flexibility and radius of curvature of the harness.
7) Identify risks involved and get agreements from all concerned parties for all last minute changes.
8) Learn from other industries like aerospace on how to minimize design issues during production.
9) Enforce a disciplined approach with wiring suppliers for CAD package development and subsequent CAD analysis like dynamic studies.

Question 3
If you have dealt with other OEMs or industries that use wiring harness, please describe any best practices or methods that we can adopt to minimize design related wiring issues.

Question 4
What kind of wiring professional are you?
APPENDIX B

Verbatim for Question 1 where the respondents were asked if they had any other top reasons to contribute.

"Poor communication between teams. Most frequent example: Power train changes strategy and information does not get to wiring until already at the build. Almost all device owners guilty of this."

"1.ICD's(InterCompany Design transmittals) not readily available for required change. Connector Library not updated with new connectors / terminals / seals required. Terminals / connectors dropped from library without notification causing delay in 3-D and logical development"

"The 3D to 2D CAD translation process has errors that cause late changes. The wiring CAD design (packaging) is late to UNV1 or UPV1. Consequently, the wiring routing is compromised forcing the team to have to choose between undesirable alternatives. (This is the #1 problem - late planning and packaging of wire routings causing inadequate clearances to accommodate for real world manufacturing tolerances). GAP requirements and SDS clearances are not adhered to (We violate our own packaging requirements). Shields, extra retention, etc are added because REAL WORLD WIRING POSITIONAL TOLERANCES ARE NOT ACCOMODATED IN CAD. TEAMS ARE NOT USING DIAS EFFECTIVELY, even if the DIAS zones are modeled, many of the buck leaders turn off the zones or ignore the interferences."

"Manufacturing capabilities, including ability to contain complexity, are not integrated into design releases"
APPENDIX C

Verbatim of recommendations for improvement or minimize issues

"Provide design envelopes as early as possible (Basic Design) to protect space. Also, re-use common routing patterns to establish packaging space. Get ALL data in CAD for the entire vehicle-- even if it is an envelope. Then refine designs as progression is made"

"Use/Review manufacturing as early as possible. Make sure that the "True" stakeholders are involved with the decisions."

"Wiring complexity is driving a significant hidden design cost to -----, via the virtual design process. Either reduces complexity by giving away more wiring components, or simplified the vehicle offerings. How is it that there are 62 difference body wiring harnesses, designs, digital buck files, also, including design reviews, buck maintenance, supplier design cost, ----- design cost for one vehicle?"

"Late program direction PDL or MCR add that are not ready are often crammed into the program at the last minute by upper management. There is not a sufficient amount of time for validation and prove out before parts have to be built. Often CAD is not even complete as most have to be Advanced PCI'ed /alert into build to barely make the builds."

"There are thousands of wiring harnesses out in the system. Surely wiring harness suppliers can come with mechanical harnesses for "fit" evaluation long before a functional harness is due. The suppliers shouldn't have to build any wire harnesses."

"Assign Compartment Managers to address all Digital Buck compatibility issues. Today each functional area is expected to resolve their own problems"

"Better up front planning with Core involvement and Program concurrence to reduce changes."
"Engage the wiring designer and engineer during the initial packaging of the module. If the module is designed specifically for the program, review the design during the development process. Build mockup/trial parts before the Prototype builds."

"Better and more disciplined alignment of the technology/feature cycle plan with the vehicle cycle plan so that late subsystem changes or introductions are minimized"
APPENDIX D

Interview with wiring suppliers and the findings

Questions for Supplier Interviews

1.) What are your issues pertaining to the EDS Design and Release Process? How can they be improved?
2.) Do you use Digital Buck? How? Where?
3.) Do you use the DIAS tool to check clearances?
4.) What other tools are used or can be used during the Design and Release process? Issues?
5.) How is design changes tracked?
6.) How is missing/needed data communicated?
7.) Do you follow the Electrical Design Process (EDP)? If not, why?

Findings / Recommendations

1.) Update the existing GPDS Design Review Checklists (and verify during TDRs) to incorporate the following:
   a.) Compare 2D views and sections to 3D data to check for consistency.
   b.) Virtually review critical lengths and harness areas for tolerance stack-ups and excess length positioning.
      c.) Review Clearance zone checks (VVT tool already does this in GPDS).
      d.) Review anti-rotation applications for design and assembly issues.
   e.) Review fastener applications with VO for process, commonality, lengths, head size, and tool clearance.
      f.) Develop hanking and stowage strategy virtually.
      g.) Use hand clearance models to ensure proper assembly clearances.

2.) Update the Virtual VO review documentation for DPA5 (in GPDS) with the following:
   a.) Verify anti-rotation application meets VO/Ergo requirements.
   b.) Verify fastener applications with for process, commonality, length, head size, and tool clearance.
      c.) Verify hanking and stowage strategy.
      d.) Hand Clearance models/usage.
e.) Verify blind operations, build sequencing, fastener attachment. (All are already covered in the DPA5 VO checklists.)

f.) Use a truncated version of the VO Checklist for all Virtual Trials.

3.) Standardize use of DIAS:
   a.) Any retention > 200mm
   b.) Any areas with relative movement.
   c.) Any areas routing near sharp edges.
   d.) Any substandard clearance or retention violations.

4.) Develop a Virtual "Fresh Eyes" Checklist similar to the existing Routing Quality Assurance (RQA) Document used on Physical Builds. Use RQA as a starting point.

5.) Areas to investigate further. Need to develop/obtain a tool which:
   a.) can analyze pull off forces for 2-piece grommets or insertion efforts of grommets/fasteners.
   b.) will auto-check in 3D for retainer spacing, routing thru s/m holes, and other SDS's to prompt designers for further evaluation? (Prior to running DRCs.)
   c.) can more accurately predict harness flexibility/stiffness.
   d.) can better simulate harness routing based on bundle size. (CATIA 5 (2/06) has a tool incorporated into it.)
   e.) models motion/vibration/stresses on wiring and wiring components during vehicle operation (in the vehicle environment, engine roll, door cycle, Chassis vibration, etc).

6.) Suppliers need to be onsite so that they can take advantage of the performance improvements, the use of Digital Buck, and communication with the program team.

7.) Program Teams need to use AIMS as a tool for getting data from other teams.

Suppliers need to follow the EDP process for every change so that process improvements can be made and there is consistency and better use of the automated tools inherent to the new CAD toolset.

8.) Design Review Checklist

Need to ensure that clearance zone checks are performed/results are reviewed during design reviews.
Compare of 2D vs. 3D for sections and views.

Results from VO review of Anti-rotation of eyelets during Virtual Build.

Critical dimension review of tolerance stack-up and excess length positioning.

DIAS review of all critical areas and any takeout with >200mm retention.

Results from fastener reviews with VO.

9.) Virtual Build Checklist

Anti-rotation of eyelets review with VO.

Hole verification on Frame, Structures, and S/M.

Verify fastener lengths, head size, and tool clearances.

Predict harness trapping and propose/verify assembly sequence.

Areas for further investigation

Limitations of DIAS with respect to obstructions and predicting harness movement.

Is there a CAD/CAE Tool that can analyze pull off forces for 2-piece grommets.

Is there an auto-check in 3D for retainer spacing, routing thru s/m holes, and other SDS's to prompt designers for further evaluation?

Can/Will CAD predict flexibility/stiffness of harnesses?

What are the capabilities of vibration modeling for EDS?

Can we come up with a flowchart for action (similar to connector selection in SDS details)

Should grommet be stored in closed and open position.

DIAS only operates on Sun Stations and not all FSS use Sun Stations
APPENDIX E

Interview with EDS experts in an aerospace company

Are the CAD tools able to model wiring flexibility and motion?

Simulating the behavior of cables using integrated CAD-CAE tools during the product design process is an important requirement in the automotive and aerospace industries. Real components such as flexible tubes, hoses, wires and electrical wires are so flexible that their shape depends totally on the context in which they are used. This behavior has to be correctly taken into account in design and simulation processes. There is a CAD tool available in CATIA that is dedicated to simulate flexible slender bodies taking into account their physical properties. It provides other applications, such as Electrical Harness Installation. Based on bundle segment properties (length, diameter, etc.), CATIA computes the effective Young modulus and other input needed by the algorithm (cross section shape, flexibility). The algorithm takes into account protective coverings, internal splices as well as wires and wire groups:

- If no wires nor wire groups are routed; bundle segment stiffness is based on individual bundle segment flexibility
- If wires and wire groups are routed, bundle segment stiffness is based on the properties of the wires and wire groups. In this case, individual bundle segment flexibility is ignored.

The simulator tool is able to simulate a harness across a moving assembly (Land Gear, Access Door, Wing Fold, etc.).

Do you use common, consistent routing/retention for their harnesses, allowing lessons learned and experience to drive variability and tolerance control?

The creation of and Consumption of Space Reservations and Pathways start very early in the preliminary design phase. These Space Reservations and Pathways are taken into the Topological Network (Topology is a view of the wire harness routing in the context of the vehicle). The general rules for the placement of the space reservations are based upon lessons learned and experience and is supported by automated trade study tools that look at various design configurations to optimize weight and minimize wire harness count.
The Topological Network provides for Functional and Logical design to have a filtered view of the Physical Requirements for the placement of active equipment and the interconnection. The physical aspects of the vehicle are split into design zones (e.g. pressurized, unpressurized, swamp areas in wheel wells, etc.). The lessons learned are captured in standard design practices and, the KnowledgeWare product has the potential to automate the compliance to these rules.

☐ When is the mechanical package of the wire harness designed? Upfront with established main routes and hard points?

Electrical Systems Physical Design starts in the conceptual design phase by reserving the space for Equipment and Pathways for routing. During this phase many interfaces to structures and other systems are identified and documented. Also at this early stage, the major components or product structure for each harness is defined…allowing concurrent definition of the manufacturing planning.

The automated trade study tool discussed above is used in the conceptual design phase to define the equipment placement and major wiring pathways. Major pathways are defined concurrently with the trade studies for various shapes of the vehicle and studies to define the location of equipment placement. The final output of the trade study is 3D "space reservation" pathway models in the same context with structures and other systems - this methodology essentially forces a discussion & consideration of the needs to reserve and respect the space needs for wiring. Also, this approach enables discussions with the other design teams to provide positive means of separation from structural penetrations, moving mechanism and sharp edges, etc.

☐ What are the type of design issues you would see during installation of wiring harness in the aircraft?

Electrical design considerations for harness and bundle installation are controlled by appropriate manuals and may include but are not limited to:

- The environment and hazards that the harness is in or may encounter;
- Provide prevention chafing of harness or harnesses;
- Slack in harnesses and or bundles;
- Support harnesses and or bundles;
- Tying wire groups and bundles;
• Complying to Bend Radius design requirements;
• Complying to Drip Loops design requirements;
• Complying to harness and bundle splicing design requirements;
• Complying to harness and bundle bonding and grounding design requirements;
• Contact and terminal lug installation requirements;
• Provide for designed harness and bundle loops;
• Allowable modifications or reworks of a harness;
• Electrical installations inspected requirements.

A: Chafing is a very big concern of ours. Some of our aircraft are designed for supersonic speed; can land on an aircraft carriers; and also pull many G's. The wiring support has to be very robust to withstand tremendous vibration and shock loads. We can't allow for wiring to come into contact with something that will cause it to chafe. We also have environmental issues. Carrier based aircraft must deal with salt spray. All components must be able to tolerate salt, and also the cleaning solutions the Navy uses to wash the aircraft. Most of our calls from the shop involve: 1. Wires too long or short. 2. Breakouts not in the correct direction. 3. Wires touching other surfaces or are too close.

**What Mechanical CAD tools do they use to take into account wiring variability and tolerance for wiring package design and compatibility verification?**

- **tolerance for wiring package design** - nothing different that what is explained below for "tolerance limits for the length of wiring harness"

- **compatibility verification** - When we package our wiring bundle, in 3D CAD, we use a CAD tool called Digital Buck... The Digital Buck can be used for verifying the harness is compatible with the surrounding environment. Here we are referring to the part-to-part geometric compatibility of the wire harness to its surrounding environment. For example, we require the wire harness to maintain clearance to certain surrounding parts (6mm to static components, 19mm to dynamic/moving components) in order to avoid cuts, pinches, chafes, etc.. to the wiring harness. This is what we mean by verifying the compatibility of the harness (at least in the mechanical world).
General Comment: Wiring variability has a different context in aerospace. In the "Physical" context, the Standard manufacturing tolerance for a wire harness is 0.25 inches, and in our design standards, we maintain 0.25 inches from structure. In cases where constraints force violations of these design standards, we provide supports and clamping to maintain positive separation. In the "Functional and Logical" context, there are a number of procedures in place to tailor the equipment and wire harness configuration based upon customer options - ultimate goal to minimize weight of the vehicle and meet customer configuration needs.

In cases where the length of the harness is critical to ensure clearance from moving parts, we utilize critical length flag markers to ensure the appropriate amount of slack between clamping points. The manufacturing tolerance on the placement of these critical flag markers is 0.10 inches.

Yes, CATIA V5 Electro-Mechanical Engineering tools account for a great deal of the differences between the 3D and the 2D (Form board & PI). Electrical Systems Physical Design is done in CATIA.

Lastly, after design lengths are developed we added the design lengths to the programs cut lengths formula to establish a manufacturing length for each wire or cable. The manufacturing length is used during cut and code.

- **What are the tolerance limits for the length of wiring harness?** .25 total

- **Tolerance limits for the length of wiring harness** - Due to the limitations of wiring manufacturer, we have to consider wider tolerance limits for the wire harness length... Example - if the distance between two retainers is 100mm we have to provide the supplier with a tolerance of +/- 10 mm. There are also tolerance limits on the overall length of a given wire harness bundle segment. What are your requirements in terms of wire harness manufacturing?

Because of the wide variety of harness lengths there has never been a one size fits all definition of tolerance limits. There must be some discretion left to the designer (given some guidelines) of what tolerance to put on any individual harness. The guidelines include various factors that include the length of the harness, the criticality of signal loss within the harness, the cost of the materials involved, etc. Electrical systems requirements for most systems are in the tens of inches. However a number of systems have much closer tolerances (Like tuned antennas). As for the Installation tolerances these are noted within the design. For the physical design of harnesses we are constrained by signal length requirements.
General Comment: Historically, Most programs have a lesson learned involving major re-design and manufacturing impacts due to wire routing considerations. The vehicles tend to be large, but the requirements for systems separation (e.g. Left Buss separate from the Right Bus, systems redundancy), separation from moving parts, sharp edges, etc. are not easy to maintain – especially when Wire Installation design is an “afterthought” in the design process, or it is viewed as “flexible” and not worthy of up-front design considerations by other design skills.

Over time, cross-functional design teams helped reduce the quantity of issues, however, the overall impact of design teams did not eliminate the problems because the Wire Installation team members were not armed with information in the initial implementations of these teams – even when structures designers were willing to listen, the Wire Installation designers were not armed with the detailed information necessary to provide design needs/requirements in time to support the structures design schedule.

We are not aware of any efforts to attempt to tighten the tolerance of wire harness length in an attempt to minimize wiring chaffing in vehicle designs. Since very small changes in wire length result in significant changes in the sag of a wire harness between clamping points, we recommend an alternative approach that addresses the root causes of the issues.

Assuming the entire design team is sharing models in 3D space and the team is conducting design reviews (to eliminate 3D model clashes). On more recent programs, leveraging automated trade study tools which contained general wire installation needs and routing rules has armed the wire installation designers with information and “best guess” needs. Creating space reservations in conceptual and preliminary design has changed the nature of the role of the wire installation designer in the preliminary design teams – this approach forces the discussions early in the design lifecycle. The result is significantly fewer issues and less impact to structures as the final wiring configuration is defined. Examples of how Wiring Space Reservations initiate discussions with Structures designers:

- Penetrations (holes) in major structural elements. In addition, structures designers providing bracket for supports.
- Positive separation from sharp edges. Routing wiring past a structural stiffener can create a chaffing problem. In the discussion structures designers often volunteer to increase the size of a stiffener to allow a wiring support bracket or clamping device to be installed on the harness.
This approach does have challenges – at the design team level, and in the program planning. Program plan is impacted by changing the criteria for closing of the different design phases and in the staffing of programs. These, are in effect cultural changes which take time to have full effect.
APPENDIX F

While the recommendations are mentioned in bold bullets, the difficulty or easiness to implement them is mentioned below each recommendation in italics.

Design and Packaging Development

- Provide design envelopes as early as possible (Basic Design) to protect (example: protect for a larger wiring bundle size, sheet metal trough, wiring shields package protect...) space. Work with other commodities to get wiring routing paths designed into the components up front (i.e. wiring channels in sheet metal, space for wiring along frame rails, "river bed" in sheet metal etc). Establish more common/consistent routing and retention of main harness bundles so that a common BOP (Bill of Process) can be developed and there is an emphasis on continuous improvement of the package rather than a constant re-design (or start from scratch) approach.

*The program teams typically aren't staffed early enough in the program to do this work. The EDS have never been real successful in getting that level of commitment helping with the wiring design. Programs though start with an electrical based architecture and preferred routings to achieve, but ability to deliver to those routings is largely impacted by the Program and Design Studio as well as the packaging efforts and designs of other groups.*

- Wiring complexity is driving a significant hidden design cost (designs, digital buck files, also, including design reviews, buck maintenance, supplier design cost) via the virtual design process. Reduce the complexity by tying features or offerings. Example anyone that orders a Satellite radio option would also get the DVD player.

*Complexity needs to be maintained at a reasonable amount, but reduced complexity in give away or reduction in offerings has negative cost implications. Bundling of options is a good idea.*

- Put extra care in the design of service loops. They too often become a manufacturing problem because of the difficulty to control their resting location. Some rattle/squeaks/chaffing can be avoided by this.

*This idea can easily be implemented.*

CAD tools
• Improve CAD tools to provide designers with wiring characteristics (either on paper or in the tools) to ensure that they are aware of the bundle characteristics as they route in CAD. Make it a conscious effort to deviate from actual wire characteristics.
Develop tools which can simulate actual wire bundle shape for assembly evaluation

*We have design rules the designers are to follow and continuously evaluate the rules in the CAD for things like bend radius to try to prevent designers from showing unrealistic designs. CAD is not automated and Engineers and Designers need to use the tool to create the design. As mentioned in Chapter 3, there is developmental work happening in the industry that may not have immediate solutions.*

• Use CAD tools can to evaluate wiring tolerance and other items (like clips, gravity etc).

This is the role of the EDS Design Engineer, and goes back to many years of having FSS suppliers for EDS. Accordingly, the company has lost some of this design experience and it will take time for new EDS engineers to develop these skill teams

**Interfacing teams**

• Enforce interfacing teams to meet gateways with good quality design transmittals.

*Our design transmittal submission requirement does not always match the program milestones. We ask for them too early before program decisions are made and component engineers have time to complete the design.*

• Create reporting feature for all electrical teams that requires all changes be reported and review for impact by Electrical PMT's. Some method to eliminate "blind" changes that impact required wiring pin-outs.

*This already exists and is done via milestone compatibility reviews led by the systems engineers.*

• Use/Review manufacturing as early as possible. Make sure that the "True" stakeholders are involved with the decisions. Have samples made to evaluate designs before builds.

*Not a bad idea, but that will create added stress on the EDS and systems team to complete the schematics and prints earlier and thus the process further ahead of the program milestone.*

• VO should be more involved and have more ownership at Design Reviews and there should be a DIAS sign-off where VO Approves each harnesses DIAS envelopes.

*Can be easily implemented.*
• Conduct pre-build review with VO (Vehicle Operations) on a physical buck at the time of breadboard.  

* This is very effective and need to roll out on to all vehicle programs.  

• Design teams to need to have a better understanding of assembly constraints, i.e. ergonomic issues & complexity.  

* This comes with experience of the EDS design engineer.  

• Critical and significant characteristics related to process need to cascade early to VO.  

* This is part of the current process and need to be more disciplined in cascading.  

Compatibility review  

• Assign Compartment leaders to address all Digital Buck compatibility issues. Today each functional area is expected to resolve its own problems.  

* This needs an organizational change where more authority is given to the Compartment leader. The compartment leader will do the cost trade off study and give direction to the appropriate sub-system for the compatibility issue resolution.  

• Fresh Eyes with senior engineers from other programs performed during Virtual Phase and early Physical Phase. Perform Virtual RQA.  

* This is a very good idea and can definitely gain from the wealth of experience and lessons learned from cross member teams.  

• Any dynamic component or surface must provide models of variable positions. Currently only nominal positions are shown or provided. (Seats, steering column, etc.).  

* This is part of today's PD process.  

• Wire harness suppliers should come with wire harnesses for "fit" evaluation long before a functional harness is due for the actual build. The suppliers shouldn't have to build any wire harnesses. They build advance proto types of portions/sections of wire harnesses to understand flexibility issues not seen in digital builds/reviews.  

* This can be easily implemented.  

Last minute changes  

• Better and more disciplined alignment of the technology/feature cycle plan with the vehicle cycle plan so that late subsystem changes or introductions are minimized.
This needs commitment from senior management. Marketing and Business Strategy Office need to align with the Program. Even when there is alignment, if the customer trend changes or there is a demand for a new customer feature there is going to be a last minute change. A recent example is the introduction of Sync as part of the vehicle infotainment systems. This was a go-fast project that was executed in about 18 months.

- Do not accept late system additions; especially all new systems which require new routing and new components. If we accept then, identify risks involved and get agreements from all concerned parties for all last minute changes.

Of late this has become the practice where the working level teams reject late additions. They are then brought into the agreement with all concerned parties.

General

- Make it a discipline to review Lessons Learned and document them diligently. Too many similar issues are coming up from different programs.

We have the process to capture the lessons learned but need to improve the process. The lessons learned from issues are captured in a central repository. Quite often this is overlooked while designing for a new program. The CPS and the technical specialist for the program are additional resources that can share lessons learned.

- Avoid late sourcing of parts.

The company in order to reduce the material cost has developed a strategy called ABF (Aligned Business Framework). Key suppliers are being made strategic partners and have awarded them long time contracts. This strategy also minimizes the number of suppliers the company would have for a commodity. Late sourcing of parts will reduce considerably when the ABF becomes stabilized.

- Reduce the variability in the manufacturing of the wiring harnesses, or plan extra package space (clearances) for the variability that you are going to see. Sheet metal stamping tolerances for holes are +/- 0.25 mm, wiring tolerances for the retainers that go into those holes are +/- 10 mm. At CAD nominal everything looks great but when you get to the first prototype builds ...the tolerance incompatibilities surface ...wire too long, wire too short, wire interferes with another part... need to add convolute...need to add shield...
Making the tolerance tighter on all the wiring will increase the cost (labor time) for no reason. This can be accomplished design diligence to evaluate tolerance stackups. The engineer can always request tighter tolerance where needed for manufacturing or functional reasons.

Ideas for improvement from other OEM experience

- Other OEMs held to design freeze dates and stopped changes following the prototype and development phases.

This is not so simple. As part of the verification phase in the PD process, if we have a design verification test failure or repairs in the field we need to fix it.

- They hire outside workers to perform operations deemed difficult by the Plant production staff until the next model change where improvements can be effected in through the prototype and development phases.

This is very hard to implement in a union environment. Need contract negotiations.

- Options and features are not offered ala carte – hence there are only 2 to 4 variants of wire harness as compared to several variants

This needs a cultural change in the organization's marketing department.

- CAD is the master of the design.

This requires lot of discipline. When designs changes are made very rapidly especially to address issues at the item of the build, CAD is not updated as rapidly and when subsequent changes are made to the design immediately you now have a mismatch between the design and CAD.

- Bill of Process (BOP) is identified at the time of award of contract to the supplier - affects initial design attributes with respect to manufacturing assembly environment -

This is now part of the Engineering Statement of Work.

- Respects design freeze dates. The ONLY exception they make is for any safety issues or "no-builds." If a feature is not implementation ready by the freeze date then it is either incorporated in a future build or future vehicle freshening.

This is slowly being practiced in the company. In due course this will catch on to all vehicle programs.

- Other OEM's encourage design optimization and sharing of mounting brackets and similar points. The current process at this OEM encourages everyone to look out only for their own parts.
This requires a cultural change where everybody is part of the same team. This would also require more resources dedicated to the basic design group and process who take lead during the pre-program stages.